Computer-Aided Container Handling Assistance for Ergonomic Crane Operation

Final Report

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Abstract

Efficient container handling system at the ports leads to reduced ship waiting time, increased productivity, cost reduction, and lowered harmful emissions to the environment. Terminal operators use the free flow of information from the ships to streamline containers that move from the vessel through the gantry cranes or quayside container cranes to the truck or the rail, and finally transport out of the terminal gate. The loading and unloading of containers from a starting position to a destination is conducted visually by experienced crane operators from inside the crane cab situated high above the ground for several hours daily. To improve crane safety and port productivity, we proposed an assistive user interface that integrates visual and haptic (force) feedback to assist the crane operator during container handling process. In this phase, the work focuses on the design and construction of a scaled testbed with visual and force feedback system to provide motion guidance. The visual feedback is provided by a camera and the force feedback is provided through a force-feedback joystick, which are integrated in MATLAB/Simulink. The motion guidance is provided as a force cue to alert the operator of surrounding objects and avoid possible collision. A preliminary experiment was conducted on the testbed to investigate the performance of the integrated system and the feasibility of the proposed technology. Initial results indicate the potential of the system in preventing collision and improved ergonomics; however, further user experiment will be needed.

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A. Introduction

The Los Angeles and Long Beach ports have been one of the busiest U.S. container gateways for decades. Both LA and LB ports handled record-breaking 8.4 million and 7.3 million TEUs (twenty-foot equivalent units) in calendar year 2007, respectively (Goodchild, 2005). With such heavy import and export containers at ports, the loading and unloading processes become a critical component in the chain of good movement. At the ship side, crane operators may move between 220-300 containers on average during a regular 8-hour shift, approximately one container every two minutes (Port of Long Beach). This process relies heavily on the skills of the crane operators, who require extensive training and working in a demanding and poor ergonomic condition due to the fact that the crane operator needs to look downward to monitor the spreader movement and also to avoid collision with other containers and obstacles in the workspace. The vertical distance between the crane driver and the container can reach over 100 feet. To improve performance and ergonomics, we designed a testbed to investigate the application of an assistive user interface that integrates visual and haptic (force) feedback to provide motion guidance to assist crane operators during the loading and unloading tasks (Coronado 2011, Marayong 2011, Yeh 2011). Haptic feedback has been shown to improve user performance in various man-machine tasks, especially in a teleoperated environment where the operator manipulates a distant robotic device through a local robotic device (Payandeh 2002, Rosenberg 1993, Turro 2000). In this first phase of the development, the feasibility study of the application of visual and haptic feedback for port crane operation is conducted via a testbed, which is a simplified 40:1 scaled apparatus of a quayside crane and the cargo.

B. Background

As part of this research, we investigated the current quayside crane operation and practices in order to identify the area of need and develop a guideline on how the proposed technology can be applied most effectively in the actual crane operation. Existing technology related to computer-aided assistance for various crane types were also investigated.

B.1 Current Needs of Wharf Gantry Crane Operation

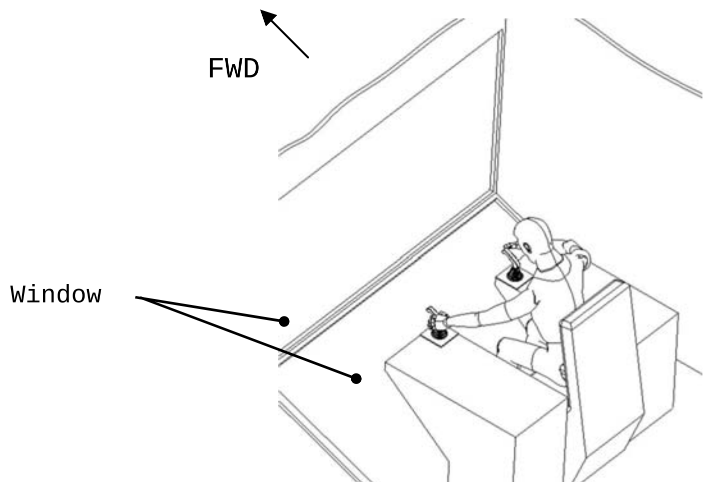


Figure 1. Illustration of the seating position in a wharf gantry crane (Coronado 2011).

At the start of the project, three crane operators were invited to the CSULB campus for an interview. Each crane operator has more than 10 years of experience with multiple crane types. At the beginning of the interview, the crane operators were asked to complete a questionnaire regarding their experience and concerns about the current working condition on quayside cranes. The interview was followed by an open Q&A session with our research team and concluded with a demonstration of the testbed components and the force-feedback joystick. Even though the overall testbed was not fully integrated during the time of the interview, the crane operators were able to comment on the operating speed, the range of operation, and the existing user interface. The list below summarizes the notable comments and observations obtained from the interview:

- On the scale of Extremely High to Extremely Low, the operators rated their work as high stress. However, they have high confidence in the safety of the current working condition.
- The most demanding aspect of the job is the variability that arises during the operation. The crane operators need to constantly monitor a highly dynamic workspace- the cargo, workers, and machineries- to ensure safety.
- Environmental factors, such as dynamic ship movement, wind, and poor visibility, contribute to the complexity of the cargo transport process. This requires the operators' quick response and experience to maintain accuracy.

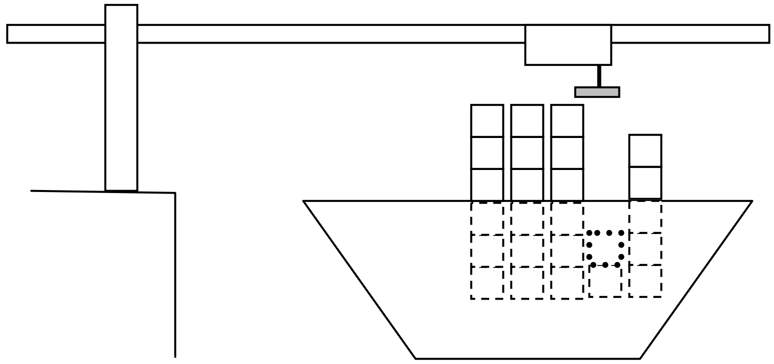


Figure 2. An illustration of “stabbing in the blind” scenario where the crane operator tries to reach the target container, shown in dark dotted line, obstructed by surrounding container

- The operators sit on a rotatable seat with a harness. All operators addressed poor ergonomic working condition, especially on their neck and back, as they need to constantly look down when picking up and dropping off the containers (illustrated in Figure 1).
- Two visual displays of the workspace are available in the trolley. One monitor displays the bird-eye view of the truck from a camera system attached to the back of the trolley. The other monitor gives the computer-generated position of the crane relative to the ship and other general operating information. However, the latter monitor is not fully used.
- In general, the crane motion is controlled by three joysticks. The first joystick controls the motion of the trolley. The second controls the lateral motion of the gantry and the hoist. The third (smaller) joystick is used to adjust the orientation of the spreader bar.
- Increasing accuracy is the operators' main concern for improvement. Accuracy is critical especially when the spreader comes in contact with the container at the truck and on ship.
- Overtime, the operators develop their own techniques to control the movement of the trolley and the container for various operating conditions, such as sway compensation and poor visibility.
- Though varied by the crane model, the trolley and the spreader speed can reach over 150 ft/min and 200 ft/min with load, respectively. The crane operators can move the crane near its full speed as it translates along the boom.
- Some automated features, such as anti-sway, automatic positioning, and speed control, are available; however, they are not always fully used. The operators expressed that they prefer to rely on their skills and execute manually as they feel that the automated control “slow down” the operation or make the crane motion “jerky”.

- In poor visibility, the operators rely on a form of force feedback to help position the spreader. An example of this scenario is called “stabbing in the blind”, illustrated in Figure 2. This occurs on the ship as the operator needs to position the spreader to pick up a container located below the hatch cover behind high stacks of containers.
- The operators are open to review new assistive technology that can work together with the operator to improve crane operation.

