DEFINITION AND NUMERICAL SIMULATION OF AN AUTOMATED SYSTEM FOR CONTAINER CRANE POSITIONING

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Abstract. The proposal of this work is to present an improvement in the shipment system of containers from a port crane in order to reduce the time of coupling of the container, which is carried out by a device called spreader. This makes possible the reduction of the costs of logistic, bigger efficiency and security in the operation. This operation of coupling of the container is controlled by the operator of the crane by means of two joysticks and by means of three buttons in which he manually adjusts the movements of rotation TRIM, LIST and SKEW of the spreader, lining up it with the container. These three buttons set in motion four hydraulic cylinders connected to the sheaves in which pass the steel cables of the hoist movement of the load, allowing some degree of freedom such that spreader can be lined up to the container. With the proposal system, this operation of alignment will be made in automatic way, where sensors installed in the spreader measure the angle of deviation with the container, sending this signal to a control system that acts in the hydraulic cylinders stroke, putting into motion the sheaves and thus adjusting the positioning of spreader. The idea is to start the correction of the motions TRIM, LIST and SKEW of the spreader before that it approaches to the container, reducing the coupling delay. In this paper, the complete automation and control system is defined, including the proper definition and selection of the sensors and the actuators. A mathematical model of the dynamics of the load and closed-loop control system is derived, and the parameters of the controller are tuned. By means of time domain simulation of the system, the total time reduction could be evaluated, comparing with typical performance of the manual procedure.

Keywords: *Logistics, Container, Container crane, Port, Ship loading*

1. INTRODUCTION

Agility, convenience and safety are very important requisites for any logistic system related to transportation of products. A world-wide solution is the utilization of standardized containers. Since its dimensions are standardized, it was possible the development of machinery for handling it, such as the container crane (Wikipedia, Figure 1). This equipment has the capacity to lift loads of approximately 50 tons, and it is possible to transport the container from the port to the ship and vice versa. In order to couple the container to the crane lines, it is used a device called spreader.

Figure 1. Container crane (extracted from Wikipedia, 2005)

1.2. Spreader and the TRIM, LIST e SKEW movements

The spreader (Figure 2) consists of a framework with sheaves which pull the steel cables of the hoist (vertical) motion. It has a hydraulic system and a telescopic mechanism to expand and adjust to the size of the container. This system also driver the motion of four latches (called twist lock) located at the corners of the spreader that lock the container so that it can be hoisted. To assist the coupling of the container, there is also a set of tabs called flippers.

All these actions are controlled by an operator situated in the crane cabin. The operator also controls the following movements of the spreader, using three pushbuttons on the console (Figure 2):

- TRIM, angular movement of the spreader around the axis perpendicular to the port;
- LIST, angular movement of the spreader around the axis that is parallel to the port;
- SKEW, angular movement of the spreader around the vertical axis.

These displacements in three axes allow the spreader to fit the misalignment between the spreader and the container at the moment of the coupling.

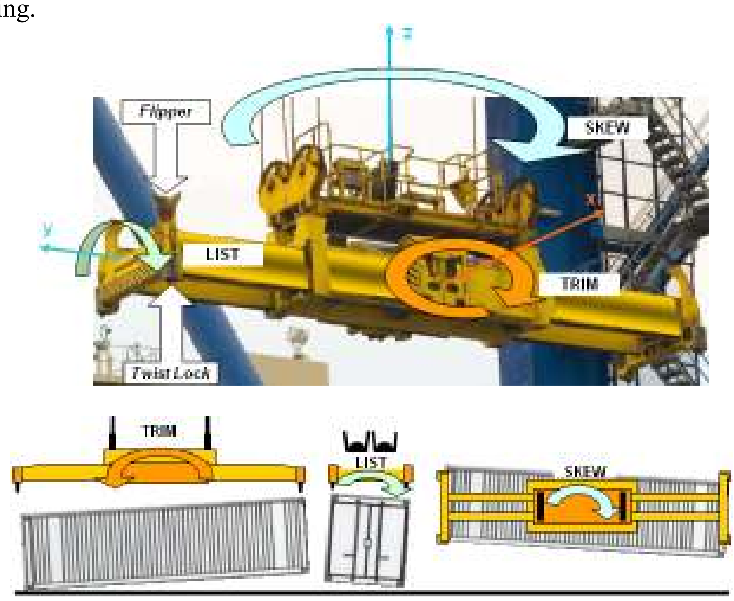

Figure 2. Spreader movements

The three pushbuttons (TRIM, LIST and SKEW) may combine in such way that set in motion four hydraulic cylinders located at the rear of the crane, whose rods move four sheaves which pull the steel cables of the hoist motion of the load (Figure 3). Each rod of a hydraulic cylinder moves a sheave, extending or retracting the cable and, combined with the other sheaves, change the position of the spreader. The maximum TRIM, LIST and SKEW angles that can be imposed to the spreader are approximately 5^{o}.

