Cooperative Hoisting with Two Crawler Cranes under Rope-Velocity Constraints

Chenhao Cui, Alessandro Giua, Alessandro Pisano*†

Abstract

Hoisting of large span and large tonnage equipment often requires two or more cranes. Usually cooperative hoisting is carried out by multiple drivers under the command of one coordinator for the task. This leads to low lifting efficiency and low safety and it is desirable to automate this process. In this paper, the physical model of double cranes is analyzed to obtain the constraints imposed by cooperative hoisting. We first solve the direct and inverse kinematic problem, obtaining the kinematic relationship between load coordinates and cable lengths. Then we consider a hoisting operation defined by an assigned trajectory and by a particular trapezoidal velocity profile, parameterized by a constant cruising velocity. We show how to compute the optimal value of the parameter that minimize the hoisting time while ensuring the admissibility constraints are satisfied. Several simulations related to two industrial crawler cranes are presented.

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1 Introduction

Chemical and construction industries have a great demand for cranes, and the requirements for crane hoisting capacity are getting higher and higher. Crane manufacturers also continue to set new records for the maximum tonnage of cranes. At present, the maximum lifting weight of crawler cranes is around 4500 t (see Sany Crawler Crane SCC45000A, introduced in June 2021), above which the cost and manufacturing difficulties required to improve the hoisting capacity of each point will be very large.

Cooperative hoisting is becoming more and more common for several reasons. The hoisting of some type of equipment (large tonnage or large size) may be done using multiple crawler cranes which have a smaller hoisting capacity but are relatively inexpensive, and this can effectively reduce operating costs. In addition, some hoisting tasks are very difficult for a single crane. A typical example is the installation of high-power wind turbines: huge wind turbine blades need to be hoisted from horizontal to vertical and this task often requires two or more cranes working in concert.

Currently, the operation of multiple cranes is usually based on single crane lifting, informal planning and manual commands. Thus it often lacks a theoretical basis needed to achieve an effective collaboration and results in low efficiency and safety risks. Even the cooperative hoisting with only two cranes is a problem significantly more complex than the traditional single crane operation. Cooperative hoisting with two crawler cranes has been implemented in industrial processes, to overcome the limits imposed by the lifting capacity of a single crane. Different approaches have been presented in the literature to address this class of problems.

Regarding the problem of multi-crane collaborative hoisting, Souissi [1] proposed a modeling and control method based on two cranes in a closed link, completed the basic modeling of the two cranes' collaborative hoisting, and studied their collaborative hoisting process. Chen *et al.* [2] proposed an agent-based simulation method for the cooperative hoisting of two truck cranes, where the agents exchange messages to coordinate the operation of the two cranes. Wang *et al.* [3, 4] proposed a simulation method for double hoisting based on geometric kinematics and considered the load as a rigid body. They also assumed that the cable is always vertical to establish an intuitive simulation model: however, due to this assumption and other modeling approximations, the actual hoisting operation may differ from the results of the simulation. Cai *et al.* [5] proposed a model of a dual-crane lifting system and provided a motion planning method for such a system. Leban *et al.* [6] presented an inverse kinematic strategy for controlling the hoist lengths and boom angles of two cranes with the objective of keeping their load fixed in inertial space, regardless of the motion of the ship on which they are mounted; however, the operation of cooperative hoisting was also ignored. Eberharter and Schneider [7] presented a control concept to synchronize two or more cranes to improve tandem lift operations, and the control system requires only one driver to operate. Nam *et al.* [8] proposes a closed-loop speed control with interlock functions for hoisting, an alarm treatment system for safety and a monitoring system during the dual lifting have been proposed to improve the dual lifting efficiency. Liu *et al.* [9] proposes an adaptive nonlinear proportional-integral-derivative-like collaborative control method for DRCs(Dual Rotary Cranes), which can realize accurate and efficient antiswing hoisting. Vaughan *et al.* [10] present two methods to limit payload oscillation during multi-hoist lifts. The two techniques utilize input shaping to design inputs for each of the hoists involved. One method uses the local suspension cable length at each hoist for control design, while the other concurrently designs the inputs based on the payload configuration. Li *et al.* [11] developed an automated collaborative lifting system that allows real-time sharing of parameter information between two crawler cranes. Tak *et al.* [12] introduced a construction site environment-based crane operation and management framework for multiple concurrent mobile crane operations in a BIM environment supported by a comprehensive database. These methods focus on controlling the angle of the boom of the crane as well as the path planning of the crane itself. In cooperative hoisting, controlling the movement of the ropes is very important for the stability of the lifting system.

