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LINEAR CONTROLLER FOR WHEEL LOADER TRAJECTORY TRACKING

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Abstract. *The paper proposes a trajectory-tracking controller for an autonomous small-sized skid-steer wheel loader. The control system consists of two parts: feedforward control and feedback control. The open loop control uses the wheel loader desired velocities and accelerations. The feedback controller is a state-space feedback controller based on a linearized kinematic model.*
Keywords: *skid-steer wheel loader, trajectory tracking, feedback linearization, state-space controller.*

Introduction

Wheel Loaders (WL) are versatile machines used in various industries to perform multiple tasks, including construction, mining, agriculture, utilities, and waste disposal. The typical workflow of a WL comprises three main phases: loading, transporting, and unloading materials. Automating these tasks offers several benefits, including improved safety by eliminating the risks associated with human error due to a driver's inexperience or fatigue [1].

Additionally, the complete removal of a driver and the ability to perform a work cycle fully autonomously further enhances safety measures [2]. Moreover, automation will ensure optimal operating modes, significantly impacting the loader's energy-saving performance, increased productivity, and improved WL maintenance [3, 4].

Analysis of publications

The automation of WL workflow is carried out in various directions. These include the automation of power plant and hydraulic drive modes [5], automation of bucket filling [6], loading of vehicles with material [7, 8], automatic movement of the loader to the place of unloading (material transport) and reverse back to the pile [3, 9, 10].

In many cases, the WL movement has a V-shaped path [6], as shown in Fig. 1, where phase V_1 is the WL moving from the initial position to the material pile, phase V_2 is loading material into the bucket, phase V_3 is returning the loader from the pile to the initial position. Phase V_4 is the WL motion to the dump truck, phase V_5 is the bucket unloading, and phase V_6 is the WL returning to the initial position.

Goal and tasks

The cyclical nature of the WL movement makes it attractive for its automation. In this paper, we address the issue of automatic WL path tracking, i.e., the fulfilment of phases V_1, V_3, V_4, and V_6 (Fig. 1).

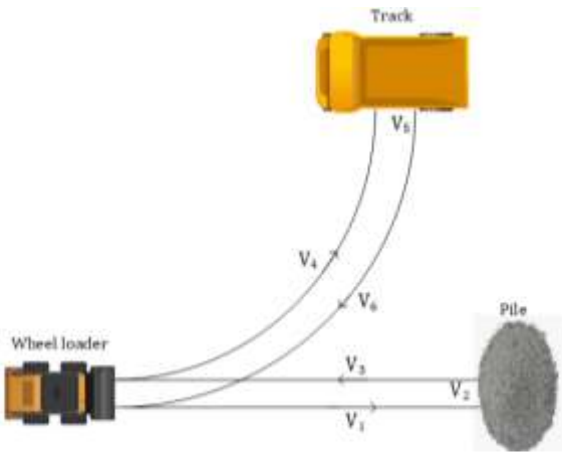

Fig. 1. V-cycle of a wheel loader

Thus, the goal of this work is to improve the efficiency and safety of the WL operation by ensuring accurate trajectory tracking. This paper focuses on the control process of a compact skid-steer wheel loader.

Creating the WL movement model, designing the control law, and evaluating its effectiveness through simulation is essential to achieving the goal.

Kinematic model of a wheel loader

In order to design a control system for a WL movement, it is necessary to consider its kinematics. This paper considers a skid-steer loader that turns by skidding or dragging its corresponding wheels across the surface. A schematic blueprint of such a WL is shown in Fig. 2 [11]. Here, we assume that a WL is moving on a flat surface. A local Cartesian frame $L\{x_l, y_l, z_l\}$ originates in the vehicle's Centre of Mass (CM) with its x_l axis pointing forward, the y_l axis pointing left, and the z_l axis pointing up. The vector $\boldsymbol{q} = [x\ y\ \theta]^T$ characterizes the position and orientation of the WL on the plane in the global coordinate system $G\{X_g, Y_g\}$.

