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Coordinate-Based Control for a Materials Handling Equipment Utilizing Real-Time Simulation

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Abstract This paper presents the development and implementation of an advanced control system for a hydraulic manipulator. Designing a suitable coordinate control system for materials handling machines is vital for desired machine performance. For this purpose, targets of developing a proper coordinate control system were defined and mathematical equations were formulated. The two common control methods, i.e. open-loop control and closed-loop control were specifically designed for the handler in question, and the performance of the machine was studied applying each control method. The simulation environment and the operation principle of the created models are discussed in detail in this paper. The two control strategies introduced were tested through real-time simulation, and the accuracy and the performance of the manipulator were investigated utilizing each control method. The limitations and problems of each control strategy are addressed, and suggestions for further research directions to improve the accuracy of tip control are recommended. The case study in this paper is a mobile harbor crane material handler provided by the Mantsinen Group.

Keywords Coordinate-based control. Closed-loop and open-loop control. Hydraulic servo systems. Material handling machine. Control of hydraulic manipulator. Real-time simulation

1 Introduction

The traditional way to operate heavy hydraulic machinery is to control each of the hydraulic actuators with joystick input. This means that one joystick input direction represents one-movement of the actuator in the machine. In order to control the machine smoothly and achieve the desired movement, the operator must be able to control all the hydraulic actuators required
to accomplish the process simultaneously. This type of eye-hand coordination is complicated and requires bountiful sessions of training to master for effective performance [1]. Simulation and control of multibody systems have been investigated in various researches [2-5]. One solution to perform the smooth control of a multibody system without the operator’s manual effort is to implement coordinate control, also called tip control, on the machine. Boom Tip Control (BTC) facilitates training and improves productivity [6-7]. Utilizing this method, instead of controlling each actuator with separate input, the joysticks of the machine directly control the tip of the hydraulic manipulator by simultaneously commanding all actuators with one general input.

Researchers have developed theoretical approaches to coordinate control of hydraulic machines since the 90s, however, these proposed methods have not become popular, as in practice they require additional mechanical components [8-14]. Besides, various methodologies have been proposed to implement advanced boom tip control for hydraulic systems [15-19]. However, the uncertainty of control during the operating region was the main reason for not implementing these methods. With the developments of new technology, advanced electrical solutions are available nowadays and manufacturers of different types of hydraulic machinery are investing in the development of coordinate controlled machinery, as it also provides opportunities for further development of machines towards semi or full-automation; for example, Ponsse offers forest harvesters machines equipped with tip control, John Deere produces machinery with intelligent boom control for forest harvesters and Technion Oy provides xCrane Techion control for hydraulic crane arm.

The goal of this research work is to develop a satisfactory coordinate control system for the Mantsinen 200 material handler without installing any additional equipment or sensors on the machine and merely using sensors that Mantsinen has already installed on its machine. Mantsinen is a Finnish corporation active in the fields of logistics, machine manufacturing, and material handling systems. Mantsinen material handlers are one of the largest hydraulic material handlers in the world [20]. In this study, two common control methods, namely open-loop and closed-loop control, have been designed and examined for the above-mentioned material handler. The operating principles of each control system are described in detail. Moreover, the effectiveness of the two proposed control systems is evaluated based on the performance of the manipulator in real-time simulation, and the pros and cons of applying each control system are determined and discussed. In this work, the number of degrees of freedom of the hydraulic manipulator is delimited to two rather than three. Also, the singularity points of the manipulator, where one or more degrees of freedom are lost, are not discussed, as Mantsinen has already implemented a dead zone compensator for its machinery.
2 Manipulator kinematics

Manipulator kinematics are used to observe position, velocity, and acceleration of the end effector, which are critical items in the successful transforming of the material handling control system into a coordinate-based control system.

2.1 Denavit-Hartenberg notation

Links along with joints of a serial robot are illustrated in Fig. 1. In order to relate the information of each link component into one kinematic solution, the local coordinate frame is attached into each link i at joint i+1. This method is called the Denavit-Hartenberg (DH) method, which is the standard method that relates components of a serial robot [21].

In Fig. 1 certain parameters of DH method are indicated which include, the kinematic length of a link \( (a_i) \), the link twist \( (\alpha_i) \), the joint distance \( (d_i) \), and the joint angle \( (\theta_i) \). These parameters are also used to describe the type of joints that the manipulator possesses [21].