In this paper we propose an approach for the optimal control of a cooperating crane system under rope-velocity constraints. The main contributions of this paper are summarized as follows. First, we present the working parameters and application scenarios of the considered cranes and we derive a kinematic model for a system composed by two cooperating cranes. We assume that the load moves in the same plane that contains the two booms and that the load can be considered as a point mass with a single hook to which both hoisting ropes are connected. Then we solve the direct and inverse kinematic problem, that allow one to express the load position as a function of the rope lengths and vice-versa. Finally we consider a motion planning problem where the load is required to move along a parabolic trajectory. In the considered setting the velocity of the load along the x-axis can be imposed to follow a trapezoidal profile with preassigned acceleration, where the constant cruising velocity is a design parameter. Achieving a minimum time operation requires maximizing the cruising velocity under the constraint that the rope length derivatives do not exceed given bounds. Two different approaches are discussed: the first provides a direct solution which may, however, be suboptimal; the second requires simulating the systems evolution for different values of the design parameter until the optimal value is found. Finally, a cooperative hoisting problem for two industrial cranes, produced by the Sany group, is simulated and analyzed.

The paper is organized in six sections. Section II describes the operating parameters of crawler cranes and the adopted notation. Section III defines the workspace and constraints of the crawler crane, and solves the direct and inverse kinematic problems. Section IV describes the considered motion planning problem and presents two approaches for computing a minimum-time solution. Section V applies the derived results to the simulation and control of the cooperative hoisting for two industrial crawler cranes. In Section VI conclusions are drawn and possible future developments are discussed.

2 Background and Notation

A crawler crane is shown in Fig. 1. A crawler crane refers to a hoisting machine in which a boom is mounted on an undercarriage fitted with a set of crawler tracks, and the boom system can rotate 360 degrees. In the hoisting process, the crawler crane relies on the turntable for slewing motion, the length of the cable is adjusted to hoist the load, and the boom angle can also be adjusted within a certain range.

The most common collaborative hoisting method is based on two cranes, and this is why in this paper cooperative hoisting with two cranes is studied under the following simplifying assumptions:

(1) The crane components (except the cable) and the hoisted objects in the system are all regarded as rigid bodies.

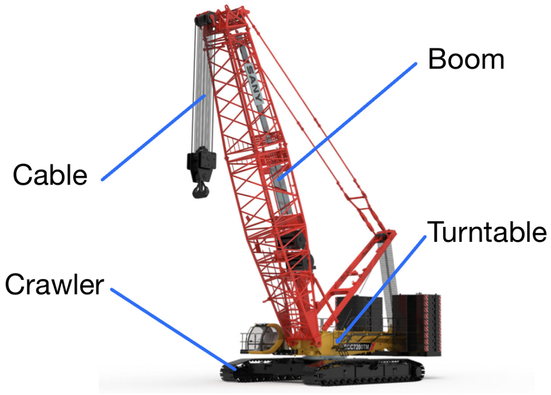

Figure 1: A crawler crane.

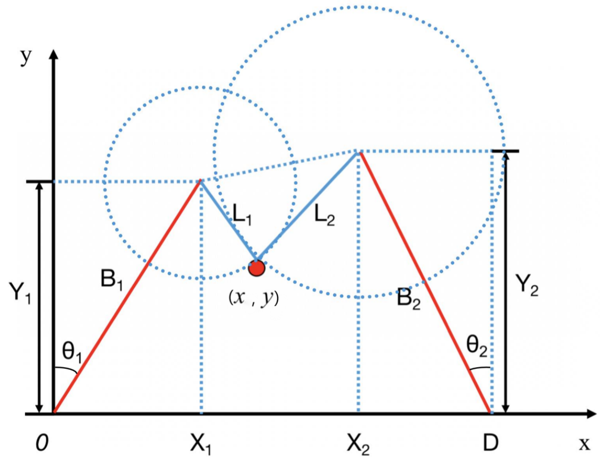

Figure 2: Schematic representation of two crawler cranes.