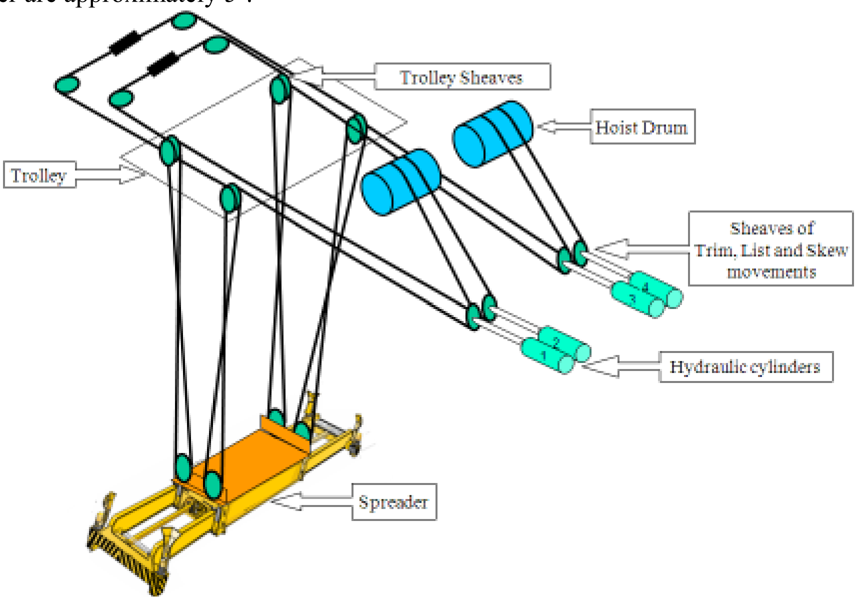

Figure 3. TRIM / LIST / SKEW configuration

2. PROPOSED CONTROL SYSTEM

The goal is to design a control system to allow the spreader performs the TRIM, LIST and SKEW movements automatically, without eliminating the existing manual control as shown in the block diagram (Figure 4). Laser sensors measure how much the container is misaligned. By a button on the console, the operator selects from manual mode to automatic mode. During the descending movement, when the spreader reaches a certain distance from the container, the sensors measure the deviations of TRIM, LIST and SKEW of the container related to the spreader.

Each closed control loop compares the angles of the spreader with the set-point (0^o). The controller drives the rods of the cylinders that move the pulleys and the spreader, thus adjusting the position of the spreader to the container.

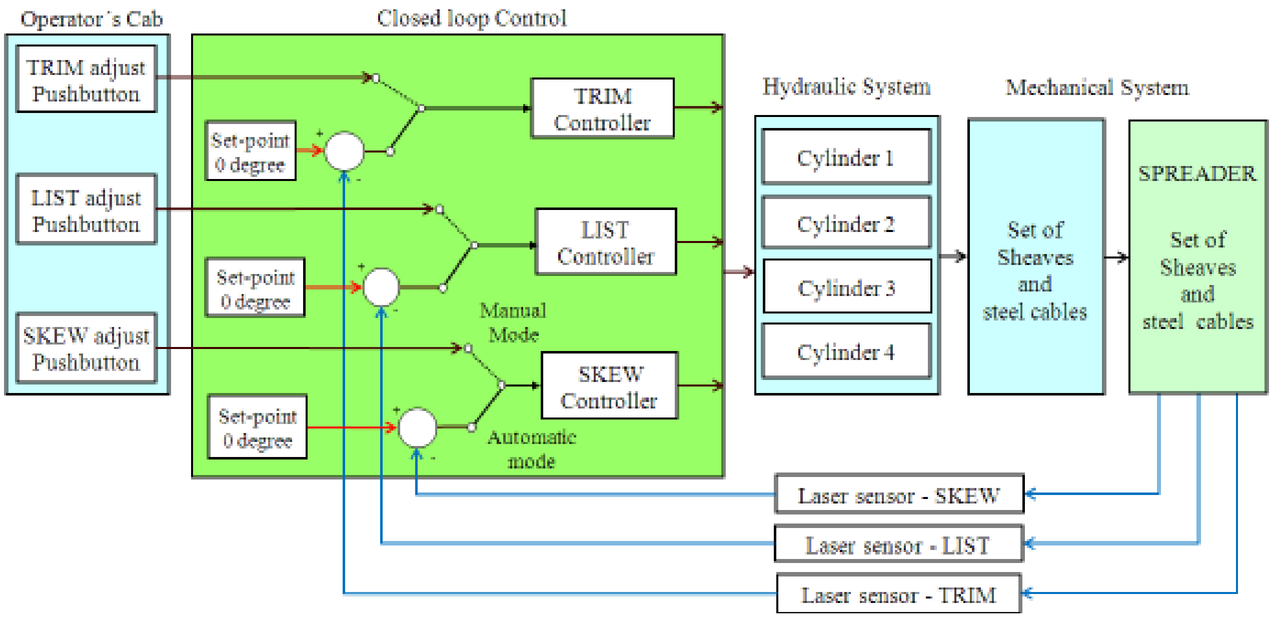

Figure 4. Block diagram of the proposal system to control the spreader

To measure the deviations of TRIM and LIST can be used an optical laser meter with range from 0.2 to 30.0 m, accuracy ± 2 mm and measurement time of 100 ms.

To measure the deviation of SKEW can be used a laser scanner with range from 0 to 65.0 m, angular resolution of 0.36 degree and a measurement time of 40 ms.

3. BENEFITS WITH THE IMPLEMENTATION OF THE PROPOSED SYSTEM

3.1. Reducing the time of coupling the container

Since the operator is far from the container, he just is able to visually fit the spreader to the container, by the TRIM, LIST and SKEW pushbuttons, when it is close to the container. With automatic control, sensors can measure the misalignment with the spreader before approaching the container, allowing the control system begins to align it, reducing a time of the coupling operation.