Based on the above inputs, we formulate the following recommendations for the development and evaluation of the proposed technology:

- Experienced crane operators can adapt and perform their job proficiently despite the variability that may arise. As the crane operators prefer to control the crane manually in most part of the operation, the proposed technology offers a fitting paradigm that provides assistance to the operator collaboratively on an as-needed basis.
- Better visual feedback and position measurement will have a critical role in improving the accuracy and the ergonomics of crane operation. This suggests that an adjustment of the viewing position and addition of visual guidance can lead to a significant improvement to quayside crane operation.
- The crane operators, though maybe unknowingly, apply some forms of haptic feedback to assist their operation. For example, the operators mentioned that they prefer the joysticks that maintain some “resistance”. In the “stabbing in the blind” scenario, the operators described gently hitting the surrounding containers to self-guide the spreader to the target location. This suggests the potential benefit of haptic feedback and the experimental scenario to test the efficacy of the proposed system.

From the interview, loading/unloading at the truck and on-ship presents the highest challenge during the container handling process with quayside cranes. This step involves accurately position the spreader at the target location in a limited view and a short time. The ship dynamics due to a weight change and weather at port increase the difficulty of this task. The loading/unloading task provides a suitable scenario to evaluate the feasibility of the proposed system. In the initial phase, the system will be tested using a loading task, similar to “stabbing in the blind”, to bring the spreader bar to the target location and pick up/drop off a container.

B.2 Prior Work

Our literature survey has revealed various developments of assistive technology for different crane types including a gantry crane (Kawai 2008, Villaverde 2007), a rotary crane (Vaughan 2010, Yano 2009), and a rough terrain crane (Yoneda, 1995, 1999). Majority of the work discuss using a multi-modal user interface, including Graphical User Interface (GUI) and/or haptic feedback device, accompanied by some forms of assistive technology focusing on payload sway control. Kawai et al discusses the use of stereo CCD cameras and laser sensors attached to the bottom of the crane trolley to provide a visual guidance to position the spreader, both vertically and horizontally (Kawai, 2008). This approach inspires the arrangement of the position sensors in our testbed. However, haptic feedback was not used in their work. A mouse-based Predictive Graphical User Interface (GUI) developed by Vaughan for a small rotary crane provides a visual representation of the predicted stopping point of the rotary crane's payload to guide the trolley position (Vaughan, 2010). The paper concludes that task completion time and positioning accuracy were significantly better with the predictive element.

A number of researchers explore the application of haptic feedback to improve accuracy of crane operation. Motion guidance provided in a form of force feedback increases accuracy and reduces operational time in various human-machine interface applications (Marayong 2004, Wagner 2005). Related to crane operation, a number of multimodal-feedback technologies have been developed. Yano and Terashima developed a joystick with a semi-automatic motion guidance to help an operator avoid obstacles (Yano, 2009). The "guidance" is created by restricting the joystick from rotating beyond certain angles that would cause the payload to collide with an obstacle. Similarly, Yoneda et al created a "control lever" to take the operator command input, and provide the operator with haptic feedback, for control of a virtual rough terrain crane (Yoneda, 1995). Unlike a traditional joystick, the control lever does not rotate about its base. Instead, its end-effector is a grip, which the operator grasps but does not twist. The control lever can provide a haptic feedback in the form of a vibratory sensation to the operator's hand via a small DC motor. The vibration intensity varies depending upon the deviation of the lever's position from the desired position. In the author's earlier work, Yoneda evaluated a multi-modal interface for a rough terrain crane (Yoneda, 1995). The interface assisted the operator with multiple forms of feedback display, including visual, auditory, and tactile feedback. For the visual display, the operator was presented with four screens, showing 1) a side view of the load with its shadow on the ground, 2) an arrow indicating desired joystick direction, 3) bars indicating desired joystick position, and 4) a side view of the crane. The auditory feedback consisted of two different audible sounds: an oscillating sound for which a higher tone indicated greater amplitude of oscillatory movement in the load and a non-oscillating sound for which a higher tone indicated faster movement of the crane. The tactile feedback was provided via a joystick. In a simulation, the interface was shown to decrease the task time.

A more recent work by Villaverde explored using a PHANTOM Omni force-feedback robot (SensAble Technologies) to teleoperate a lab-scale physical model of a gantry crane known as the 3DCrane (Inteco Limited) (Villaverde, 2007). While a force-feedback robot was used, the authors did not discuss the application of haptic feedback as a source of motion guidance, but rather using the robot simply as an input device. The research focused on the control technique developed to achieve system stability in the presence of time delay and load dynamics. Though the paper presents a novel manipulation paradigm, converting the current manual crane system to a teleoperated system will require major infrastructural changes and will be difficult to implement at the ports. In addition, the Omni may not present an ideal input device for port crane as it requires an operator to grasp a wand-like extension, an action similar to grasping a pen.

C. Testbed System

In this work, a feasibility study of a user interface with enhanced visual and haptic (force) feedback to assist quayside crane operators during container loading and unloading process was investigated. The multimodal-feedback user interface provides the assistance to the operator in the form of motion guidance commands. As illustrated in Figure 3, the system utilizes a camera system to obtain the position of the crane cab (spreader bar) and the target container relative to the environment to compute the guidance commands to be communicated to the operator through the force-feedback joystick. The camera is also used to provide the view of the workspace. The

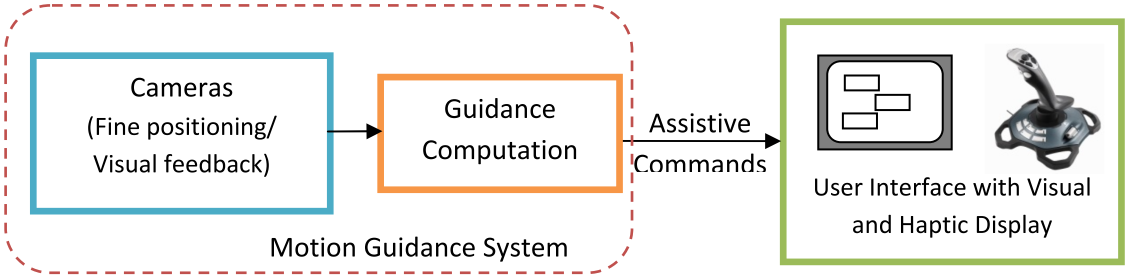


Figure 3. Overview operation of the proposed motion guidance system.

motion guidance is used for fine positioning to bring the spreader bar to the target container or a target location and avoid collision with the surrounding objects. In this first phase of the project, we developed and evaluated the concept of motion guidance system and a user interface with haptic and visual feedback on a scaled testbed. The following sections describe the design of the testbed system.

C.1 Crane Apparatus

To evaluate the proposed technology, a lab-scale testbed of a quayside crane was designed and built to allow the integration of visual and haptic feedback. To replicate the operation of the quayside crane, the testbed consists of three translational stages, a simplified model of the spreader mechanism, and model containers. The crane apparatus and the spreader mechanism are shown in Figure 4. The testbed applies approximately 40:1 scale for the crane and the cargo container. The overall dimensions for the crane testbed were based on the capacities of existing quayside gantry cranes, such as crane manufactured by Mitsubishi Heavy Industries, which can raise a container to a height of 40m, and move it horizontally a distance of 63m (Mitsubishi, 2002). Since the dimensions of gantry cranes vary by make and model, the lifting and horizontal travel capacities of these cranes are approximated as 50m. This translated to a requirement on the overall testbed dimensions of 150cm x 150cm x 150cm. The overall dimensions of the model container were set at 15.2cm x 6.1cm x 6.5cm based on the 40:1 scale of a standard-sized container, or 1 Twenty-Foot Equivalent Unit (TEU) (Port of LA, 2004). The crane motion was achieved by an assembly of three motorized translational stages. Each stage has a travel length of 40in (approximately 100cm). Two linear stages coupled together in a parallel arrangement support the third single linear stage.