(2) The hoisting system is in a static equilibrium state, which is reasonable since the typical ovement of each crane is generally slow for safety reasons.

(3) The two hoisting points of the object to be lifted are considered to overlap.

A sketch of the two cooperating crawler cranes in the vertical $x-y$ plane is shown in Fig. 2. The distance between the two crawler crane turntables is D, B_1, B_2 are the lengths of the two booms, L_1, L_2 are the lengths of the cables, θ_1, θ_2 are the angles between the two booms and the vertical direction, respectively. The position of the load is expressed in the coordinate system as (x, y), and the coordinates of the boom vertices are (X_1, Y_1), (X_2, Y_2). The boom of a crawler crane is a detachable structure that is assembled to the appropriate length before the lifting process begins. The lengths B_1 and B_2 of the boom will not change when the crane is working. The boom angles θ_1 and θ_2 are considered as fixed parameters in the present work as they are also normally set before the lifting process is started and kept constant afterward.

During an operation, the rate of change of the cable length is the main factor governing the lifting efficiency. In the operation of a large tonnage crawler crane, the magnitude of the cable lifting velocity cannot exceed given values that in the present paper are denoted $L_{1d,max}$ and $L_{2d,max}$.

3 Direct and inverse Kinematics

The coordinates of the boom vertices are given by the next straightforward relations (see Fig. 2):

$$\begin{cases} X_1 &= B_1 \sin\theta_1, \\ Y_1 &= B_1 \cos\theta_1, \\ X_2 &= D - B_2 \sin\theta_2, \\ Y_2 &= B_2 \cos\theta_2. \end{cases} \tag{1}$$

The admissible load positions within the workspace are determined by the presence of tension in both cables, so that both cranes are carrying part of the load. This region is visually depicted as the shaded area in Fig. 3 and it is analytically described as follows:

$$\begin{cases} X_1 < x < X_2, \\ 0 \leq y < min(Y_1, Y_2). \end{cases} \tag{2}$$

The relationships between the cable lengths and the load coordinates are:

$$L_1 = \sqrt{(x - X_1)^2 + (y - Y_1)^2}, \tag{3}$$

$$L_2 = \sqrt{(x - X_2)^2 + (y - Y_2)^2}. \tag{4}$$

System (3)-(4) describes two circles whose centers are the endpoints of each boom, as shown in Fig. 2 with a dashed blue line.

When the cable lengths L_1 and L_2 are given, the coordinate $(x, y)$of the load can be calculated as follows. From Fig. 2 it can be seen that system (3)-(4) has two different (x,y) solutions (the two intersection points of the circles). Clearly, the physically meaningful solution for a load subject to gravity is the one with minimal value of y. Squaring Eqs. (3) and (4) and subtracting each other the resulting relations one deduces the following:

$$x = \frac{\left(L_1^2 - L_2^2 - X_1^2 - Y_1^2 + X_2^2 + Y_2^2\right) - 2y\left(Y_2 - Y_1\right)}{2\left(X_2 - X_1\right)}. \tag{5}$$

Substituting Eq. (5) into Eq. (3) one obtains the second order algebraic equation

$$ay^2 + by + c = 0 \tag{6}$$

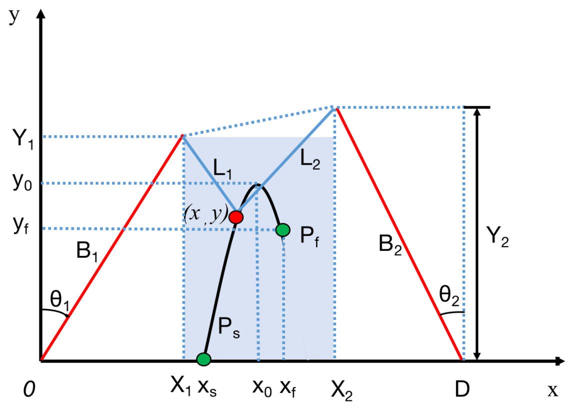

Figure 3: Desired trajectory of the load.