2.2 Forward kinematics

In this research work, forward kinematics is used to track the position of the end effector. Absolute angle data is provided by angle sensors located on the machine. The transformation matrices are formed as Eq. 1-3:

\[
^{0}T_i = \begin{bmatrix}
\cos(\theta_i) & -\sin(\theta_i) & 0 \\
\sin(\theta_i) & \cos(\theta_i) & 0 \\
0 & 0 & 1
\end{bmatrix}
\] 

(1)
\[
\begin{align*}
\frac{1}{2}T &= \begin{bmatrix}
\cos(\theta_2) & -\sin(\theta_2) & a_1 \\
\sin(\theta_2) & \cos(\theta_2) & 0 \\
0 & 0 & 1
\end{bmatrix} \\
\frac{2}{3}T &= \begin{bmatrix}
0 & 0 & a_2 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\end{align*}
\] (2) (3)

When the above matrices are multiplied, the last transformation matrix, which depends on the base frame, is achieved according to Eq. 4:
\[
\begin{bmatrix}
0 & 0 & a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2) \\
0 & 0 & a_1 \sin(\theta_1) + a_2 \sin(\theta_1 + \theta_2) \\
0 & 0 & 1
\end{bmatrix}
\] (4)

where the third term of the first row is the x-coordinate of the end effector, and the third term of the second row is the y-coordinate of the end effector, which are the functions of the absolute joint angles of the manipulator.

### 2.3 Inverse kinematics

In inverse kinematics, equations are engaged to determine the joint angles when the end effector position is known. The joint angles are specified by the trigonometry laws. The law of cosines is used to solve the real angles of the triangle formed by the boom structure. Eq. 5 displays the basic law of cosine, from which angles A and B can be solved, and Fig. 2 shows the triangle formed by the manipulator arms, where A is the angle between boom and body link, and B is the angle between boom and stick link.

\[
\begin{align*}
a^2 &= b^2 + c^2 - 2bc \cos(A) \\
b^2 &= a^2 + c^2 - 2ac \cos(B)
\end{align*}
\] (5)
Fig. 2 Manipulator arm configuration as a triangle

### 2.4 Velocity kinematics

The DH method explained in section 2.1 is also applied to velocity kinematics. The angular velocity can be combined with i+1 frames angular velocity vectors and written concerning the same frame i as formulated in Eq. 6. Notation for the equation is shown in Eq. 7 [22].

\[
i_{i+1} \omega_i = i \omega_i + i_{i+1} R \hat{\theta}_{i+1} i_{i+1} \hat{Z}_{i+1}
\]  
  \quad (6)

\[
\hat{\theta}_{i+1} i_{i+1} \hat{Z}_{i+1} = i+1 \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_{i+1} \end{bmatrix}
\]  
  \quad (7)

The angular velocity of link i+1 with respect to the frame i is presented in Eq. 8:

\[
i_{i+1} \omega_{i+1} = i_{i+1} R i \omega_i + \hat{\theta}_{i+1} i_{i+1} \hat{Z}_{i+1}
\]  
  \quad (8)

The linear velocity of the frame i+1 of manipulator is shown in Eq. 9:

\[
i_{i+1} v_{i+1} = i v_i + i \omega_i \times i p_{i+1}
\]  
  \quad (9)

When multiplying both sides with \(i_{i+1} R\), Eq. 10 is obtained:

\[
i_{i+1} v_{i+1} = i_{i+1} R (i v_i + i \omega_i \times i p_{i+1})
\]  
  \quad (10)

When Eq. 8 and Eq. 10 are applied to all of the manipulator links \(N v_N\) and \(N \omega_N\), which are the linear and angular velocity of the end effector, can be calculated.
Two degrees of freedom (DOF) manipulator is demonstrated by Fig. 3, which is similar to the system modeled in this study [21].

The x- and y-direction velocity components of the end effector of the manipulator are presented in Eq. 11 as a function of joint angles in terms of frame 3. Frame 3 is attached at the end of the manipulator.

\[
^3v_3 = \begin{bmatrix}
  a_1 \sin(\theta_2) \dot{\theta}_1 \\
a_1 \cos(\theta_2) \dot{\theta}_1 + a_2 (\dot{\theta}_1 + \dot{\theta}_2) \\
0
\end{bmatrix}
\]  \hspace{1cm} (11)

When combining the rotation matrix with Eq. 11, the end effector’s velocities with respect to the base frame are obtained, displayed in Eq. 12.

\[
^0v_3 = \begin{bmatrix}
-a_1 \sin(\theta_1) \dot{\theta}_1 - a_2 \sin(\theta_1 + \theta_2) (\dot{\theta}_1 + \dot{\theta}_2) \\
a_1 \cos(\theta_1) \dot{\theta}_1 + a_2 \cos(\theta_1 + \theta_2) (\dot{\theta}_1 + \dot{\theta}_2) \\
0
\end{bmatrix}
\]  \hspace{1cm} (12)