Also, in manual mode, the operator must release the joystick of the gantry and trolley movements in order to adjust the TRIM, LIST and SKEW pushbuttons, spending a time for that.

In automatic mode, the operator adjusts the gantry and trolley movements, while the automatic system adjusts the TRIM, LIST and SKEW movements, reducing this time yet.

This system enables a few seconds of reduction time for each operation of coupling, which becomes important if one considers the quantity of containers that are loaded (or unload) on a vessel, resulting in less time that it is anchored in the port and reducing the operating costs logistics. It will be shown that with the proposed system there is a reduction of time of 5.8 s (24%), at least, for each coupling operation comparing to a non-automated operation.

3.2. Safety

The operator manually adjusts the positioning of the spreader and sometimes needs a person on the ground to assist him in this operation by radio. This system reduces the need of a person so close to the load.

3.3. Convenience for the operator

In the left side of the console the operator just controls the joystick of gantry and trolley movement of the crane. He does not need to interrupt this procedure to adjust the spreader pushbuttons.

4. DETERMINATION OF THE MODELS TRIM, LIST AND SKEW MOVEMENTS

4.1. List movement (Ø angle)

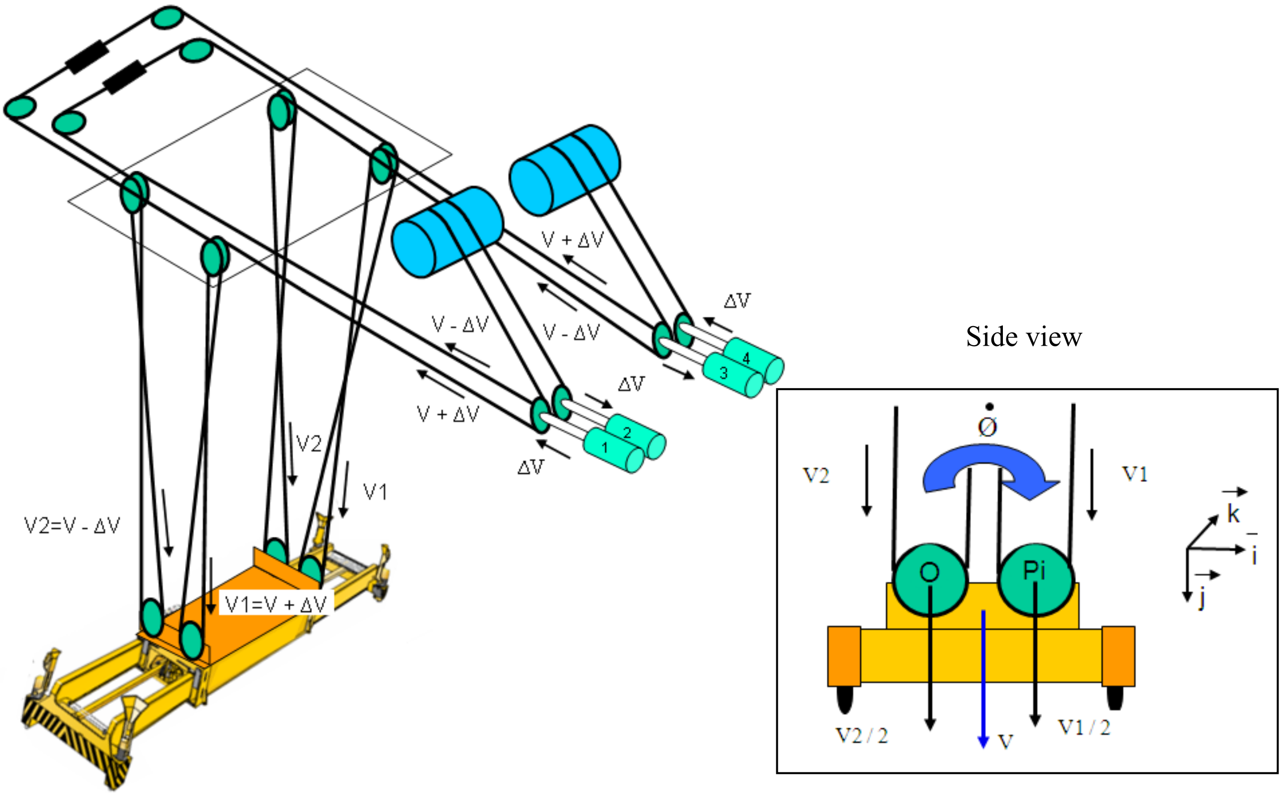

Figure 5. Composition of the angular velocity of LIST movement

The Figure 5 shows velocity vectors involved in LIST motion. The velocity of the spreader (Vg) as a function of drum velocity (V):

$$Vg = \frac{\frac{V1}{2}+\frac{V2}{2}}{2} \Rightarrow Vg = \frac{V+dV+V-dV}{4} \Rightarrow Vg = \frac{V}{2} \tag{1}$$

Considering a spreader´s velocity of 2.45 m / s, we can determine that the maximum velocity of drum is 4.90 m/s.