Assuming that the local frame L moves with a linear velocity $\boldsymbol{v} = [v_x \;\; v_y \;\; 0]^T$ and rotates with an angular velocity $\boldsymbol{\omega} = [0 \;\; 0 \;\; \omega]^T$, the following equation defines the relation between the global G and local L frames:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix}. \qquad (1)$$

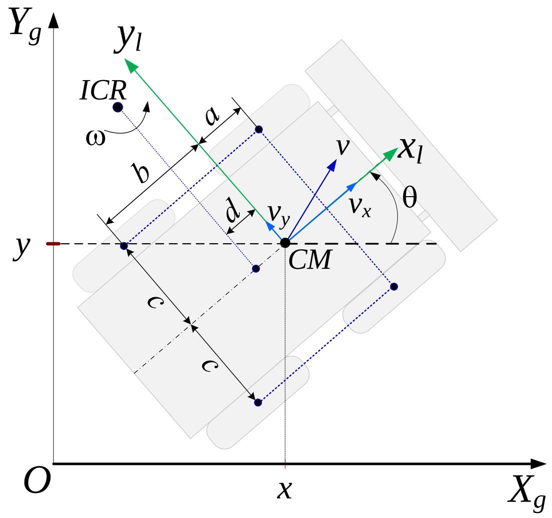

Fig. 2. Skid-steer WL kinematics

WL rotates around the instantaneous centre of rotation (ICR in Fig. 2).

The coordinate $d \in (0,b)$ in the x-axis can vary, and its determination is a separate problem. In most cases of automatic control for skid-steer vehicles, weighted factors determined experimentally are used to find the value of d [11].

If the value of d is known, equation (1) can be rewritten as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & -d\sin\theta \\ \sin\theta & d\cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ \omega \end{bmatrix}, \qquad (2)$$

where $[v_x \;\; \omega]^T$ is the control vector.

The projection of d of the CM on the x_l axis cannot be greater than b (Fig. 2).

Otherwise, the WL would lose stability due to skidding along the y_l axis. As such, a non-holonomic constraint needs to be introduced [12]:

$$v_y - d\omega = 0, \qquad (5)$$

or using generalized coordinates

$$\begin{bmatrix} -\sin\theta & \cos\theta & -d \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = 0. \qquad (6)$$

The Kinematic Path-Tracking Error Model

The task of the WL control system is to track a given trajectory. Therefore, introduce the error vector $\boldsymbol{e}(t) = [e_x(t) \;\; e_y(t) \;\; e_\theta(t)]^T$, which describes the deviations of the actual WL pose $\boldsymbol{q}(t) = [x(t), y(t), \theta(t)]^T$ from the desired pose $\boldsymbol{q}_{\text{des}}(t) = [x_{\text{des}}(t), y_{\text{des}}(t), \theta_{\text{des}}(t)]^T$ (Fig. 3). Taking into account equation (2), we get:

$$\begin{bmatrix} e_x(t) \\ e_y(t) \\ e_\theta(t) \end{bmatrix} = \begin{bmatrix} \cos\theta(t) & \sin\theta(t) & 0 \\ -\sin\theta(t) & \cos\theta(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_{\text{des}}(t) - x(t) \\ y_{\text{des}}(t) - y(t) \\ \theta_{\text{des}}(t) - \theta(t) \end{bmatrix}. \qquad (7)$$

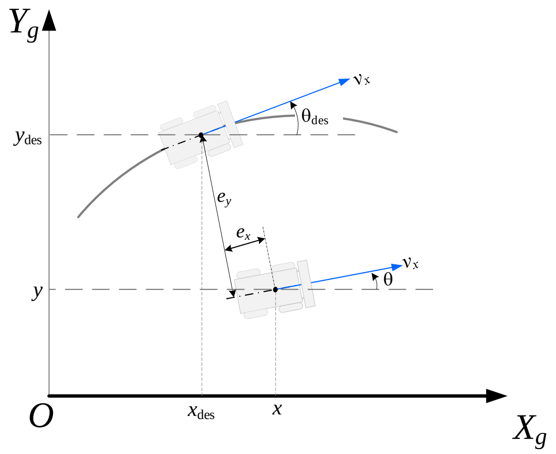

Fig. 3. Position and orientation error in local coordinates

By differentiating (7), the posture error model can be written as follows:

$$\begin{bmatrix} \dot{e}_x(t) \\ \dot{e}_y(t) \\ \dot{e}_\theta(t) \end{bmatrix} = \begin{bmatrix} \cos e_\theta(t) & -d\sin e_\theta(t) \\ \sin e_\theta(t) & d\cos e_\theta(t) \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{\text{des}}(t) \\ \omega_{\text{des}}(t) \end{bmatrix} + \begin{bmatrix} -1 & e_y(t) \\ 0 & -(e_x(t)+d) \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} v(t) \\ \omega(t) \end{bmatrix}, \qquad (8)$$

The control vector $[v, \omega]^T$ can be presented as follows [13]:

$$\mathbf{u}(t) = \begin{bmatrix} v(t) \\ \omega(t) \end{bmatrix} = \begin{bmatrix} v_{\text{des}}(t)\cos e_\theta(t) - v_{\text{fb}}(t) \\ \omega_{\text{des}}(t) - \omega_{\text{fb}}(t) \end{bmatrix} \quad (9)$$

where $v_{\text{fb}}(t)$ and $\omega_{\text{fb}}(t)$ are the feedback signals to be defined later, while $v_{\text{des}}(t)$ $\cos(e_\theta)$ and $\omega_{\text{des}}(t)$ are the feedforward signals.