Jacobians are used to relate the joint velocities to the Cartesian velocities of the hydraulic manipulator’s tip arm. This relation is described in Eq. 13:

\[
^0v = ^0J(\theta)\dot{\theta}
\]  \hspace{1cm} (13)

where \( \theta \) is the vector of the manipulator’s joint angles, and \( v \) is the vector of Cartesian velocities with respect to the base frame.
This application has a two-link arm, and by using Eq. 11, a $2\times2$ Jacobian matrix can be written that relates joint rates to the end-effector velocity in the third frame, which is shown in Eq. 14:

$$J^3(\theta) = \begin{bmatrix} a_1 \sin(\theta_2) & 0 \\ a_1 \cos(\theta_2) + a_2 & a_2 \end{bmatrix} \quad (14)$$

According to Eq. 13, the Jacobian matrix can be written in terms of the base frame formulated in Eq. 15:

$$J^0(\theta) = \begin{bmatrix} -a_1 \sin(\theta_1) - a_2 \sin(\theta_1 + \theta_2) & -a_2 \sin(\theta_1 + \theta_2) \\ a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2) & a_2 \cos(\theta_1 + \theta_2) \end{bmatrix} \quad (15)$$

For this study, the main purpose is to use the inverted Jacobian matrix to calculate the joint rates. In Eq. 16, the Jacobian matrix is inverted according to Eq. 13, and the joint rates are obtained for each joint.

$$\dot{\theta} = J^{-1}(\theta)v \quad (16)$$

The joystick inputs act as a velocity input guide for the boom tip x- and y- directions while the material handler is operating. In order to provide the right command signals for the actuator, the velocity of the joints must be known and engaged afterward to calculate the required hydraulic actuator velocities [22].

### 2.5 Actuator piston velocities in terms of joint speeds

To obtain the piston rods' velocity, the piston rod actuators' geometrics must be determined, and subsequently, the angle of joint around which the piston operates can be calculated based on the length of the piston rod actuator. The joint angles based on the geometries of pistons are presented in Eq. 23-25, while Eq. 23 is regarding the boom lift actuator, Eq. 24 is concerning the lower tilt actuator, and Eq. 25 is related to the upper tilt actuator, whereas Fig. 4 and Fig. 5 depict the geometry of the pistons. The geometry relationships are solved by Eq. 17-22. The parameter values used in the calculations are specified in Table 1. The known values are the locations of actuator attachment points C and D and the joint location at B. Also, angles $\theta_1$ (robot) and $\varepsilon_1$ (absolute) are known. BC length can be calculated from the locations B and C, and the angle $\varepsilon_5$ is acquired when a right triangle is formed between two points. Obviously, angle $\varepsilon_6$ is figured out as Eq. 17:

$$\varepsilon_6 = \frac{\pi}{2} - \varepsilon_1 \quad (17)$$
Apparently, $\varepsilon_2$ and the length of CD can be calculated as Eq. 18-19:

$$\varepsilon_2 = \pi - \varepsilon_6 - \varepsilon_5$$

$$CD = \sqrt{BC^2 + BD^2 - 2 \times BC \times BD \times \cos(\varepsilon_2)}$$

In Fig. 5, coordinate locations of E, F, G, J, and H are known, and the angle $\theta_2$ is also known from the inverse kinematic solution. Actuator lengths HE and FG and angle $\varepsilon_{10}$ are calculated as Eq. 20-25:

$$\varepsilon_{10} = \pi - \theta_2$$

$$HE = \sqrt{EF^2 + FH^2 - 2 \times EF \times FH \times \cos(\varepsilon_{10})}$$

$$FG = \sqrt{JG^2 + FJ^2 - 2 \times JG \times FJ \times \cos(\theta_2)}$$

$$\theta_1 = \pi - \varepsilon_6 - \varepsilon_5 - \tan^{-1}\left[\frac{\{4 \times BC^2 \times BD^2 - [BC^2 + BD^2 - CD^2]^2\}^{\frac{1}{2}}}{(BC^2 + BD^2 - CD^2)}\right]$$

$$\theta_2 = -\tan^{-1}\left[\frac{\{4 \times JG^2 \times FJ^2 - [JG^2 + FJ^2 - FG^2]^2\}^{\frac{1}{2}}}{(JG^2 + FJ^2 - FG^2)}\right]$$

$$\theta_2 = \pi - \varepsilon_{10} - \tan^{-1}\left[\frac{\{4 \times EF^2 \times FH^2 - [EF^2 + FH^2 - HE^2]^2\}^{\frac{1}{2}}}{(EF^2 + FH^2 - HE^2)}\right]$$

The velocity of each actuator piston rod in terms of the velocity of the joint angle is calculated as Eq. 26-28 [23]:

$$v_{CD} = \frac{(-BD \times BC \times \sin(\varepsilon_2))}{CD} \times \dot{\theta}_1$$

$$v_{FG} = \frac{(-FJ \times JG \times \sin(\theta_2))}{FG} \times \dot{\theta}_2$$

$$v_{HE} = \frac{(-EJ \times HJ \times \sin(\varepsilon_{10}))}{EH} \times \dot{\theta}_2$$
Fig. 4 Lift actuator geometry