The angular velocity of the spreader is obtained by the Poisson equation:

$$\frac{\overrightarrow{V1}}{2} = \frac{\overrightarrow{V2}}{2} + \vec{\omega}\wedge(Pi - O) \tag{2}$$

$$\vec{\omega} = \omega x\vec{\imath} + \omega y\vec{\jmath} + \omega z\vec{k} \tag{3}$$

$$\vec{\omega}\wedge(Pi - O) = \begin{vmatrix} \vec{\imath} & \vec{\jmath} & \vec{k} \\ 0 & 0 & \dot{\theta} \\ l & 0 & 0 \end{vmatrix} \quad \text{(l is the distance between the centers of the spreader´s sheaves)} \tag{4}$$

$\Rightarrow \vec{\omega}\wedge(Pi - O) = \dot{\theta}.l.\vec{\jmath} \quad \Rightarrow \frac{V1}{2}\vec{\jmath} - \frac{V2}{2}\vec{\jmath} = \dot{\theta}.l.\vec{\jmath} \quad \Rightarrow \dot{\theta} = \frac{1}{2}.\frac{V1-V2}{l}$, considering l = 0.75 m, we get:

$$\dot{\emptyset} = \frac{1}{2}.\frac{V1-V2}{0.75} \tag{5}$$

$$\emptyset = \frac{1}{S}.\frac{1}{2}.\frac{V1-V2}{0.75} \tag{6}$$

4.2. TRIM movement (θ angle)

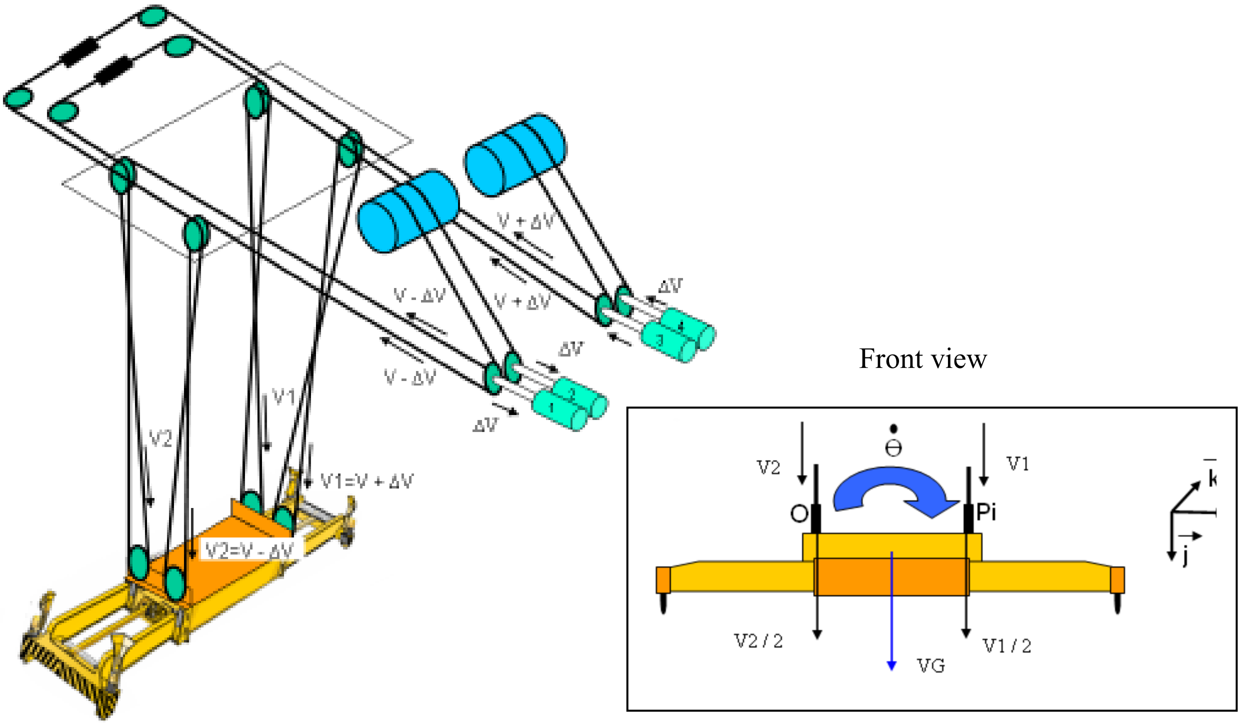

Figure 6: Composition of the angular velocity of TRIM movement

The Figure 6 shows velocity vectors involved in TRIM motion. The velocity of the spreader (Vg) as a function of drum velocity (V):

$$Vg = \frac{\frac{V1}{2}+\frac{V2}{2}}{2} \Rightarrow Vg = \frac{V+dV+V-dV}{4} \Rightarrow Vg = \frac{V}{2} \tag{7}$$

The angular velocity of the spreader is obtained by the Poisson equation:

$$\frac{\overrightarrow{V1}}{2} = \frac{\overrightarrow{V2}}{2} + \vec{\omega}\wedge(Pi - O) \tag{8}$$

$$\vec{\omega} = \omega x\vec{\imath} + \omega y\vec{\jmath} + \omega z\vec{k} \tag{9}$$

$$\vec{\omega}\wedge(Pi - O) = \begin{vmatrix} \vec{\imath} & \vec{\jmath} & \vec{k} \\ 0 & 0 & \dot{\theta} \\ c & 0 & 0 \end{vmatrix} \quad \text{(c is the distance between the centers of the spreader´s sheaves)} \tag{10}$$