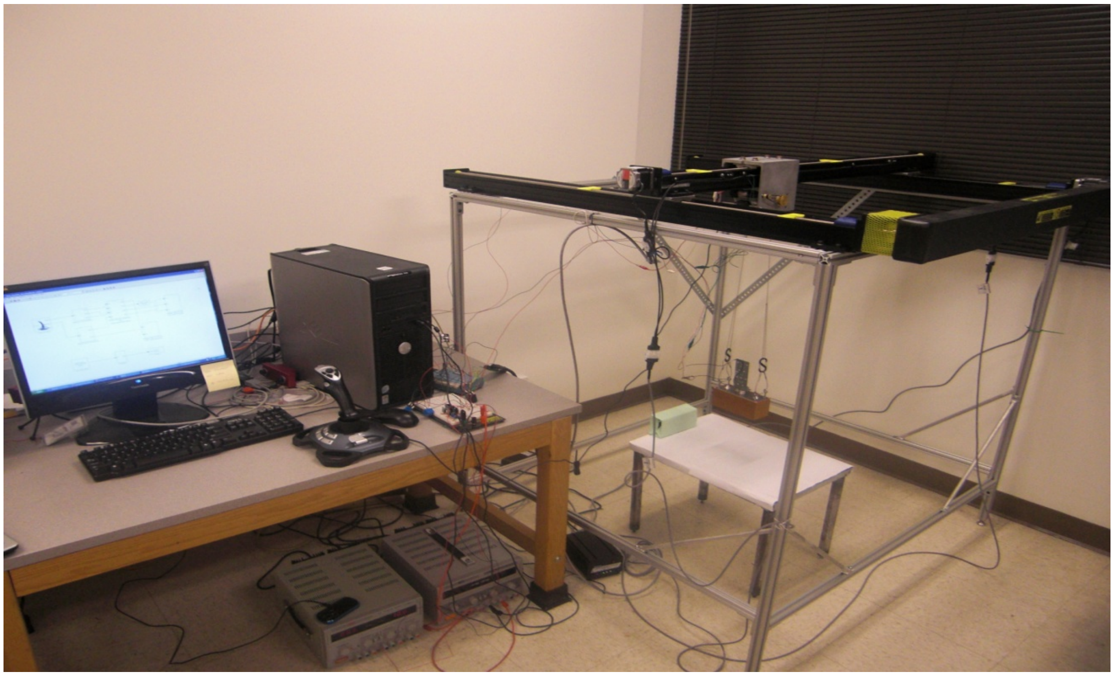
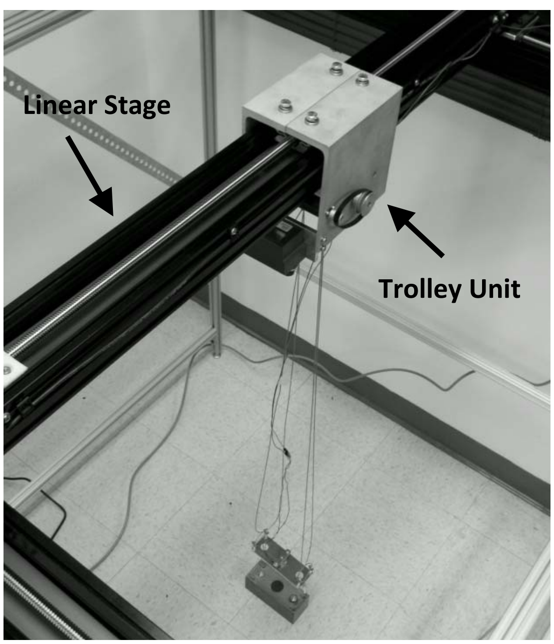


Figure 4. Overview of the crane testbed with joystick control through a PC.



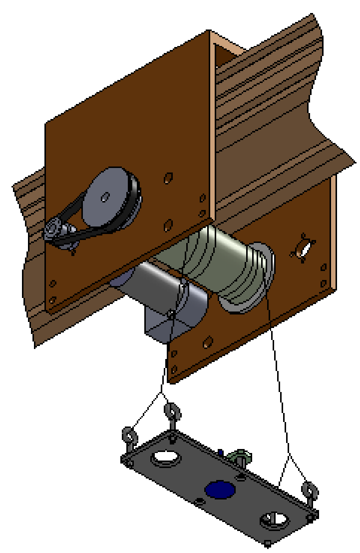


Figure 5. (Left) Testbed's trolley unit on the single linear stage, which moves on the parallel stages and (right) the exploded CAD drawing of the hoisting mechanism.

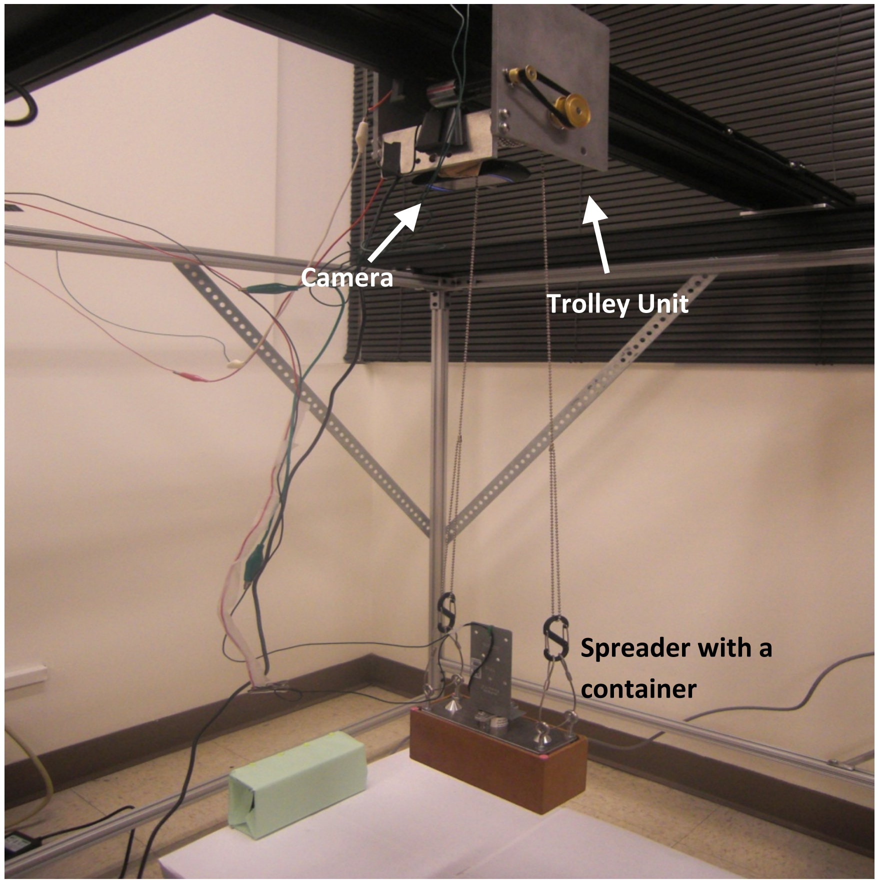


Figure 6. The final trolley unit with the camera, spreader, and a scaled container.

The testbed trolley, as shown in Figure 5, is mounted directly below the carriage of the single linear stage. The parallel stages create the motion of the trolley in the direction along the ship's length. These stages support the motion of the third stage simulating the trolley movement along the boom across the ship. The hoisting mechanism for the model container is located entirely within the testbed trolley unit shown in Figure 5. The hoisting mechanism consists of a motor-driven drum onto which two wire ropes wind. Rotation of the drum in one direction unwinds the wire ropes, which lowers the spreader assembly, and rotation of the drum in the opposite direction winds up the ropes to raise the spreader. The spreader, made of a 3.3mm thick rectangular aluminum plate, has an eyebolt at each corner for attachment of the hoisting mechanism's wire ropes. Instead of using a mechanical latching as in the actual crane, the testbed spreader secures and releases a model container via an electromagnet switch. When the spreader is lowered onto a container, holes in the spreader align with guides on top of the container to position the electromagnet onto a mild steel disk affixed to the container. A web camera is attached to the trolley unit to provide the top view of the workspace with the spreader and container unit below. Figure 6 shows the final assembly of the trolley unit with a container attached at the bottom.