Fig. 5 Tilt actuator geometry
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Actuator 1 lower attachment</td>
<td>2.68;0.835 (m)</td>
</tr>
<tr>
<td>D</td>
<td>Actuator 1 upper coordinate point</td>
<td>4.774;1.082 (m)</td>
</tr>
<tr>
<td>E</td>
<td>Actuator 2 central lower coordinate point</td>
<td>11.82;1.548 (m)</td>
</tr>
<tr>
<td>H</td>
<td>Actuator 2 central upper coordinate point</td>
<td>15.506; -1.2 (m)</td>
</tr>
<tr>
<td>F</td>
<td>Actuator 2 side lower coordinate point</td>
<td>11.517;0.599 (m)</td>
</tr>
<tr>
<td>G</td>
<td>Actuator 2 side upper coordinate point</td>
<td>15.3680;1.192 (m)</td>
</tr>
<tr>
<td>a₁</td>
<td>Boom length</td>
<td>15.506 (m)</td>
</tr>
<tr>
<td>a₂</td>
<td>Stick length</td>
<td>12 (m)</td>
</tr>
<tr>
<td>a₃</td>
<td>Boom start to stick end</td>
<td>(initial)</td>
</tr>
<tr>
<td>d₁</td>
<td>Origin to boom start x-direction</td>
<td>1.4 (m)</td>
</tr>
<tr>
<td>d₂</td>
<td>Origin to boom start y-direction</td>
<td>2.309 (m)</td>
</tr>
<tr>
<td>θ₁</td>
<td>Absolute angle boom link</td>
<td>(rad)</td>
</tr>
<tr>
<td>θ₂</td>
<td>Absolute angle stick link</td>
<td>(rad)</td>
</tr>
</tbody>
</table>

3 Material handler properties

This research work was carried out utilizing a material handler supplied by Mantsinen based on the Mantsinen 200 machine, which is described as a mobile harbor crane designed to handle bulk materials and standard size containers and general cargo. Mantsinen 200 is shown in Fig. 6 with the tracks as the undercarriage structure [20].

![Fig. 6 Mantsinen 200 with tracks moving shipping containers](image)

The hydraulic control pattern of the material handler follows the ISO 10968:2017 standard in which the left-hand joystick controls the swing direction by moving left or right and the sticks directional movement by shifting forward and backward. In contrast, the right-hand joystick controls the opening and closing of the bucket by shifting left or right and raising or lowering the boom up or down by moving back and forth as shown in Fig. 7.
Mantsinen 200 is equipped with a boom, which its length varies from 10.5 to 21.5 meters and a stick which its length varies from 9 to 18 meters, providing 37 meters of horizontal access. The Mantsinen 200 hydraulic system operates with $4 \times 420$ liters per minute hydraulic oil flow at the operating pressure 330 bars. The swing system has its own independent oil flow system, which provides up to 540 liters per minute oil flow and 300 bar pressure. The machine is powered by a Volvo TAD1643VE diesel engine that produces 565 kW of power at 1800 rpm. The machine’s total weight is between 230 to 280 tons depending on the configuration [20].

4 Principles of coordinate control

In this study, coordinate control methodology is utilized to control the material handler, and the following two sub-methods are investigated, namely open-loop and closed-loop control systems. Applying open-loop method, the control system acts purely with the input signals provided, and the system is independent of the output signal; while applying the second method, the output signal is fed back to the system and compared with the desired input to exert a control action in order to make the output the same as the reference input. Fig. 8 illustrates the operating principle of the open-loop control system, and Fig. 9 illustrates the operating principle of the closed-loop control system for the material handling machine in question.
Fig. 8 Open-loop control system operating principle

Fig. 9 Closed-loop control system operating principle
In both systems, the joystick determines the x- and y-direction linear velocities of boom tip; however, the angles data is obtained from the sensors of the system to calculate the locations of x and y boom tip. Afterward, they are transformed into robot angles, which are used to calculate the actuators’ lengths. The robot’s angles are inserted to a Jacobian matrix with the desired linear velocity inputs of the arm structure. The angular velocities are formed in the Jacobian matrix, which are then used to calculate the actuator velocities to create valve guidance signals.

In the closed-loop system, the joysticks act the same way as in open control system, though angular velocity sensors are employed to provide the feedback for the system, and the angle sensors data are fed directly to the Jacobian matrix with the linear velocity inputs. The Jacobian matrix computes the angular velocities compared with the angular velocities data achieved from the angular velocity sensors. The difference between angular velocity signals is calculated and fed to the PI controller to be adjusted and sent to the valves.