$\Rightarrow \vec{\omega}\wedge(Pi - O) = \dot{\theta}.c.\vec{\jmath} \quad \Rightarrow \frac{V1}{2}\vec{\jmath} - \frac{V2}{2}\vec{\jmath} = \dot{\theta}.c.\vec{\jmath} \quad \Rightarrow \dot{\theta} = \frac{1}{2}.\frac{V1-V2}{c}$, considering c = 4.88 m, we get:

$$\dot{\theta} = \frac{1}{2}.\frac{V1-V2}{4.88} \tag{11}$$

$$\theta = \frac{1}{S}.\frac{1}{2}.\frac{V1-V2}{4.88} \tag{12}$$

4.3. SKEW movement (Ψ angle)

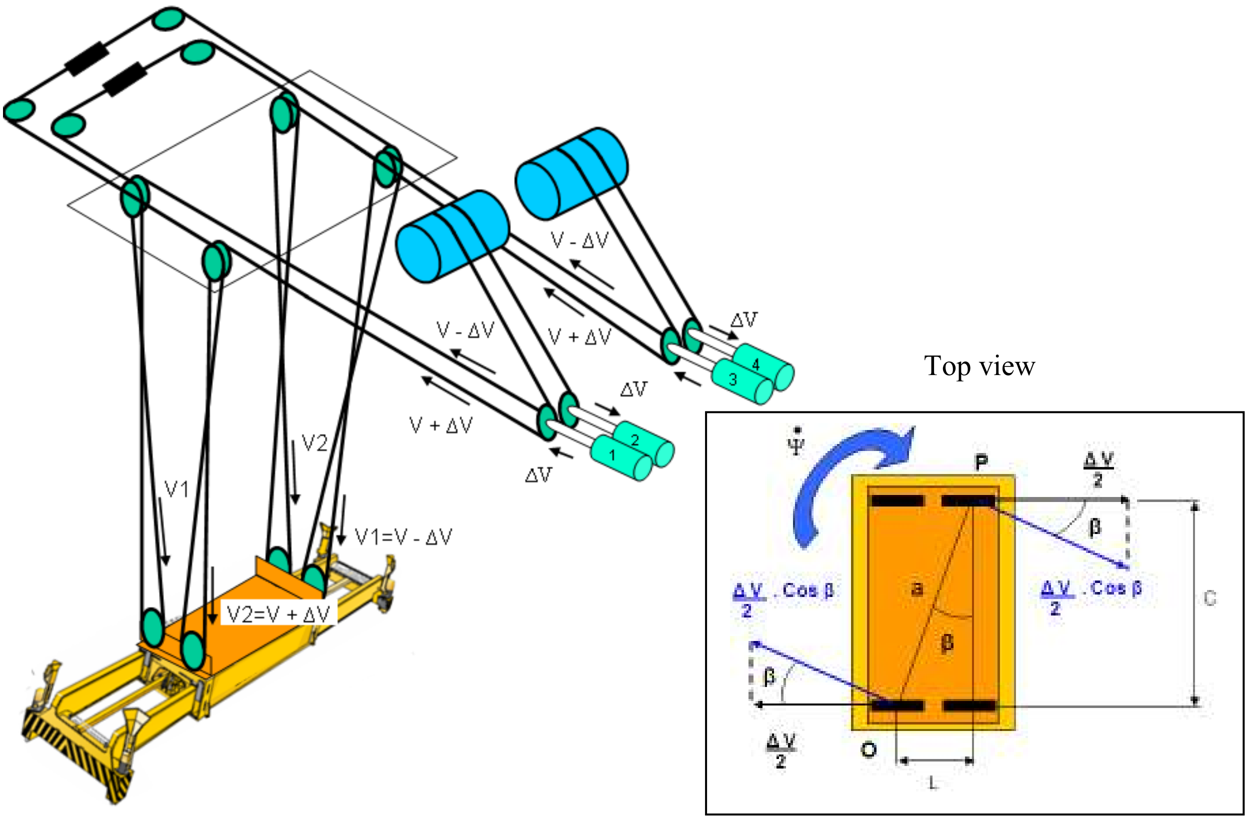

Figure 7. Composition of the angular velocity of SKEW movement

The Figure 7 shows the velocity vectors involved, where we verify that the displacement of the cylinders´ rods cause a rotation movement in the spreader in SKEW direction.

Calculating the distance "a" between the sheaves and the value of Cos β:

$$a^2 = (l)^2 + (c)^2 \quad \Rightarrow \quad a = \sqrt{l^2 + c^2} \tag{13}$$

$$\cos\beta = \frac{c}{\sqrt{l^2+c^2}} \tag{14}$$

Calculating the angular velocity of the spreader using the Poisson equation:

$$\frac{\overrightarrow{\Delta V}}{2}\cos\beta = \frac{\overrightarrow{-\Delta V}}{2}\cos\beta + \vec{\omega}\wedge(Pi - O) \quad \Rightarrow \quad \frac{\Delta V}{2}\cos\beta + \frac{\Delta V}{2}\cos\beta = \dot{\theta}.a \;\Rightarrow\; \frac{2\Delta V}{2}\cos\beta = \dot{\theta}.a \tag{15}$$

Since $2\Delta V = V1 - V2$ (16)

$$\Rightarrow \dot{\theta} = \frac{1}{2}.\frac{V1-V2}{a}\cos\beta \tag{17}$$

Changing "a" and "Cos β" obtained from equations 13 and 14, we have:

$\dot{\theta} = \frac{1}{2}.\frac{V1-V2}{\frac{l^2+c^2}{c}}$, doing $D = \frac{l^2+c^2}{c}$, we have $\dot{\theta} = \frac{1}{2}.\frac{V1-V2}{D}$, considering l = 0.75 m and c = 4.88 m, we get:

$$\dot{\theta} = \frac{1}{2}.\frac{V1-V2}{5} \tag{18}$$

$$\theta = \frac{1}{S}.\frac{1}{2}.\frac{V1-V2}{5} \tag{19}$$

5. DEVELOPMENT AND SIMULATION OF A CONTROL SYSTEM TO TRIM, LIST AND SKEW ANGLE

With the models obtained in the previous sections, three PID loop control of the movements were numerically evaluated, with the configuration for each motion presented in the Figure 8. Matlab/Simulink was used.