Open Loop Control

First, let us get the expressions for $v_{\text{des}}(t)$ and $\omega_{\text{des}}(t)$ in (9). From Fig. 3, we can write the following expression for the velocity $v_x(t)$ [11]:

$$v_x(t) = v_{\text{des}}(t) = \sqrt{\dot{x}^2_{\text{des}}(t) - \dot{y}^2_{\text{des}}(t)}\,, \quad (10)$$

where $\dot{x}_{\text{des}}(t)$ and $\dot{y}_{\text{des}}(t)$ are desired generalised velocities of the WL.

The orientation angle $\theta(t)$ of the WL depends on the ratio of these generalised velocities:

$$\theta(t) = \text{arctg}\left(\frac{\dot{y}_{\text{des}}(t)}{\dot{x}_{\text{des}}(t)}\right), \quad (11)$$

hence, the angular velocity can be found by differentiating (11) in time:

$$\omega_{\text{des}}(t) = \frac{\dot{x}_{\text{des}}(t)\ddot{y}_{\text{des}}(t) - \dot{y}_{\text{des}}(t)\ddot{x}_{\text{des}}(t)}{\dot{x}^2_{\text{des}}(t) + \dot{y}^2_{\text{des}}(t)}, \quad (12)$$

where the function (12) is undefined only if $v_x = 0$.

The obtained relations (9) and (11) could ensure the WL motion along a given trajectory in the ideal scenario, that is, in the absence of uncertainties, disturbances, measurement errors of the initial and current pose, etc.

These assumptions are never fully fulfilled, and therefore, it is necessary to introduce a feedback loop into the control system.

Linear Feedback Controller

The error model (9) is nonlinear. Thus, in order to design a trajectory-tracking controller, we will linearize the error dynamics equations (8)–(9) around the zero error ($e_x = e_y = e_\theta = 0$) when feedback linear and angular velocities are also equal to 0 (that is $v_{\text{fb}} = 0$ and $\omega_{\text{fb}} = 0$). Linearizing equations (8)–(9) around the zero-error yields the following:

$$\begin{bmatrix} \dot{e}_x(t) \\ \dot{e}_y(t) \\ \dot{e}_\theta(t) \end{bmatrix} = \begin{bmatrix} 0 & \omega_{\text{des}}(t) & 0 \\ -\omega_{\text{des}}(t) & 0 & v_{\text{des}}(t) \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} e_x(t) \\ e_y(t) \\ e_\theta(t) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & d \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{\text{fb}}(t) \\ \omega_{\text{fb}}(t) \end{bmatrix} + \begin{bmatrix} 0 & -d \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{\text{des}}(t) \\ \omega_{\text{des}}(t) \end{bmatrix} \quad (13)$$

The obtained system (13) is a state-space representation of a dynamic linear time-varying system where all the states are accessible. This system is controllable if the desired path consists of straight-line segments and circular arcs (that is, $v_{\text{des}}(t)$ and $\omega_{\text{des}}(t)$ are constant), which for the WL is generally true (see Fig. 1).

The control system consists of two loops: feedforward and feedback (Fig. 4). Since the expressions for $v_{\text{des}}(t)$ and $\omega_{\text{des}}(t)$ are defined above in (10) and (12), respectively, we will, therefore, design a feedback controller. Thus, the goal now is to choose v_{fb} and ω_{fb} to appropriately drive the errors in (13) toward 0. For this purpose, consider the linear feedback

$$v_{\text{fb}}(t) = -k_x e_x(t), \quad (14)$$

$$\omega_{\text{fb}}(t) = -k_y e_y(t) - k_\theta e_\theta(t), \quad (15)$$

where k_x, k_y, and k_θ are feedback coefficients on the corresponding state coordinates.