5 Simulation environment

The main simulation program used for this work is the Mevea Industrial Simulator, which consists of three elements, including Modeler, I/O toolbox, and Solver. In this study, the material handler model was provided by Mantsinen, which is the same as the real machine of the company. The composition of the material handler in the Mevea simulation environment is presented in Fig. 10 [24].
5.1 Model description and parameters

A Simulink interface block was developed to act as a communication hub between the Simulink code and the Mevea Solver to transfer the data required for further calculations, and the necessary signals were added to the Mevea Modeler I/O socket interface. The machine has pilot and Hybrilift valves, and when Mantsinen model is used, these valves should be controlled manually every time the arm is driven. The mentioned issues were resolved by applying these signals to Simulink and automating their control based on the actuator control signals. The joystick values include each joystick’s direction and the input value that the operator exerts to each joystick, which changes the scale from 0 to 250. The joystick values are utilized to create the desired actuator speeds that the operator has requested from the system. As the system is pressure compensated, the actuators' area can be reduced into one area that receives the maximum flow rate that the system can provide. The maximum speed of the hydraulic actuator can be calculated by Eq. 29:

\[ v_{\text{max}} = \frac{Q_{\text{max}}}{A_p} \]  \hspace{1cm} (29)

where \( v_{\text{max}} \) is the maximum velocity of the hydraulic piston, \( Q_{\text{max}} \) is the maximum flow rate and \( A_p \) is the combined piston area. The formula is used to calculate the lifting and lowering speeds of the actuator [25]. Table 2 shows the calculation results for each direction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yref_pos</td>
<td>x-direction max speed up</td>
<td>0.1883 (m/s)</td>
</tr>
<tr>
<td>Yref_neg</td>
<td>x-direction max speed down</td>
<td>2.598 (m/s)</td>
</tr>
<tr>
<td>Xref_pos</td>
<td>y-direction max speed forwards</td>
<td>0.1474 (m/s)</td>
</tr>
<tr>
<td>Xref_neg</td>
<td>y-direction max speed backwards</td>
<td>0.7958 (m/s)</td>
</tr>
</tbody>
</table>

Depending on the joystick direction, the control algorithm creates a different input signal value, ranging from 0 to 10. In other words, the signal ‘one’ is formed by the forward direction of the joystick from the operator and signal ‘two’ is formed by the toward direction of the joystick to the operator, while the left side direction of joystick creates ‘four’ signal and the right side creates ‘eight’ signal. In the same way, the center generates ‘zero’. When the joystick is moved to one of the four corners, the signal formed is the sum of the signals related to surrounding directions. Joystick control pattern signals is displayed in Fig. 11. This design for the coordinate control model was altered to allow only one direction input at once. The limit made
with this pattern prevents the simultaneous operation of the bucket and arm y-direction movement or swing and arm x-direction movement.

![Joystick control pattern signal forming for Mantsinen 200M](image)

**Fig. 11** Joystick control pattern signal forming for Mantsinen 200M

Boom and stick are both equipped with their sensors, and the measured angles are absolute angles; however, the machine has the end effector location as a CAN (Controller Area Network) bus that can interact directly with the Simulink model.

### 5.2 Model control values parameters

The last step in the model is to convert the obtained actuator speeds to actual control valve voltages, which is performed by dividing the actuator speed by the maximum speed of each joint based on the direction of movement. The operating values are listed in Table 3. When lowering the boom, the machine opens the load control valve to allow the boom to come down and recharge the Hybrilift energy storage system. The stick load control valve is used simultaneously with three of the control valves when bringing it towards the cockpit. In the closed-loop system, the total number of parameters is significantly less than in an open control system, simplifying the system. In the actual model, the computed angular velocities are summed up with the angular velocities achieved from sensors, and finally are sent to a controller, which calculates directly the desired signals for 8 valves that control the boom and stick of the machine. In this work, a PID-controller is used to control the valve signals for the hydraulic actuators; however, because in PID controller, the derivate coefficient Kd increases the noise of the system, which eventually leads to significant oscillation, Kd coefficient is set to zero, which means the controller is converted to PI [26].

**Table 3** Valve and joystick control values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_left</td>
<td>Joystick direction left</td>
<td>1-2</td>
</tr>
<tr>
<td>J_right</td>
<td>Joystick direction right</td>
<td>1-2</td>
</tr>
<tr>
<td>J_force</td>
<td>Joystick push force</td>
<td>0-250</td>
</tr>
<tr>
<td>U_bpool</td>
<td>Pressure compensated proportional valve boom</td>
<td>0-800 (mV)</td>
</tr>
<tr>
<td>U_{spool}</td>
<td>Pressure compensated proportional valve stick</td>
<td>-800 to +800 (mV)</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>U_{blc}</td>
<td>Load control valve control voltage boom</td>
<td>12.5% to 83.7%</td>
</tr>
<tr>
<td>U_{slc}</td>
<td>Load control valve control voltage stick</td>
<td>12.5% to 83.7%</td>
</tr>
<tr>
<td>V_1</td>
<td>Valve 1 guidance compensation</td>
<td>46.2%</td>
</tr>
<tr>
<td>V_2</td>
<td>Valve 2 guidance compensation</td>
<td>43.7%</td>
</tr>
<tr>
<td>V_3</td>
<td>Valve 3 guidance compensation</td>
<td>41.2%</td>
</tr>
<tr>
<td>V_4</td>
<td>Valve 4 guidance compensation</td>
<td>38.7%</td>
</tr>
</tbody>
</table>