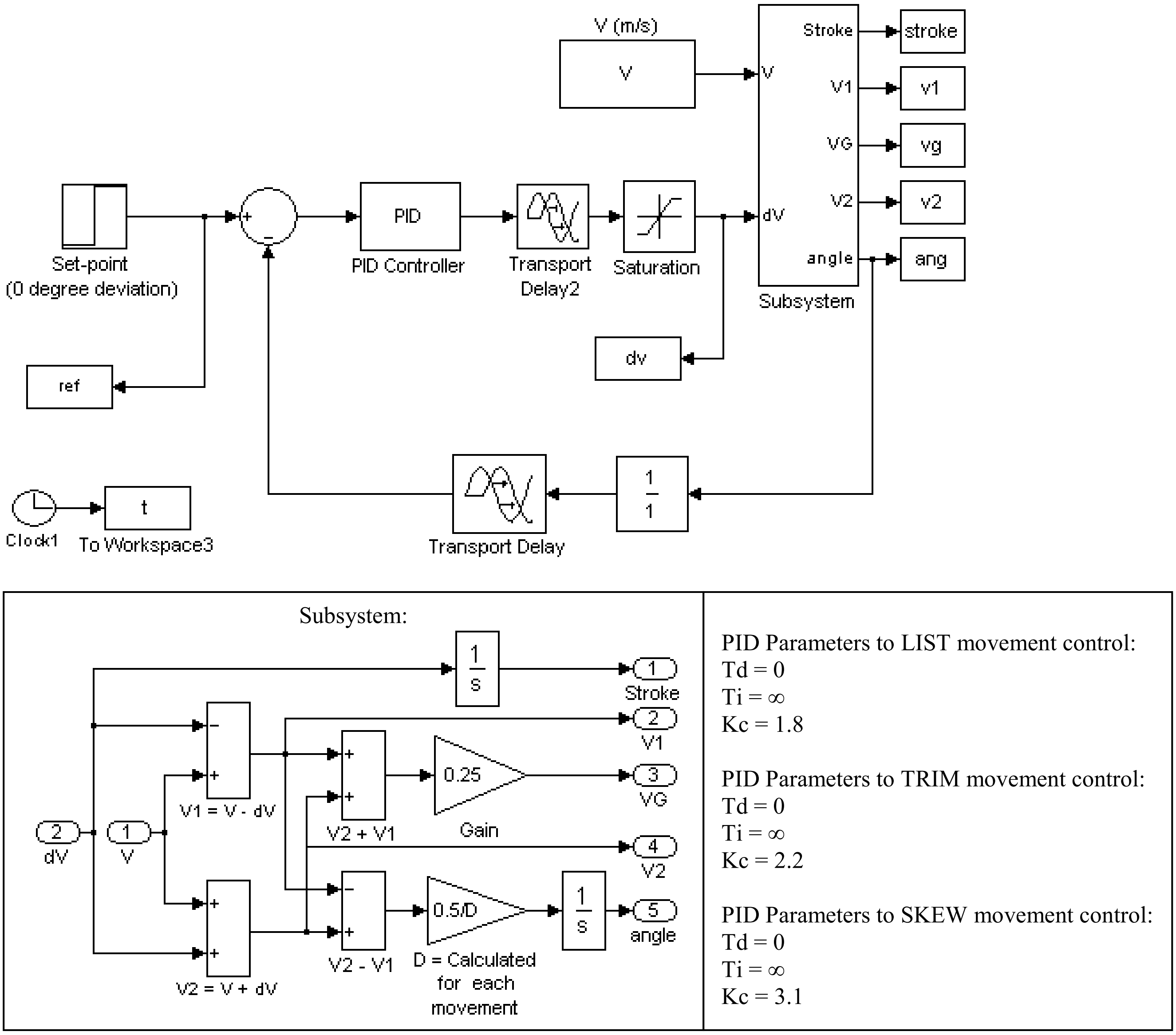

Figure 8. Closed loop control to TRIM, LIST e SKEW movements

We considered the following parameters for calculation and simulation of the control loop:

- Length between the sheaves of the spreader, c = 4.88 m
- Width between the sheaves of the spreader, l = 0.75 m
- Maximum speed of the spreader, Vg = 2.45 m/s
- Maximum speed of the cylinder rod, ΔVmax = 0.028 m / s
- Transport delay due the measurement time of the laser sensors to the control system: 100 ms from TRIM deviation sensor, 100 ms from LIST deviation sensor and 40 ms from SKEW deviation sensor.
- Transport delay 2. In this case, the hydraulic system response was modeled as a maximum actuation speed (0.028 m/s) with a delay of 100 ms due the response time of the hydraulic unit, a set of cylinders, pumps and control valves.