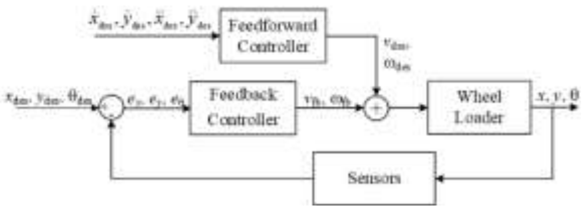

Fig. 4. Control system block diagram

Controls (14) and (15) lead to the following coefficients matrix of the closed-loop linearized system:

$$\mathbf{A}_f = \begin{bmatrix} -k_x & \omega_{\text{des}}(t) & 0 \\ -\omega_{\text{des}}(t) & -dk_y & v_{\text{des}} - dk_\theta \\ 0 & -k_y & -k_\theta \end{bmatrix}, \quad (16)$$

The values of the coefficients k_x, k_y, k_θ can be obtained in various ways, e.g. using the linear-quadratic regulator technique [14] or evolutionary algorithms [15–17]. Here we will use the already classical and well-proven pole placement method. To reduce the yaw of the WL, we will require from the system dynamics close to critical damping, that is $\zeta \approx 1$. Then, the characteristic equation of the closed-loop system is as follows:

$$\det(s\mathbf{I} - \mathbf{A}_f) = 0, \qquad (12)$$

where $\mathbf{I}$ is the (3×3) identity matrix and s is a Laplace variable.

The characteristic equation of the desired system can be written as:

$$(s + \alpha)^3 = 0, \qquad (13)$$

where α are the desired real poles of the system.

By calculating the determinant in (12) and equating the terms at the corresponding powers of s in (13), we could find the controller coefficients k_x, k_y, k_θ values. However, to simplify the design, let us use the MATLAB `place()`.

Simulation results

A MATLAB simulation of the WL motion was performed to evaluate the control system's effectiveness. The WL was required to move with the velocity of 1.4 m/s, which corresponds approximately to 5 km/h, along a circular trajectory with a radius of $r = 15$ m, described by the following equations:

$$x = r\cos\frac{2\pi}{67}t, \qquad (19)$$

$$y = r\sin\frac{2\pi}{67}t, \qquad (20)$$

with initial conditions: $x(0) = 12$ m, $y(0) = -2$ m, $\theta(0) = -\pi/4$ rad. This corresponds to the initial pose error $e_x(0) = 3$ m, $e_y(0) = 2$ m, $e_\theta(0) = 3\pi/4$ rad.

It should be mentioned that the provided trajectory is an example, and the synthesis of trajectories for the WL is a separate problem that is not considered in this paper.

The MATLAB function `place()` was used to determine the matrix $\mathbf{K}$ of the state controller coefficients. The sampling time was used as $T_s = 0.01$ s, and the coordinate is $d = 0.2$ m (see Fig. 2). As mentioned above, we intended the system to be close to the critical damping ($\zeta \approx 1$), which requires three real poles. Due to the limitations of the MATLAB `place()` function, the desired poles must either be unique or have multiplicities that do not exceed the rank of the matrix $\mathbf{B}$ in (13). Therefore, we chose two complex conjugate poles with small imaginary parts to avoid this issue: $p_1 = -3$, $p_2 = -3 + 0.2i$, $p_3 = -3 - 0.2i$. This allowed us to achieve the desired dynamics without exceeding the rank constraint. The simulation results are shown in Figs. 5–7.

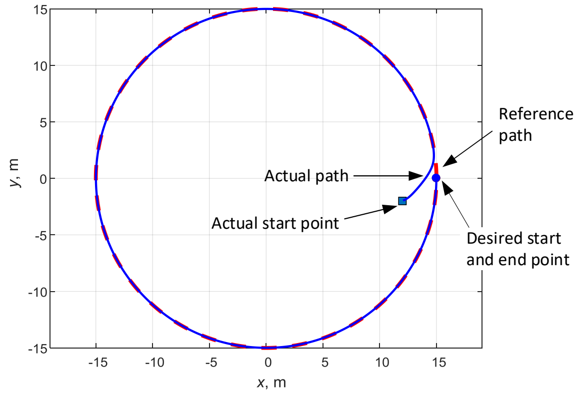

Fig. 5. Reference and actual WL path

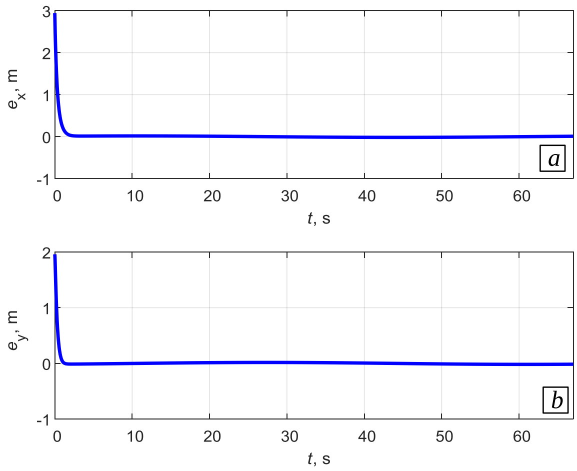

Fig. 6. Tracking errors in the x-axis (a) and y-axis (b)