whose coefficients are

$$\begin{cases} a = & \frac{(Y_2-Y_1)^2+(X_2-X_1)^2}{(X_2-X_1)^2} \\ b = & \frac{2(Y_2-Y_1)X_2}{X_2-X_1} - 2Y_2\left(X_2-X_1\right) - \\ & \frac{(Y_2-Y_1)\left(L_1^2-L_2^2-X_1^2-Y_1^2+X_2^2+Y_2^2\right)}{(X_2-X_1)^2} \\ c = & \frac{\left(L_1^2-L_2^2-X_1^2-Y_1^2+X_2^2+Y_2^2\right)^2}{4(X_2-X_1)^2} - L_2^2 + Y_2^2 \\ & -\frac{X_2\left(L_1^2-L_2^2-X_1^2-Y_1^2+X_2^2+Y_2^2\right)}{X_2-X_1} + X_2^2 \end{cases} \tag{7}$$

Among the two solutions of Eq. (6), the smallest one is clearly

$$y = \frac{-b-\sqrt{b^2-4ac}}{2a} \tag{8}$$

Introducing the additional parameter

$$d = \frac{L_1^2-L_2^2-X_1^2-Y_1^2+X_2^2+Y_2^2}{2\left(X_2-X_1\right)} \tag{9}$$

and inserting Eq. (8) into Eq. (5) one obtains the x coordinate of the load as follows:

$$x = d + \frac{\left(b+\sqrt{b^2-4ac}\right)\left(Y_2-Y_1\right)}{2a\left(X_2-X_1\right)} \tag{10}$$

Notice that the inverse kinematic problem, i.e., computing the cable lengths L_1, L_2 corresponding to a given load coordinate (x, y) can straightforwardly be solved using Eqs. (3) and (4).

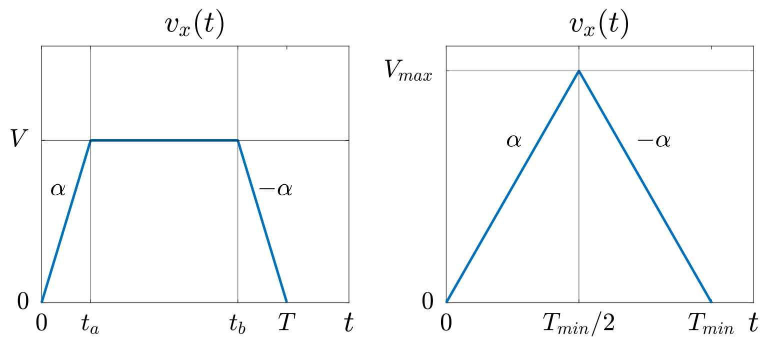

Figure 4: Desired velocity profile $v_x(t)$ as a function of time t for a given acceleration α. The limit case on the right corresponds to the minimum time hoisting assuming no bounds on the rope-length velocities are given.

4 Dynamic Solution

In the lifting operation of two crawler cranes, the position of the load can be controlled by changing the length of the two cables. We assume the desired trajectory of the load is given as a parabolic curve as shown in Fig. 3. Here $P_s = (x_s, y_s)$ denotes the starting position of the load and $P_f = (x_f, y_f)$ the final position. Such a trajectory can be described by:

$$y = k\,(x - x_0)^2 + y_0, \quad \text{for } x \in [x_s, x_f] \tag{11}$$

where $k < 0$ is a negative coefficient and (x_0, y_0) is the vertex of the parabola which in this case denotes the maximum value of the quadratic function.

To move the load along the desired trajectory, we impose a trapezoidal velocity profile $v_x(t) = dx(t)/dt$ along the x-axis shown in Fig. 5 on the left and described by

$$v_x(t) = \begin{cases} \alpha t & t \in [0, t_a] \\ V & t \in [t_a, t_b] \\ \alpha\,(T - t) & t \in [t_b, T] \end{cases} \\ \text{with} \quad t_a = \frac{V}{\alpha} \quad \text{and} \quad t_b = T - \frac{V}{\alpha}. \tag{12}$$

In the first phase (acceleration) the velocity increases with a constant slope α until a cruising velocity V is reached at time t_a. In the second phase (cruising) the velocity remains constant until a time t_b is reached. Finally, in the third phase (deceleration) velocity decreases with slope $-\alpha$, thus reaching the desired final position x_f. The total hoisting time is denoted T. This velocity profile imposes the following evolution of