The entire system is supported by a frame constructed from 80/20 aluminum T-slot framing assembly. Taking into account the height of the trolley, the maximum travel in the z-direction is approximately 91cm. The linear stages are driven by stepper motors, and are capable of positioning accuracy of 0.076mm. Although capable of high accuracy in positioning, the stages are not capable of high speed; both sets of stages have the maximum speed of 2cm/s. Based on the information obtained for a port crane, the maximum speed of the trolley and the spreader can reach close to 76cm/s and 100cm/s with load, respectively. However, the resolution requirement in positioning of the actual crane is unknown. Though the workspace scaling was achieved, the requirement for speed and resolution is more challenging due to the physical limitation of the hardware available.

C.2 Control of Crane Motion

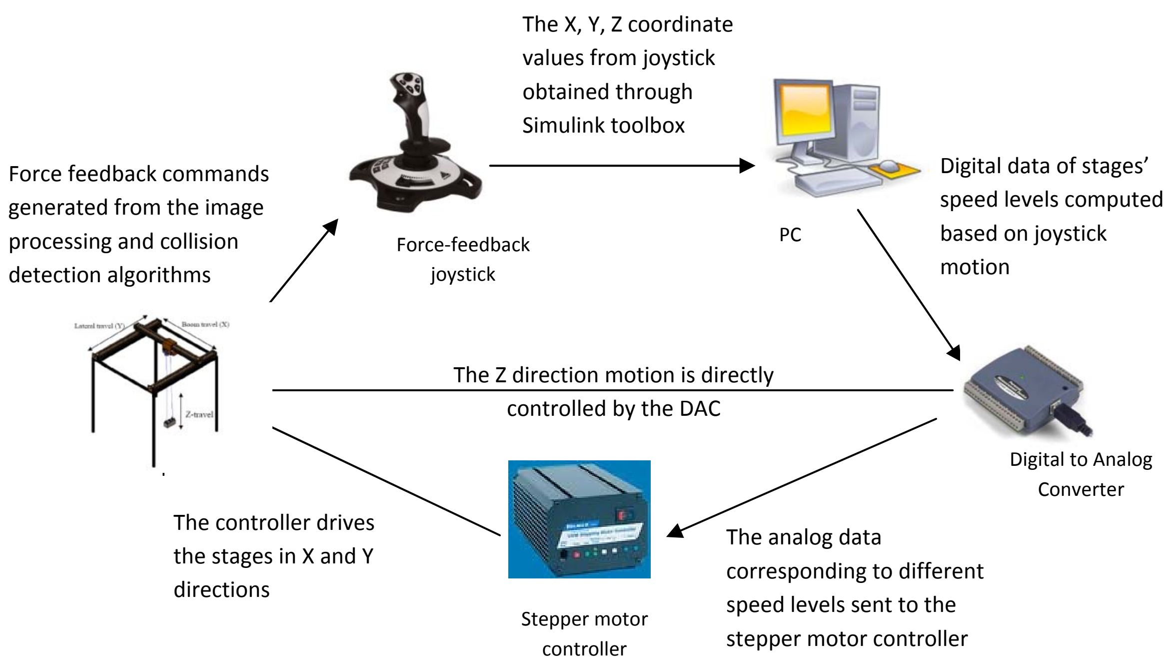
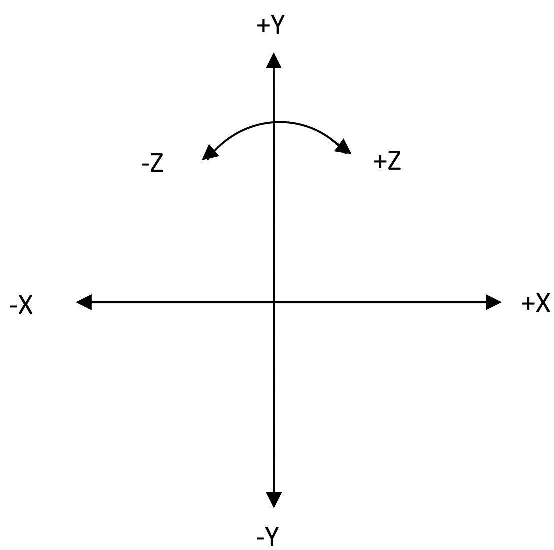


Figure 7. Operational flow diagram of the motion control of the crane apparatus.

The crane testbed and the user interface are integrated and controlled through MATLAB/Simulink on a PC. The diagram shown in Figure 7 depicts the subcomponents the motion control system of the testbed. The user controls the 2-dimensional (X and Y) planar motion of the linear stages and vertical (Z) hoist via a Logitech Force 3D Pro force-feedback joystick. Figure 8 describes the directional mapping of the joystick motion and the motion of the stages and the hoisting mechanism. The left-right motion of the joystick corresponds to the motion along the negative and positive X direction, respectively. The forward-backward motion of the joystick moves the stage along the positive and negative Y direction. To control the hoisting mechanism, the user twists the joystick clockwise and counterclockwise to move the container up and down, respectively. Currently, the motor is set to move at a constant speed in both upward and downward direction. The speed can be adjusted by changing the output voltage to the motor from the separate power supply. An electromagnet switch is used to grab and release the model container from the spreader. A trigger button on the joystick is used to activate and deactivate the electromagnet. The controls for the trigger is designed to toggle between activate and deactivate by using relay circuits. Total of three relays have been used, two relays for the Z axis movement and one relay for the electromagnet On/Off operation. Two relays act as a switch for the motor operation in clockwise and counterclockwise direction. The relays are activated by two DAC outputs, which are controlled by the twisting motion of the joystick through Simulink.



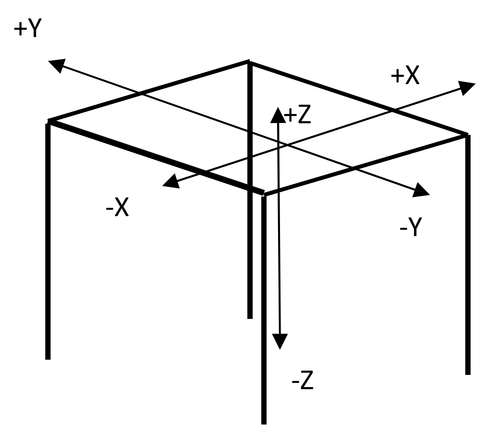


Figure 8. Directional mapping of the joystick and the testbed motion

The stepper motor controller, VXM (provided by Velmex, Inc.), has a 10-bit analog-to-digital converter (ADC) for general use, motor speed setting, or for use with an analog joystick. The joystick essentially behaves like a potentiometer, which varies resistance and, hence, the voltage output when the user moves in either the positive direction or the negative direction. With the Logitech force-feedback joystick used, the two extreme voltage values are between +5V and 0V in both left-right (±X) and forward-backward (±Y) direction. The "zero" position of the joystick is at the center with the voltage output of +2.5V. The position of the joystick is measured in increments from -100 to 100, with the extrema being the extreme position of the joystick in its XY direction. A deadzone is set for the joystick position between ±40 increments. To relate the joystick position to the linear stage velocity, the following linear control law is used for the X and Y stage motion. The voltage outputs vol_x and vol_y are the voltage commands to the stepper motors of the two linear stages.