6 Numerical results

All the experiments were performed by moving the joystick in one direction and measuring changes in tip position. By comparing the resulted values from applying two different control systems with all four different joystick inputs, it can be concluded which control method is more satisfactory for the machine. The reference was specified by measuring the tip position changes when the machine was operated by applying Mantsinen control system.

6.1 Open-loop results

For the open-loop system, all the input signals were given as step functions. The simulation time for each control direction was limited to 20 seconds, and a total of 100 seconds was simulated.

6.1.1 Positive Y-direction

The purpose of the first given input was to move the arm in positive y-direction, i.e., upwards, with a maximum joystick input force from 5 seconds to 25 seconds in the simulation, plotted in Fig. 12. The solid line and dashed lines represent boom and actuator velocities, respectively. Fig. 13 depicts the results of changes in the tip head coordinate, while the solid line and dotted line correspond to x-coordinate and y-coordinate, respectively. Fig. 13 shows that the tip x-value varies from 15.49 to 17.57 meters and y-value from -3.27 to -1.52 meters.
6.1.2 Positive X-direction

The second input was given in the positive x-direction, which means moving the tip further away from the cabin, with maximum joystick input and simulation time from 30 to 50 seconds. The calculated velocities of the tip are depicted in Fig. 14. Changes in the tip head coordinate are plotted in Fig. 15. The same line principles, the same as the previous section, are used here as well. Fig. 15 reveals that the tip x-value varies from 17.51 to 20.77 meters and the y-value changes from -1.54 to -0.21 meters.

6.1.3 Negative X-direction

The input was given in the negative x-direction, which means moving the tip towards the cabin, with maximum joystick input and simulation time from 55 to 75 seconds. Fig. 16 and Fig. 17 show the velocities and the tip position changes with negative x-direction. The calculated velocity of y-direction decreases slowly overtime after the step input is given, however, with less decline than the two previous directions. Also, the x-direction velocity increases to more
negative. Fig. 17 presents that the tip x-value changes from 20.90 to 20.29 meters and y-value varies from -0.17 to -0.50 meters.

![Fig. 16 Calculated velocities of the tip in the negative x-direction](image)

**Fig. 17** Tip position change with the negative x-direction input

### 6.1.4 Negative Y-direction

The input was given in the negative y-direction, which occurs by moving the arm downwards, with a maximum joystick input and a simulation time of 80 to 100 seconds. **Fig. 18** and **Fig. 19** show the velocities and tip position changes in the negative y-direction with the same line properties as previously described. **Fig. 19** shows that the tip x-value varies from 20.28 meters to 16.13 meters and y-value changes from -0.51 to -1.74 meters.

![Fig. 18 Calculated velocities of the tip in the negative y-direction](image)

**Fig. 19** Tip position changes with the negative y-direction input

### 6.2 Closed-loop results

The experiments were conducted for the closed-loop system using both right and left joysticks to evaluate the controller’s performance and to measure the tip position changes subsequently. Step input is not valid for a closed-loop system, as it increases the probabilities of oscillations.
As a solution, a slider was inserted to control the input signal force manually. In both joystick tests, the machine operated for 20 seconds, in which the arm was moved in one direction with the control input; however, the machine still had minor initial movement in the first ten seconds, which is the reason for commencing the simulation with a slight delay. The feedback references were amplified by 4 and 8, respectively. For the designed PI controller, the proportional gain value \( K_p \) was set to 25 for the boom link controller and 20 for the swing link controller, while the integral gain \( K_i \) was set to one.