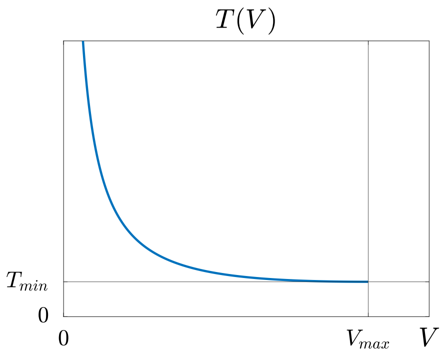

Figure 5: Hoisting time T as a function of the constant cruising velocity V.

the load along the x-axis:

$$x(t) = \begin{cases} x_s + \dfrac{\alpha}{2}t^2 & t \in [0, t_a] \\ x_s - \dfrac{V^2}{2\alpha} + Vt & t \in [t_a, t_b] \\ x_f - \dfrac{\alpha}{2}(T-t)^2 & t \in [t_b, T] \end{cases} \tag{13}$$

whereas the evolution $y(t)$ along the y-axis can be immediately obtained by substituting Eq. (13) in Eq. (11).

Note that:

$$x_a = x(t_a) = x_s + \frac{V^2}{2\alpha} \text{ and } x_b = x(t_b) = x_f - \frac{V^2}{2\alpha}, \tag{14}$$

while in the cruising phase (constant velocity) it holds that $x_b - x_a = V(t_b - t_a)$ which implies

$$t_b - t_a = \frac{x_b - x_a}{V} = \frac{x_f - x_s}{V} - \frac{V}{\alpha}, \tag{15}$$

from which we obtain

$$T = t_a + (t_b - t_a) + (T - t_b) = \frac{V}{\alpha} + \frac{x_f - x_s}{V}. \tag{16}$$

Assuming the parameter α is given, the previous equation allows one to write the hoisting time as a function of the constant cruising velocity V, keeping in mind that the admissible values of V are those that satisfy $t_b - t_a \geq 0$, i.e., according to Eq. (16):

$$V \leq V_{max} \overset{\text{def}}{=} \sqrt{\alpha(x_f - x_s)}. \tag{17}$$

In the admissible range of cruising velocities $V \in (0, V_{max}]$, the hoisting time is always decreasing, as shown in Fig. 5. As expected, the minimum time $T_{min} = 2\sqrt{(x_f - x_s)/\alpha}$ corresponds to the velocity profile described by the plot in the right of Fig. 4, which reaches the maximum velocity V_{max}.

In reality, such a minimum time profile may not be admissible because there are also constraints on the rate of change of the rope length that must be satisfied. To take this into account, let us first compute the rope length derivatives, $\dot{L}_1(t)$ and $\dot{L}_2(t)$. From Eq. (3) one obtains

$$\dot{L}_1(t) = \frac{d}{dt}L_1(t) = \left(\frac{\partial}{\partial x}L_1 + \frac{\partial}{\partial y}L_1 \cdot \frac{\partial}{\partial x}y\right)\frac{d}{dt}x(t)$$

which also taking into account Eq. (11) yields

$$\dot{L}_1(t) = \frac{(x - X_1) + 2k\,(x - x_0)\,(y - Y_1)}{\sqrt{(x - X_1)^2 + (y - Y_1)^2}} \cdot v_x = h_1(x)\, v_x. \tag{18}$$

Similarly, from Eq. (4) one obtains

$$\dot{L}_2(t) = \frac{(x - X_2) + 2k\,(x - x_0)\,(y - Y_2)}{\sqrt{(x - X_2)^2 + (y - Y_2)^2}} \cdot v_x = h_2(x)\, v_x. \tag{19}$$

The rope derivatives must satisfy for all $t \in [0, T]$ constraints

$$\left|\dot{L}_1(t)\right| \leq L_{1d,max} \quad \text{and} \quad \left|\dot{L}_2(t)\right| \leq L_{2d,max} \tag{20}$$

where $L_{1d,max}$ and $L_{2d,max}$ are suitable bounds that depend on the cranes.

We can finally state the problem we want to address.