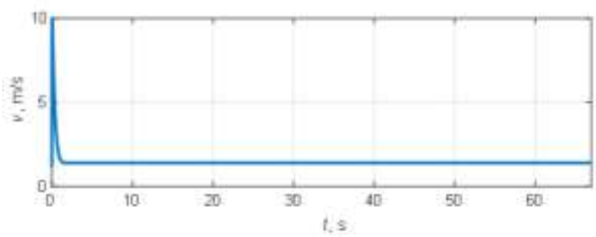

Fig. 7. The wheel loader speed

The simulation results show the high trajectory-tracking control system performance. Despite the essential difference between the desired and actual initial conditions, the WL comes close to the desired path after about 3 seconds, and the subsequent tracking error is near 0 along the x-axis and the y-axis of the global coordinate system (Fig.6).

Meanwhile, the desired speed of 1.4 m/s is maintained (Fig. 7).

However, it should be noted that only the kinematic model of the WL was taken into account in the simulation, so in practice, the trajectory tracking error will be more significant. In addition, the value of d varies with ICR (Fig. 2), which will also affect the control system's performance.

Conclusion

The efficiency and safety of skid-steer wheel loaders are closely related to their automation and robotisation. One of the tasks to be performed by an automated WL is to move to a pile and, versa, to the unloading place along a given trajectory. For this purpose, a two-loop trajectory-tracking controller is designed in this paper. The feedforward loop generates control actions based on the desired velocities and accelerations of the loader. The feedback loop uses a state-space controller with errors in the position and orientation of the loader in its local coordinate system. The simulation results show that the controller ensures the loader moves along a given path at the desired velocity with virtually no error.

It is important to note that the designed controller is based on the loader's kinematic model. Considering its dynamics can result in trajectory tracking errors. When designing the state-space controller, it was assumed that all state coordinates are accurately measured, which is not always achievable in practice. The authors' future work will focus on addressing these issues.

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Лінійний регулятор для забезпечення руху колісного навантажувача заданою траєкторією

Постановка проблеми. *Малогабаритні фронтальні навантажувачі з бортовим поворотом є універсальними машинами, що широко застосовуються в різних галузях промисловості. Проте помилки оператора, який керує машиною вручну під час інтенсивного робочого циклу та в складних умовах навколишнього середовища, часто призводять до надмірного споживання палива, інтенсивного зношення шин, а також поломок машини. Крім того, фронтальні навантажувачі часто використовуються для ліквідації наслідків природних катаклізмів і техногенних катастроф, що підвищує небезпеку оператора. Автоматизація процесу керування навантажувачем дає змогу покращити ефективність та безпеку його роботи. Одним із напрямів автоматизації цієї машини є забезпечення її автономного руху за заданою траєкторією – від забою до місця розвантажування матеріалу та в зворотному напрямку.* ***Мета роботи:*** *підвищення ефективності та безпеки експлуатації фронтального навантажувача з бортовим поворотом за допомогою забезпечення точного відстеження траєкторії його руху.* ***Методика.*** *Для розроблення системи керування рухом фронтального навантажувача використано кінематичну модель, що бере до уваги особливість бортового повороту машини. Запропоновано двоконтурну систему керування, що містить упереджувальний контур і контур зворотного зв'язку. Упереджувальний контур використовує для розрахунку керуючих впливів задані швидкості та прискорення навантажувача, а в контурі зворотного зв'язку використано регулятор стану. Для налаштування регулятора впроваджено модальний метод синтезу.* ***Результати.*** *Розроблено систему керування з критичним демпфуванням. Результати моделювання в MATLAB продемонстрували, що запропонована система керування забезпечує рух навантажувача за заданою траєкторією із заданою швидкістю із незначною похибкою.* ***Наукова новизна роботи*** *полягає в подальшому розвитку сучасної теорії керування завдяки її застосуванню до нового об'єкта – малогабаритного фронтального навантажувача з боковою системою повороту.* ***Практична значущість.*** *Упровадження запропонованої системи керування дасть змогу підвищити продуктивність навантажувача, зменшити кількість аварійних ситуацій на будівельних майданчиках, а також знизити експлуатаційні витрати внаслідок забезпечення раціональних режимів руху та економії палива.*

Ключові слова: *фронтальний навантажувач з боковим поворотом, відстеження траєкторії, лінеаризація зворотним зв'язком, регулятор у просторі станів.*

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