For each control loop the following simulations were done:

- It was assigned values to the reference signals for the control loops, varying them from 0.5 to 5.0 degrees. For each loop was observed the proportional control and tuned the value of Kc that provided the best response time of the output signal (angle) of the system, shown in the Figure 8.
- For each control loop, it was set up a chart with the time needed to correct every angle assigned.
- It was made a correlation of this chart with the chart of the down movement of the spreader, considering the travel in maximum speed from a height of 30 m to 2 m of the container.
- It was verified that there is a gain of time when you start to correct the deviation angle before the spreader reaches the container.

5.1. Simulation to LIST movement (Ø angle)

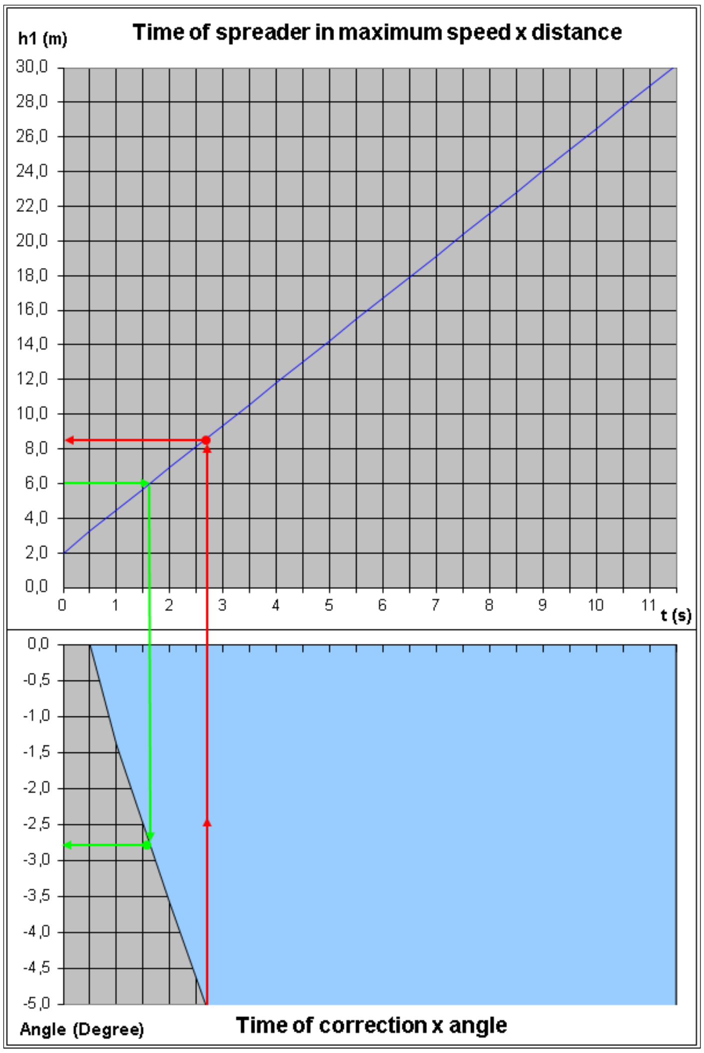

Figure 9. Correlation of the travel of the spreader and the angle corrected in the LIST movement

We can identify by the green arrow of the chart in the Figure 9 the following event:

- The spreader moves down in maximum speed (2.45 m/s) to load a container;
- When it reaches the distance h1= 6 m, above of this container, the control loop is started;
- The sensors measure the angular deviation between the spreader and the container and send this value to the control loop;
- The control loop drives the hydraulic cylinders for adjusting the angular position (LIST movement) of the spreader in order to couple the container;
- From the distance from 6 m to 2 m of the container, the spreader takes 1.6 s;
- In this time interval of 1.6 s the control system has the ability to adjust the deviation of 2.7 degrees between the spreader and container;
- From 2 m, the system checks if the time was sufficient for the control loop to correct the deviation angle;
- If the deviation angle is greater than 2.7 degrees, there was not enough time to the correction and the system will limit the speed of the spreader so that the control loop finishes the procedure;

By the red arrow in the chart, we verify that the maximum LIST angle of 5 degree is corrected if the spreader is above the distance of 8.2 m of the container, in maximum speed.