$$vol_x = \begin{cases} 2.5, & |x_j| \leq 40 \\ \frac{2.5(x_j - 40)}{60} + 2.5, & \text{Otherwise} \end{cases} \quad (1)$$

$$vol_y = \begin{cases} 2.5, & |y_j| \leq 40 \\ \frac{2.5(y_j - 40)}{60} + 2.5, & \text{Otherwise} \end{cases} \quad (2)$$

x_j and y_j are the joystick position in the X and Y direction, respectively. Figure 9 gives the voltage output profile of the control law. For the forward motion (positive direction), the voltage output ranges from 2.5 V to 5V, as applicable for both X and Y direction. For backward motion (negative direction), the voltage output ranges between 2.5 V to 0 V. The speeds of the stepper motors are directly proportional to voltage applied with 2.5V to 5V resulting in motion in the positive XY direction and, similarly, 2.5V to 0V results in movement in the negative XY direction. The voltage versus speed profile of the stepper motor is also shown in Figure 9. The minimum speed is 0.006 in/sec (i.e. 24 steps/ second), and the maximum speed at 5V is 1.5 in/sec (6000 steps/second). In our testbed system, the user is allowed to move the linear stages along one direction at a time. Though the controller is capable of commanding simultaneous XY motion, the sequential motion is used as it more closely represents the actual motion of the port crane in which the crane operator can only move one direction at a time.

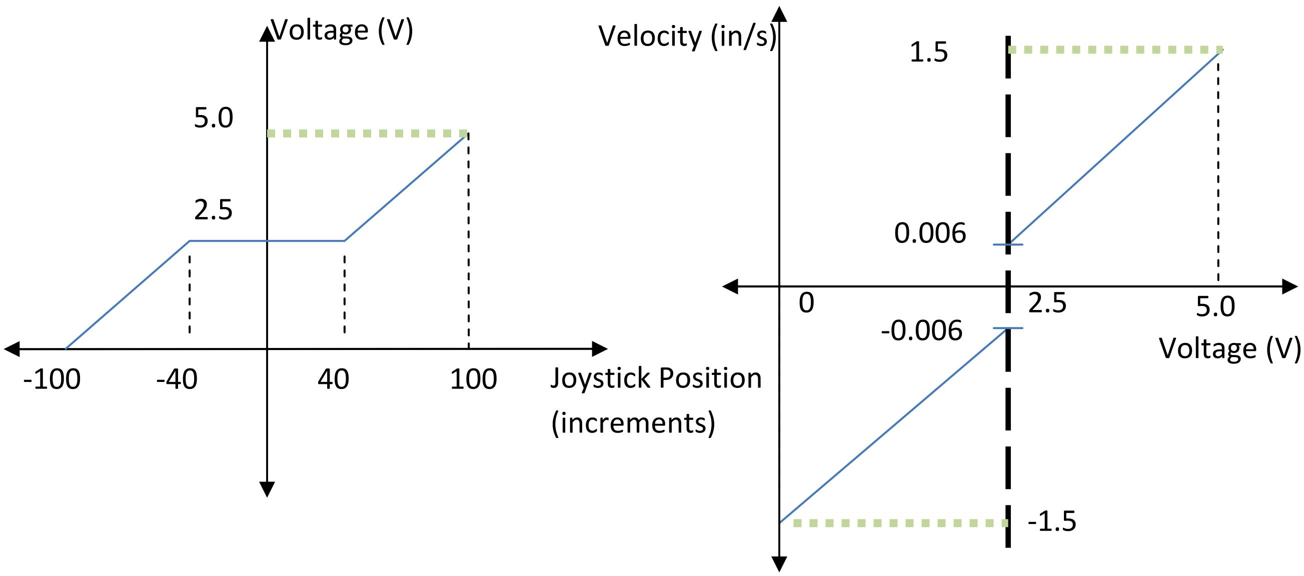


Figure 9. (Left) voltage output profile based on the joystick position and (Right) the commanded voltage vs. velocity profile of the stepper motor.

D. User Interface with Visual and Haptic Feedback

To create the motion guidance command, the position of the container relative to surrounding objects must be known in real time. To achieve this, a camera is used as the position sensor in our testbed. The camera is mounted on the moving trolley unit. It is used to determine the relative position between the container and surrounding obstacles via image processing techniques. Additionally, the camera provides a live video as a visual feedback to assist the operator during container handling process. Real-time position measurements obtained from the camera is used to compute the force feedback that is displayed to the operator through the joystick. The diagram shown in Figure 10 describes the integration of the crane apparatus and the visual and haptic interfaces.

D.1 Integration of Visual Feedback

Visual feedback is added to provide the operator with the view of the workspace and the relative position of the spreader/container with respect to the environment. The later information is needed for the force feedback calculation. As a preliminary setup to prove the concept of visual and force feedback, we used a Logitech color web camera and perform simple color

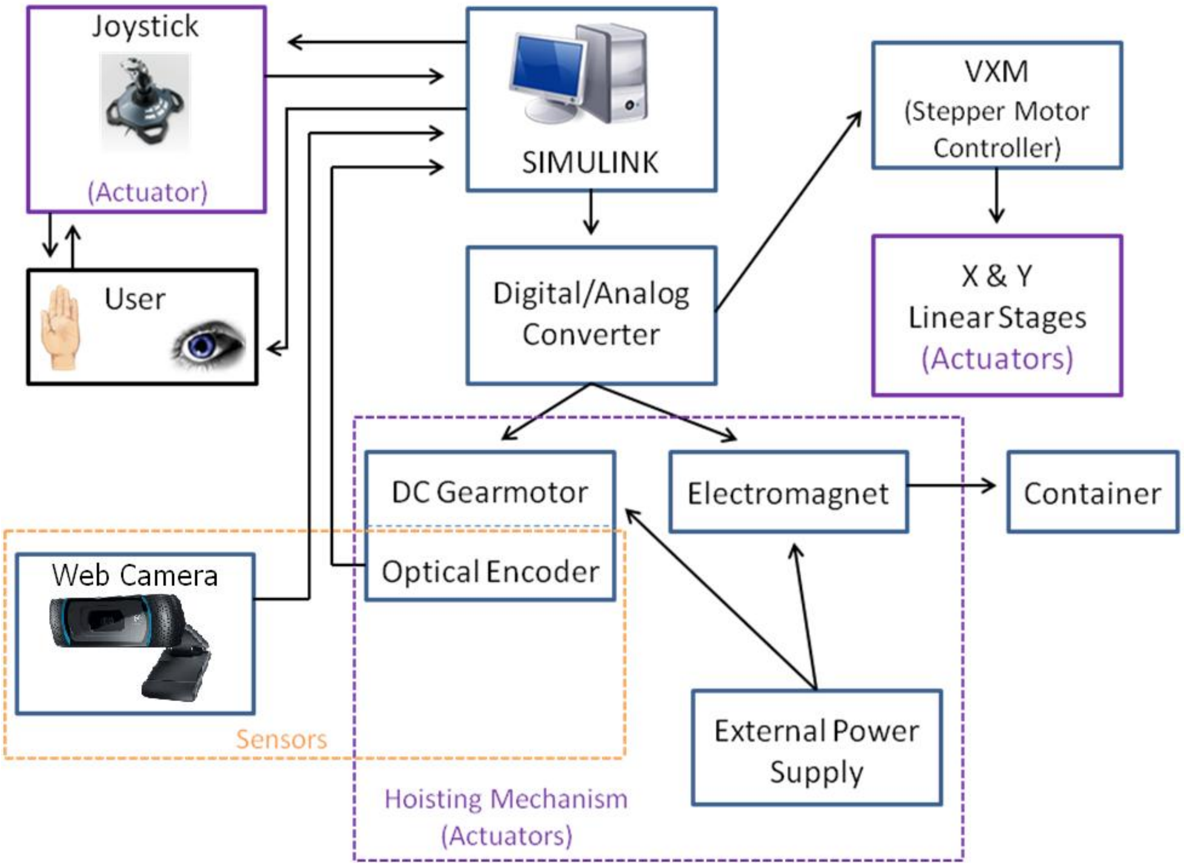


Figure 10. Operational flow diagram of the crane testbed, the user interface, and their components.

detection with colored makers placed on the container and an obstacle. Figure 11 shows the view of the workspace that the operator sees from the computer console and the tracked colored markers on the container and the obstacle. The image processing algorithm is implemented using MATLAB/Simulink Image Acquisition toolbox to display real-time video and Computer Vision System toolbox for image processing.