### 6.2.1 Positive Y-direction

The first input was given to move the tip in the positive y-direction in the simulation with maximum joystick input force from 10 seconds to 30 seconds. The tip position change is plotted in **Fig. 20**. The solid line is the x-coordinate and the dotted line is the y-coordinate of the tip. The tip x-value changes from 15.50 to 16.06 meters, and the y-value changes from -3.27 to -1.65 meters. The angular velocities of the two links are presented in **Fig. 21** and **Fig. 23**. The solid line is the value obtained based on calculations, and the dotted line is the value achieved based on the feedback value from the sensors. As can be seen from **Fig. 21**, the boom link velocity has a small overshoot of roughly 10% of the requested speed after 2 seconds of simulation; however, the velocities catch each other eventually. **Fig. 22** and **Fig. 24** present the valve control signals and their change over the simulation time. The controller reacts immediately to the control signal; however, the actuator requires time to move the manipulator’s arm. **In Fig. 24**, the stick control values for the three actuators are the positive values mentioned in Table 3; however, they cause no movement in the manipulator, and the angular velocity of the stick stays positive due to the movement of the first link.
6.2.2 Negative Y-direction

The second input was given to drive the tip in the negative y-direction with maximum joystick input force from 40 seconds to 60 seconds in the simulation. The tip position change is plotted in Fig. 25. The tip x-value changes from 16.27 to 14.01 meters, and the y-value varies from -0.87 to -3.24 meters. Fig. 26 and Fig. 28 display the angular velocities of the two links. In both links, the angular velocity drops to an extreme negative value at second 46.4 of the simulation and again stabilizes over the next 4 seconds, during which the tip hits the ground and the velocity signal stops at 0. Fig. 27 and Fig. 29 present the valve control signals and their change during the simulation time. As shown in Fig. 28, from the second 46 to the second 50, the system purely oscillates because the bucket reaches the ground. The tip continues moving in x-direction after touching the ground. The same oscillation also occurs in the valve control voltage shown in Fig. 29.
Fig. 25 Tip position change with the negative y-direction input

Fig. 26 First link calculated angular velocity and reference angular velocity

Fig. 27 Valve control signals of the first link valves

Fig. 28 Second link calculated angular velocity and reference angular velocity

Fig. 29 Valve control signals of the second link valves

6.2.3 Positive X-direction

The third input was given to drive the tip in positive x-direction with a maximum joystick input force from 40 seconds to 60 seconds in the simulation. Fig. 30 presents the change in tip position. The tip x-value varies from 16.20 to 18.23 meters, and the y-value changes from -1.08 to -0.64 meters till the 53.7 second when the system reacts unexpectedly and drops the tip to the ground. After that although the manipulator is still able to move in the x-direction, it gets
stuck in the y-direction since the control system still exerts negative y-direction control. The drop that occurred during the simulation was unusual and was further investigated. The system was simulated for another 30 seconds, as shown in Fig. 35, and it was figured out that the same behavior occurred regularly. The boom load control valve has a steady signal raise shown in Fig. 32 until the above-mentioned second when the signal jumps to the point that the boom is allowed to fall down freely and the control of the system is lost. Fig. 31 shows that the angular velocity input for the boom link was negative; however, based on the sensor data, the system had little to no reaction to this; nevertheless, the load control valve opened, and control values increased linearly in Fig. 32. Fig. 33 displays the stick link's angular velocities following the input signals, although it suffers from the significant negative peak, and starts oscillating towards the end of the simulation period. Negative peak values also negate the valve control signals of the second link, as shown in Fig. 34, which otherwise do not reach the maximum values.

**Fig. 30** Tip position change with the positive x-direction input

**Fig. 31** First link calculated angular velocity and reference angular velocity

**Fig. 32** Valve control signals of the first link valves

**Fig. 33** Second link calculated angular velocity and reference angular velocity
6.2.4 Negative X-direction

The last input was given to drive the tip in negative x-direction with maximum joystick input force from 20 seconds to 40 seconds in the simulation. Tip position change is displayed in Fig. 36. The tip x-value varies from 16.27 to 8.24 meters and y-value changes from -0.13 to 0.98 meters. This last input causes the largest displacement in the tip positions compared to other tests previously performed. Fig. 37 shows the boom link angular velocities. As shown, the feedback signals do not reach the input values until the 24.6 second, when a massive overshoot occurs in the boom velocity signal from the sensors, causing the system to undershoot as counter reaction. Boom valve signals also show the same symptoms as displayed in Fig. 38. The second link's feedback value oscillates over the simulation time as it tries to follow the input signal, which causes the tip of the manipulator to move remarkably during the simulation and the control signal to overshoot the desired values as shown in Fig. 39. The same reaction occurs in the valve control signals in Fig. 40, where the signals are at maximum values for a large part of the simulation. The same line properties of the figures similar to the previous sections are also valid here.
6.3 Mantsinen control system