Problem 1 (Minimum time hoist)

$$\begin{aligned}
& \min_{V} \quad T = \frac{V}{\alpha} + \frac{x_f - x_s}{V} \\
\textit{s.t.} \quad & \textit{(a) } V \in [0, V_{max}] \\
& \textit{(b) } \left|\dot{L}_1(t)\right| \leq L_{1d,max}, \quad \forall t \in [0, T] \\
& \textit{(c) } \left|\dot{L}_2(t)\right| \leq L_{2d,max}, \quad \forall t \in [0, T] \\
& \textit{under Eqs. (11), (12), (13).}
\end{aligned}$$

As we have observed, in the solution space $T(V)$ is decreasing, hence the optimal value of the decision variable V^* is the maximum value of the cruising velocity that satisfies constraint (a), (b) and (c).

To solve this problem we consider two approaches.

4.0.1 Direct approximate solution

Let us consider constraints (b) and (c) which according to Eq. (18) and (19) can be rewritten and manipulated, for $i = 1, 2$, as follows:

$$\left|\dot{L}_i(t)\right| = |h_i(x)|\, |v_x(t)| \leq h_{i,max} v_x(t) \leq h_{i,max} V$$

Figure 6: Cooperative hoisting with two crawler crane produced by Sany.

where $h_{i,max} = \max_{x\in[x_s,x_f]} |h_i(x)|$ only depends on the desired trajectory in Eq. (11) and not on the velocity profile. Thus constraints (b) and (c) are satisfied when

$$V \leq \frac{L_{1d,max}}{h_{1,max}} \quad \text{and} \quad V \leq \frac{L_{2d,max}}{h_{2,max}}, \tag{21}$$

and a direct approximate, although possibly suboptimal, solution of Problem 1 is

$$V = \min\left(V_{max}, \frac{L_{1d,max}}{h_{1,max}}, \frac{L_{2d,max}}{h_{2,max}}\right). \tag{22}$$

4.0.2 Line search optimization

Given a value of V one can compute $v_x(t)$, $x(t)$ and $y(t)$ for $t \in [0, T]$ from Eqs. (11), (12), (13). Substituting in Eq. (18) and (19) one obtains the profile of $\dot{L}_1(t)$ and $\dot{L}_2(t)$ for $t \in [0, T]$ and can directly verify if constraint (b) and (c) are satisfied.

Starting with $V = V_{max}$, one proceeds to iteratively reduce V by a step a suitable size, until constraint (b) and (c) are satisfied. This numerical procedure can determine the optimal solution T^* and the optimal value V^* of the velocity with the desired degree of accuracy.

5 Simulation Case Study

The specific crawler cranes considered in the present simulation case study are both produced by the Sany group and are shown in Fig. 6: the red crane is model SCC7200TM and the blue crane is model SCC1200TM. Their dimensional parameters are

$$\begin{aligned} &B_1 = 61m, \quad B_2 = 73m, \\ &\theta_1 = 15°, \quad \theta_2 = 22°, \end{aligned} \tag{23}$$

whereas the distance D between their turntables is set as

$$D = 80m. \tag{24}$$

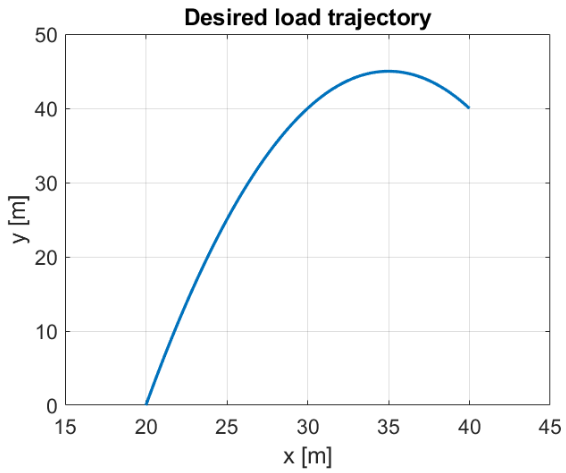

Figure 7: Desired load path.