The boundary calculation of the obstacle is simplified by the detection of circular colored markers placed along the one of the edge of the obstacle. A set of circular markers with a different color is placed on the corners of the mock container and is used to determine its position in real-time. For simplicity, we elaborate on the algorithm for one color detection. The same algorithm is repeated with minor changes to detect the other color. RGB color scheme is used for the color detection algorithm. In each frame, the live video image is extracted into three 2D matrices corresponding to the Red, Green, and Blue color components. To detect red objects, the red intensity image is used. Using the red intensity image, the red objects are then extracted

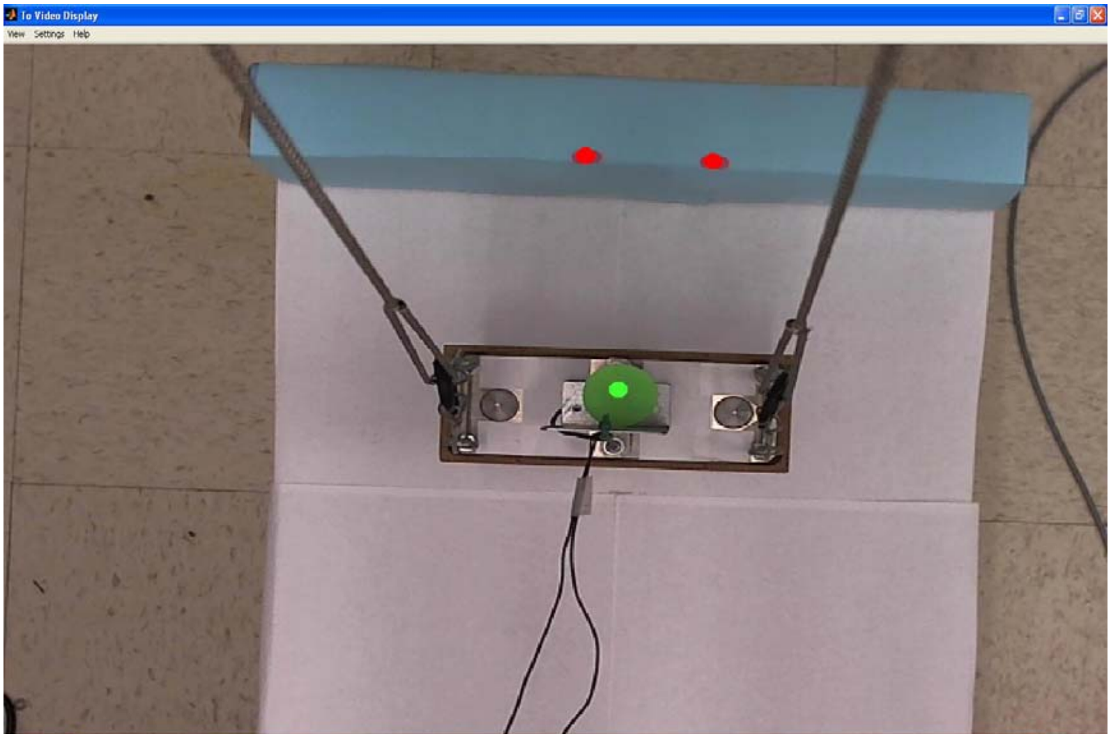


Figure 11. The operational view from the trolley's camera with the overlay of color detected objects.

through a binary image by setting a threshold. The threshold value may be adjusted based on the lighting conditions and the color intensities. With the extracted colored objects in the scene, additional filtering techniques are performed to reduce noise and improve accuracy. Median filtering and morphological erosion technique are used to remove the unwanted pixels from the binary image. We compute statistics for connected regions in the binary image using Blob analysis. Using the computed centroids of all the detected colored regions, the lines representing the edge of the obstacle and the container and their relative distance are computed. All quantities are calculated in pixels.

D.2 Integration of Visual and Force Feedback

In this study, force feedback is used to alert the crane operator of a possible collision with an obstacle in the workspace, such as a surrounding container, and to help guide the operator during the loading/unloading task. The implemented force feedback model is illustrated in Figure 12. To prevent the operator from moving the spreader/container into a surrounding object, a safety margin is created as a *virtual wall* at a distance in front of the object. This safety margin is predefined and can be adjusted based on the application. The force feedback is created, if operator moves the container pass the virtual wall. When the spreader/container assembly approaches and crosses the safety margin, a force is generated opposite to the motion of the spreader assembly which guides and alerts the crane operator. The force feedback is modeled with Hooke's law for spring force can be given as follows,

$$F = \begin{cases} k(d-p), \text{ if } & p \leq d \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

k is a positive stiffness constant, which can be tuned to increase or decrease the level of force feedback. In our case, k is 0.0033. The force is sent to be displayed through the force-feedback joystick. From this model, the force feedback increase proportionally to the amount of penetration passing the safety margin. The user receives force feedback only when a collision with the virtual wall occurs. The force feedback can be turn on or off by the user.

A screenshot of the visual feedback as seen from the Simulink display window can be seen in Figure 11. In this test scenario, the image procession algorithm described in the previous section detects the color markers on the obstacle and the container. The overlays of the detected colored regions are shown in the figure. As this preliminary experiment, the container position is represented by a single color marker. The relative distance between the closest edge of the obstacle and the container is then used for the force feedback calculation using Equation (3). The flowchart for the integration of image processing and force feedback generation is described in Figure 13.