5.2. Simulation to TRIM movement (θ angle)

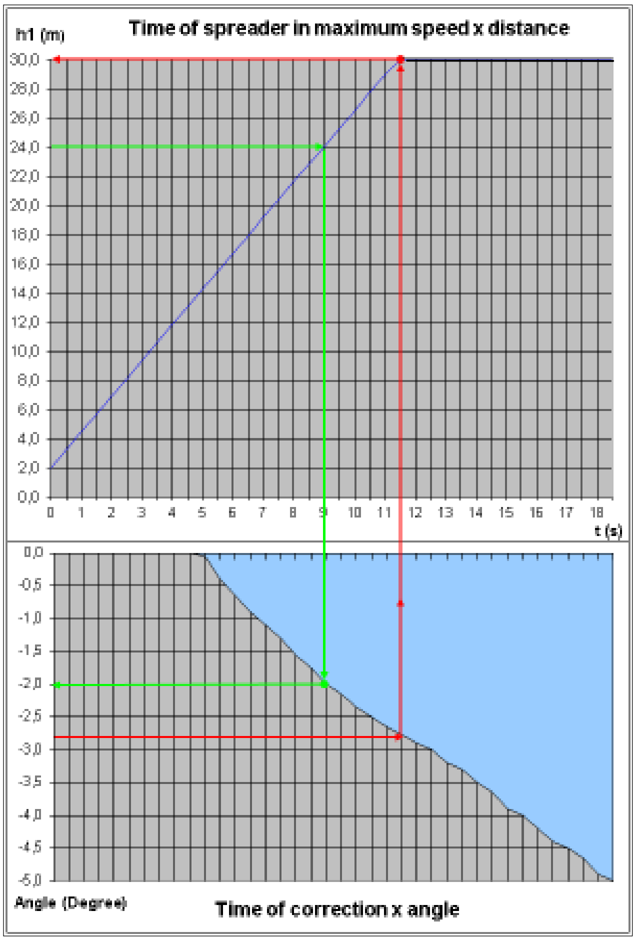

Figure 10. Correlation of the travel of the spreader and the angle corrected in the TRIM movement

We can identify by the green arrow of the chart in the Figure 10 the following event:

- The spreader moves down in maximum speed (2.45 m/s) to load a container;
- When it reaches the distance h1= 24 m, above of this container, the control loop is started;
- The sensors measure the angular deviation between the spreader and the container and send this value to the control loop;
- The control loop drives the hydraulic cylinders for adjusting the angular position (TRIM movement) of the spreader in order to couple the container;
- From the distance from 24 m to 2 m of the container, the spreader takes 9.0 s;
- In this time interval of 9.0 s the control system has the ability to adjust the deviation of 2.0 degrees between the spreader and container;
- From 2 m, the system checks if the time was sufficient for the control loop to correct the deviation angle;

By the red Arrow in the chart, we verify that the maximum angle of 2.75 degree is corrected if the spreader down from the maximum distance of 30.0 m of the container, in maximum speed.

In the chart is also observed that the correction of the maximum TRIM angle of 5 degrees is done in 18.2 seconds.

5.3. Simulation to SKEW movement (Ψ angle)

Similar to the other movements, the same correction procedure is made for the SKEW movement in Figure 11. In the chart is also observed that the correction of the maximum SKEW angle of 5 degrees is done in 17.0 seconds.

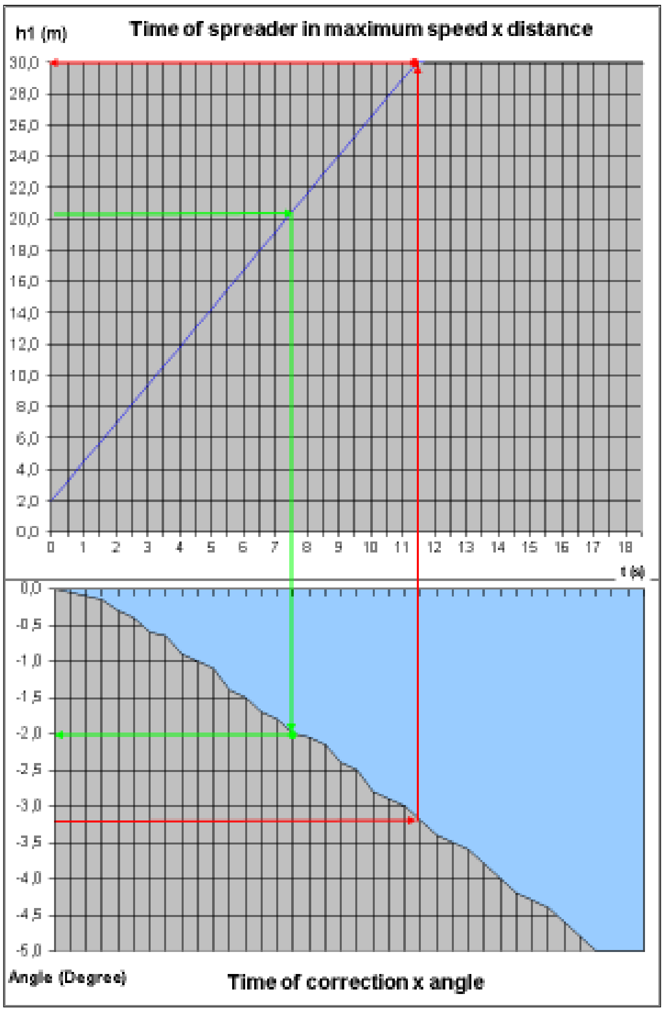

Figure 11. Correlation of the travel of the spreader and the angle corrected in the SKEW movement

6. CONCLUSION

The studies of a manufacturer for this type of crane obtained an average time to approach, positioning and locking the container by the spreader of 24.0 s (Konecranes, 2002).Thus, considering in the simulations that the worst case was the correction of the deviation of 5 degrees of TRIM movement in 18.2 s, there is a reduction of time of 5.8 s (24%), at least, for each coupling operation.

Once the theoretical results obtained by simulations were satisfactory, the next step is to implement the described system in a port crane and to compare these results in a real operation.

This automatic system can be applied in the most part of the port cranes, requiring the installation of the laser sensors in the spreader, the wiring of them and a modification of the existing software in the controllers of the machines. Furthermore, as showed in the figure 4, it does not eliminate the manual mode of operation.

7. ACKNOWLEDMENTS

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