The maximal allowed cable velocity values are taken the same for both cranes, i.e.

$$L_{1d,max} = L_{2d,max} = 0.2m/s \tag{25}$$

The box needs to be lifted from the ground to a height of $40m$ for installation and then released downward. Therefore, the following parameters are set for the parabolic load lifting trajectory in Eq. (11):

$$\begin{aligned} &x_s = 20m, \quad x_f = 40m, \\ &x_0 = 35m, \quad y_0 = 45m, \\ &k = -0.2. \end{aligned} \tag{26}$$

The desired load trajectory is displayed in Fig. 7. The acceleration/deceleration parameter of the chosen horizontal load velocity Eq. (13) is set as $\alpha = 0.5m/s^2$. According to Eq. (18), this yields the maximal allowed cruising velocity

$$V_{max} = 3.162m/s. \tag{27}$$

According to Eq. (17), setting $V = V_{max}$ would yield a total travel time $T = 12.64s$ and the load coordinates vs. time displayed in Fig. 8. The resulting rope lengths and rope velocities are displayed in Fig. 9, and both $\dot{L}_1(t)$ and $\dot{L}_2(t)$ turn out to heavily violate the admissible bounds in Eq. (20).

Let us then apply the two methods previously outlined to compute the largest possible value of V which makes the constraints (20) satisfied. Functions $h_1(x)$ and $h_2(x)$ are displayed in Fig. 10. The bounds $h_{1,max} = 5.913$ and $h_{2,max} = 5.838$ are found at the initial position. Evaluating V according to Eq. (22) yields

$$V = 0.0338m/s \tag{28}$$

The travel time is $T = 591.14s$, as can be seen from Figs. 11 and 12 which display the time evolution of the load coordinates and of the cable lengths along with the corresponding derivatives. As observed in Fig. 12, the rope attains its maximum velocity after a very short transient. The value $x_a = x(t_a) = 20.001$

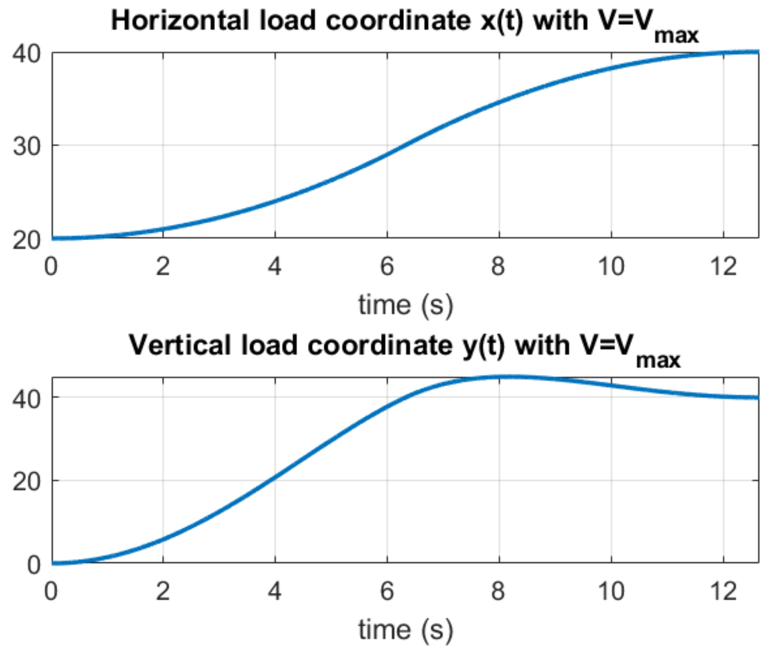

Figure 8: Actual load path with $V = V_{max}$.

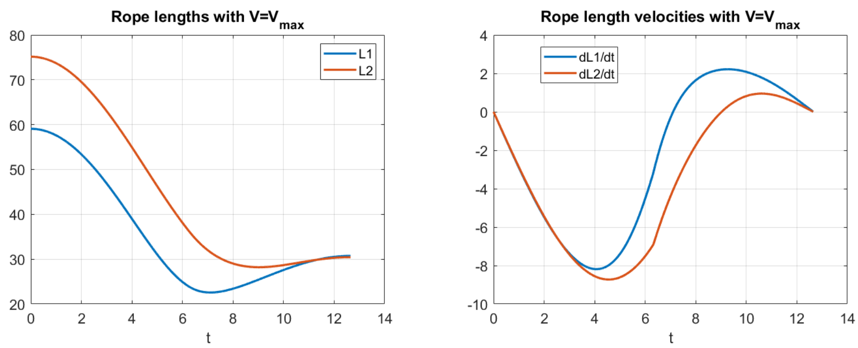

Figure 9: Rope lengths (left) and rope velocities (right) with $V = V_{max}$.