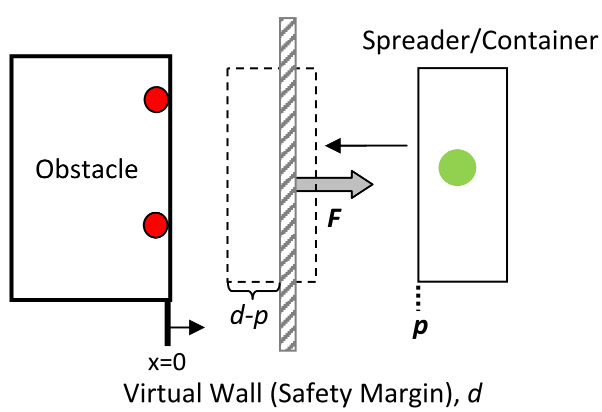


Figure 12. Schematic representation of the force feedback model

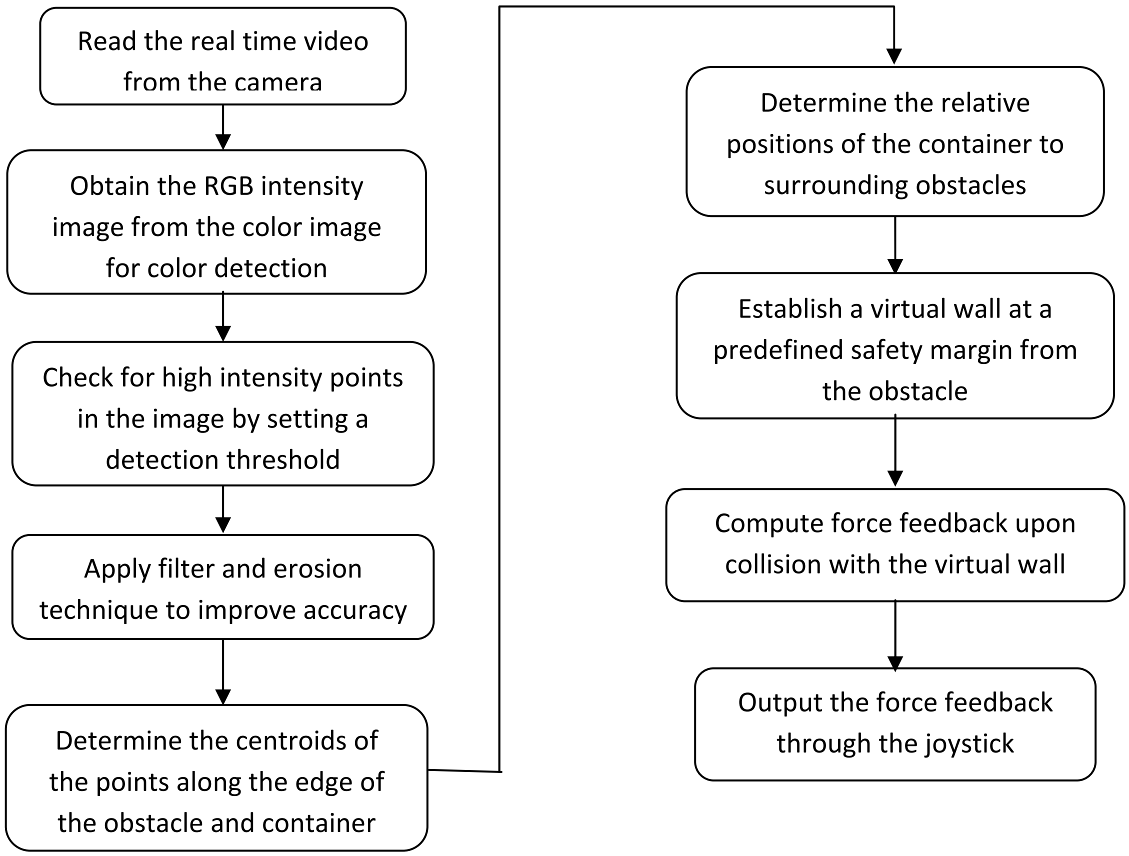


Figure 13. Flowchart of the image processing and force feedback algorithms.

E. Preliminary Results

To evaluate the integration of force feedback in the testbed, an experiment scenario was created to replicate the movement of a container to a target location in the vicinity of a virtual boundary as illustrated in Figure 14. The virtual boundary represents the area in which the moving container should not enter in order to avoid a collision, such as the location of a neighboring container. The first evaluation applied simulated virtual boundaries that were defined pre-operatively to generate the force feedback commands without the knowledge of target and the surrounding objects from the camera. After the initial calibration of the stages, during which the stages were positioned at the origin of the workspace (point O) in Figure 14, the user manipulated the joystick, one axis at a time, to move to the target location as instructed. When a contact with the virtual boundary occurred, the user felt a force through the joystick directed away from the boundary. The experiment was performed with one novice user. Figure 15 shows the force and position versus time plots for the user's movement along the y-axis

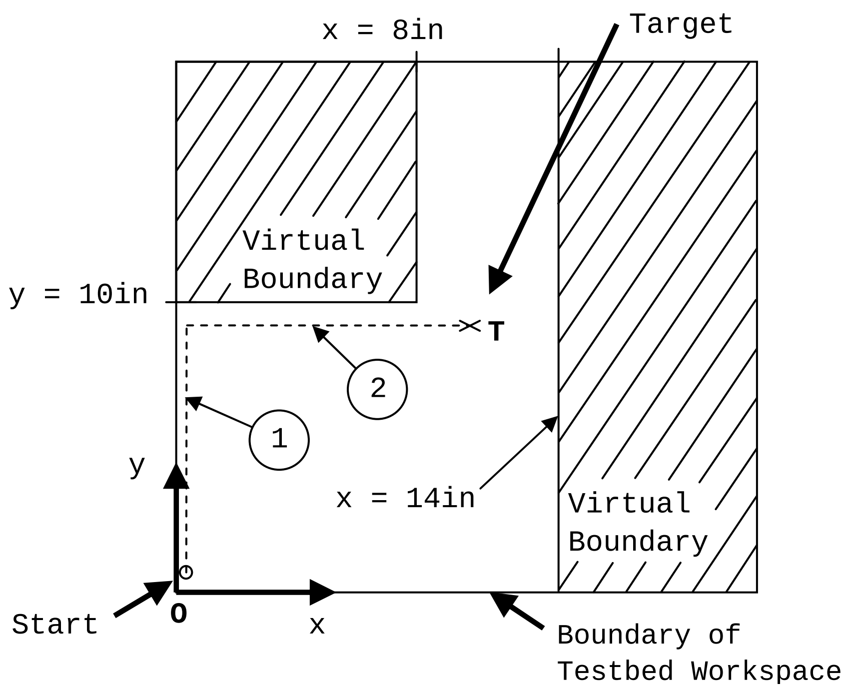
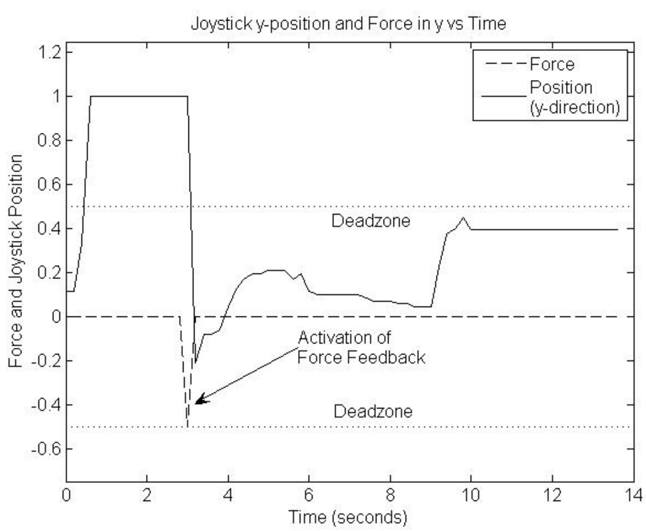


Figure 14. Diagram of force feedback test scenario. The testbed user will feel a force if contact is made with the virtual boundaries while moving a container from O to T.



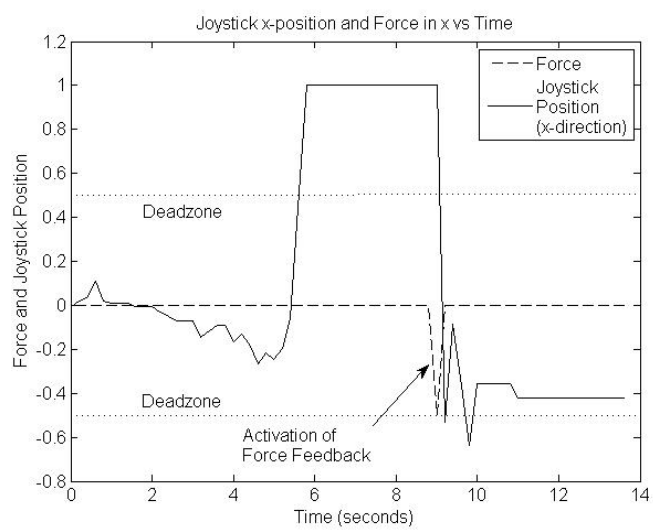


Figure 15. Force and joystick position versus time plots for (left) movement along the y-axis and (right) movement along the x-axis. The changes in the user motion after the activation of the force display can be seen from the plots.

(labeled as section 1 in Figure 14) and the subsequent motion along the x-axis (labeled as section 2 in Figure 14). In both plots, the peak forces observed indicate the moment when the user encountered the virtual boundaries and felt the force feedback. Also, both plots reveal that the user retracted from moving forward into the undesired region as the joystick was returned to zero soon after the force was displayed.