The Mantsinen control system was examined likewise the two developed control systems. Mantsinen control system tests were performed merely to obtain the results of tip position change in order to be compared with the results of coordinate control. Each of the four directions is driven with a maximum input of 250 given as a step input to the machine for 20 seconds, the results of which are presented in Fig. 41 to Fig. 44, while the solid line in the figures shows the y-coordinate change and the dotted line shows the x-coordinate change. Fig. 41 indicates that when the swing link is driven into a positive direction, the tip x-value changes from 16.17 to 20.78 meters, and the y-value changes from -1.1 to 0.63 meters. Fig. 42 displays that when the swing link is driven into a negative direction, the tip x-value varies from 20.48 to 9.642 meters, and the y-value changes from -1.76 to -1.42 meters. Fig. 43 shows that when the boom link is driven into a positive direction, the tip x-value changes from 15.5 to 16.17 meters and y-value varies from -3.27 to -1.10 meters. Fig. 44 displays that when the boom link is driven in the negative direction, the tip x-value varies from 20.78 to 20.09 meters, and the y-value changes from 0.63 to -3.28 meters. At the second 58.4 of the simulation, the bucket hits the ground, and the movement stops.
6.4 Result comparison

The test results of applying the two coordinate control strategies explained in sections 6.1 and 6.2 in addition to applying the Mantsinen control system are summarized in Table 4. Comparison of the results of the coordinate changes by applying different control systems for comparison. The values mentioned in the table are the changes in tip position in the defined coordinate direction. Ideally, when the tip is driven to either x- or y-direction, the other coordinate should remain unchanged. A comparison of errors applying different boom tip control methods reveals that the positive Y closed-loop system has less error in x-direction than the open-loop control system, and the same also occurs in the negative Y direction. Also, in the X direction, the closed-loop system has less error than the open-loop system. Therefore, it can be concluded that the closed-loop control system operates more precisely than the open-loop system as expected. Moreover, it is evident that the closed-loop system has a similar performance as the Mantsinen control system, although it is more inaccurate than the Mantsinen control system.
Table 4 Comparison of the results of the coordinate changes by applying different control systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Open-loop</th>
<th>Closed-loop</th>
<th>Mantsinen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>X</td>
<td>2.08 (m)</td>
<td>0.56 (m)</td>
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<tr>
<td>Positive</td>
<td>Y</td>
<td>1.75 (m)</td>
<td>1.62 (m)</td>
</tr>
<tr>
<td>Error</td>
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<td>-4.15 (m)</td>
<td>-2.26 (m)</td>
</tr>
<tr>
<td>Negative</td>
<td>Y</td>
<td>-1.23 (m)</td>
<td>-2.37 (m)</td>
</tr>
<tr>
<td>Positive</td>
<td>X</td>
<td>3.26 (m)</td>
<td>2.03 (m)</td>
</tr>
<tr>
<td>Error</td>
<td>Y</td>
<td>1.33 (m)</td>
<td>0.44 (m)</td>
</tr>
<tr>
<td>Negative</td>
<td>X</td>
<td>-0.61 (m)</td>
<td>-8.03 (m)</td>
</tr>
<tr>
<td>Error</td>
<td>Y</td>
<td>-0.33 (m)</td>
<td>0.85 (m)</td>
</tr>
</tbody>
</table>

7 Conclusion

The purpose of this research work was to develop a coordinate control system for a material handler machine. The case study in this paper was a machine provided by the Mantsinen Group. Two different control methods that are open-loop control and closed-loop control were implemented with the aim of fully or semi-automation of the manipulator motions. The mechanism of action and working principles of each control system were described and mathematically formulated. The open-loop system is more complicated than the closed-loop system and requires more calculations to obtain the correct values for the input signals. In order to maximize the effectiveness of the open-loop system, all the kinematics should be verified. Both developed control systems were tested in real-time simulation, and the results were compared with each other. The closed-loop system was figured out to perform better than the open-loop system as expected, although it suffers from some unexpected signal changes that impair the system performance, which occurs when the Jacobian matrix gives a negative signal. However, both control systems require further optimization to reach their full potential. It is noteworthy that the velocity directions in the x-direction are the same for both open and closed-loop systems; however, the fact is not the same in the y-direction. In open-loop control system, velocity direction in positive y-direction yields both control signals as positive, however with closed-loop control system, the stick signal starts as negative; nevertheless, the change towards the positive continues and steadily increase until the end of simulation. The same occurs in the
negative y-directions, as in the open-loop system both signals are negative; however, in closed-loop system the stick signal is positive.

In this study, the hydraulic manipulator's direct tip control by simultaneous commanding of all actuators with one general input was achieved. The conducted research has an impressive contribution to implementing the coordinate control system in industrial heavy hydraulic machineries in the near future, since satisfactory results were obtained by applying the control systems developed in this study on a real material handling machine from Mantsinen. Future directions for research are executing the developed code in a simulator with real joysticks as input devices to evaluate system performance. Moreover, since some characteristics of the material handler hardened to achieve the desired results, another future plan is to improve controlling of the system by introducing another controller to the boom link load control valve without the integrator gain component ($K_i$) and re-tuning the other two controllers afterward. Also, further experiment with the amplification of the control signals is another future research direction.

References