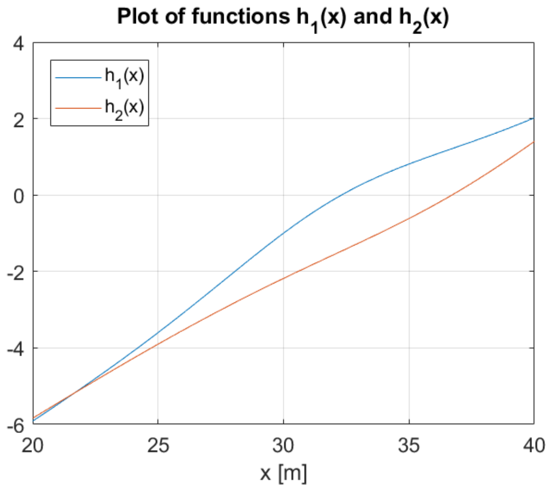

Figure 10: Functions $h_1(x)$ and $h_2(x)$.

can be obtained based on Eq. (14), and it turns out to be very close to the initial position. It can be seen constraints (20) are actually fulfilled along the entire travel of the load. Since the constant cruising velocity V is reached at a position x_a very close to the initial position where $|h_1(x)|$ is maximal, the iterative line search optimization procedure gives a result that is almost coincident with that in (28), meaning that the direct approximate solution is almost optimal in this particular example.

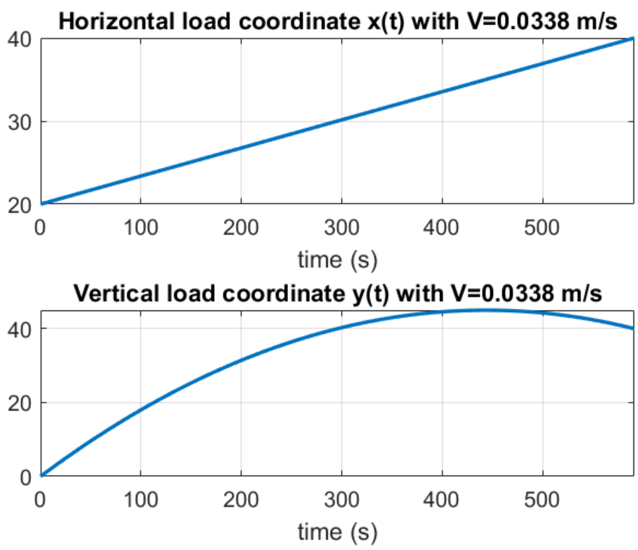

Figure 11: Actual load path with $V = 0.0338 m/s$.

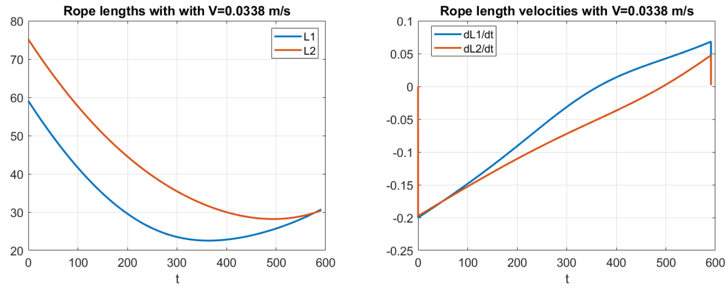

Figure 12: Rope lengths (left) and rope velocities (right) with$V = 0.0338 m/s$.

6 Conclusion

In this paper, the problem of cooperative hoisting and load transfer of two crawler cranes is investigated. A method is proposed to adjust the lengths of the two cables in order to transfer the load along a predefined path while satisfying boundedness constraints on the magnitude of the rope length velocities. Possible extensions of the present work to be tackled in future activities could be the joint optimization of V and α according to additional constraints on the rope length accelerations. In addition, differently shaped velocity profiles could certainly be investigated. Three-dimensional (rather than planar) load transfer problems with a possible desired change of attitude of the load during the lifting motion will also be the subject of future investigation.

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