To test the overall operation of the visual and force feedback interface, we conducted a similar scenario in which the user is allowed to move toward an obstacle, representing a surrounding container, along one direction. The safety margin was placed at 120 pixels away from the edge of the obstacle. The user sat and observed the workspace from the computer monitor placed directly in front of the user. During the task, the joystick position, force output, and the relative position (in pixels) of the spreader/container to the obstacle were recorded. The joystick position, force, and position profiles as a function of the run time are shown in Figure 16. The peak observed in the force profile indicates that the user has encountered the virtual boundary and feels the force feedback. Also, the plots reveal that the joystick is returned to zero soon after the force is displayed when safety margin is reached at time 0.97 sec. This indicates that the user has stopped from entering into the undesired boundary and move to the opposite direction as indicated in the top plot. There is a 0.2 sec time delay from the joystick sharply changing direction at time 1 sec to observe that the relative distance of the container to the obstacle overturned from decreasing to increasing at time 1.2 sec. In Figure 16, the joystick position values on the graph are scaled down by 100:1 ratio (1 unit =100 coordinate units for the joystick position). The deadzone is established and indicated in the plot with dotted lines at +/- 0.4, which corresponds to the ±40 units as noted earlier in Figure 9.

These preliminary results provide an initial validation on the performance of the overall system integration with visual and force feedback. During the experiment, delay due to image processing was observed and should be minimized since the delay will have a significant effect on the motion guidance calculation and the overall performance. A user experiment with experienced crane operators is needed to verify the intuitiveness and the effectiveness of user interface in improving the crane operation and ergonomics. Addition of position sensors, such as range detection sensors and additional camera system, to provide redundant position

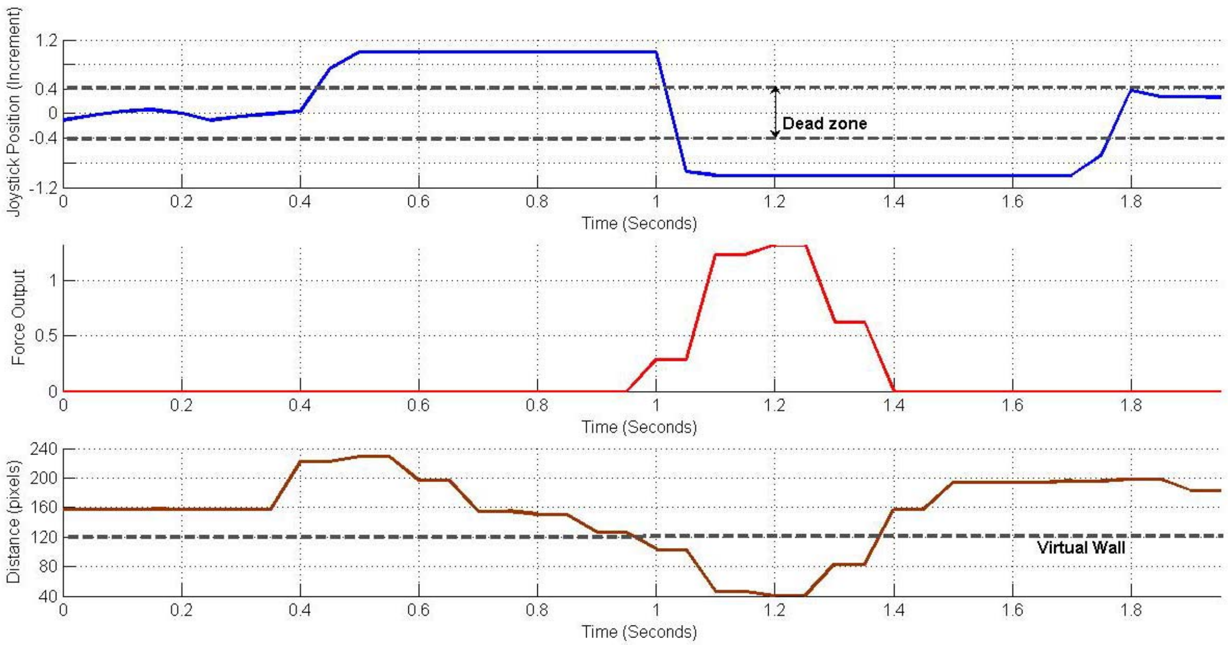


Figure 16. The plots of joystick position, force, and relative position of the target container to the obstacle versus run time. The force feedback is displayed when the container reached the virtual wall set at 120 pixels from the obstacle.

measurements will be important for the actual deployment of the system at the port as some of the sensors may become unavailable due to factors such as poor lighting condition, fog, and obstruction.

F. Conclusions and Recommendations

In this work, we investigated the integration of enhanced visual and force feedback to the operator interface of wharf gantry cranes to improve port productivity. A survey of the current needs of wharf gantry crane operators was performed by reviewing research literature on existing crane technology, and by interviewing three operators with extensive experience on the cranes. From the survey, addition of visual and force feedback have a potential in improving the accuracy and the operating condition of the more demanding positioning tasks with poor visibility, such as stabbing in the blind. A cooperative assistance such as the technology proposed, in which the operator can maintain the ultimate control over the task and turn on/off the automation as desired, is preferred.

In order to evaluate the feasibility of the proposed technology, a scaled testbed was designed and constructed in our laboratory. As the first phase of the development, the work focuses on the development of the testbed, system integration, and the algorithms for generating motion guidance. A camera system is integrated to provide the operational view of the workspace and position measurements of the target container (spreader) and surrounding objects. Force feedback is provided through a commercial force-feedback joystick. This mode of feedback was then studied based on a test scenario devised to replicate actual container handling scenarios. The use of force feedback offers a potential solution to prevent a collision in actual crane operation, which can be expensive and extremely dangerous. The haptic model used may be modified so that it provides a warning to the user of an impending collision, such that the collision can be avoided. The initial results of the test scenario support the idea that force feedback can be a valuable means of communicating to the testbed user the position of the payload container relative to obstacles, though further user experiment is needed to verify this claim. Another potential benefit of the proposed system is an improvement in ergonomics. With the system, the operator looks forward to see the workspace rather than constantly looking down at the payload container. We hypothesize that the forward position of the operational view can alleviate the physical discomfort associated with the traditional quayside crane operation.

In this initial phase, the majority of the project development was focused in the design and construction of the testbed system. Based on the preliminary results, several research questions remain to be answered as part of the next development before we can begin a full user study with port crane operators. First, the system delay and the accuracy of position measurement must be improved. Additional sensors including a range sensor will be added to the current testbed. Improvement to the image processing algorithms and hardware are needed to improve the system's speed and robustness in order to handle real time tracking of dynamic workspace. Measurements from multiple position sensors, including a camera and range detection sensors, will be combined to improve the speed and accuracy of the system. A user study with experienced crane operator using the testbed is needed to verify the benefit of the addition of visual and force feedback to the port crane operation. The appropriate level of visual and force feedback also need to be determined from the study.

G. Implementation

In this early development stage, the testbed provides a valuable platform to further study the feasibility of the proposed technology for the real implementation at the port. Based on our surveys with the crane operators, assistive technology such as this one can lead to a significant improvement in the operation and working condition of wharf gantry crane. Based on our initial experiment, force feedback offers a solution to improve safety and accuracy of the container loading and unloading task. More importantly, we believe that enhancement of visual feedback provided to the crane operator will have an even more significant role in improving the performance and the ergonomics of the crane operation. Visual guidance commands, such as a visual display of a guidance command, will be integrated and tested on the testbed. As mentioned earlier, the issue of delay must be resolved for the real implementation of the system. In addition, the method of integration of the system on the current wharf gantry crane at the ports must be considered. In the next phase of our work, an embedded system will be tested to improve the operating speed of image acquisition and processing and sensor integration. As an ongoing research, we are investigating a use of single-board computer to eliminate the dependency on a PC, which will ease the integration of the system on the actual port cranes.

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