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DESIGN OF A CONTROL SYSTEM WITH A PREDICTIVE MODEL FOR A TWO-DRIVE MANIPULATOR WITH A PARALLEL STRUCTURE

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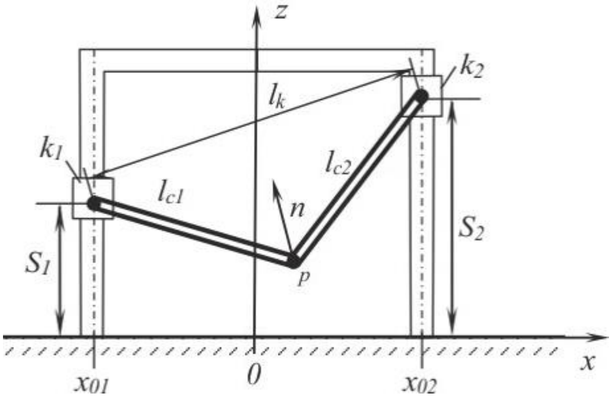
Abstract: *This work intends to contribute to the corpus of knowledge on parallel manipulators and their control by making the most use of Model Predictive Control. We aim to investigate parallel manipulator kinematics, dynamics, and control strategies in detail in order to open up opportunities for enhanced performance, flexibility, and precision in these robotic systems.*

Keywords: *frame installation, manipulator, model predictive control, parallel structure, control system.*

Recently, parallel manipulators have garnered significant attention in robotics and automation due to their distinct advantages over serial manipulators, including increased rigidity, payload capacity, and precision [1]. However, effectively controlling parallel manipulators poses challenges due to their complex kinematics and dynamics. Model Predictive Control (MPC) has emerged as a promising approach due to its ability to handle nonlinearities and uncertainties. This paper explores the application of MPC to parallel manipulators, focusing on design, dynamics, and control strategies to enhance performance and versatility. By integrating MPC, challenges related to trajectory tracking, obstacle avoidance, and energy efficiency can be addressed. The paper reviews foundational concepts of parallel manipulator kinematics and dynamics, and discusses MPC principles.

An example of such a frame installation of a parallel structure (fig. 1a) is a research stand with two guide rods which consist of a metal frame, which is equipped with two stepper motors, drives, hinges and a working body, which can be used as any technological tool such that paint head for varnishing, paints, cutting tools etc [2]. The kinematic diagram illustrates the manipulator's structure and components, while the mechanical motion of the drivers involves the translation of electrical signals into motion. The kinematic scheme (fig. 1b) of a frame installation with parallel structure focuses on its mechanical motion and drivers [3]. The installation comprises guide rods with stepper motors, drives, hinges, and a working body adaptable for various technological tools. To move the working tool, carriages along the guide rods are driven by the operation of drivers.

a) Layout of the installation



b) Kinematic scheme

Figure 1 – Two-drive manipulator with a parallel structure

The mechanical motion of the drivers particularly focuses on hybrid stepper motors. The closed-loop control system of a hybrid stepper motor is presented in Fig. 2, depicting both inner and outer loop control mechanisms [4].

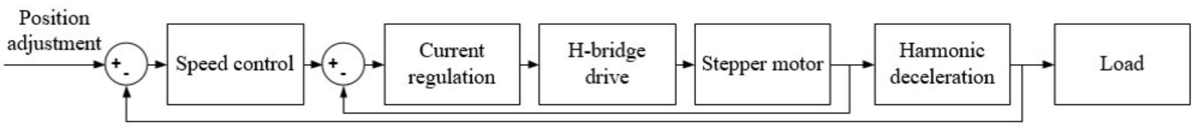


Figure 2 – Block diagram of the closed-loop control system of a hybrid stepper motor

The transfer function of the stepper motor system is detailed in Fig. 3, outlining the relationship between input signals and mechanical output [5].

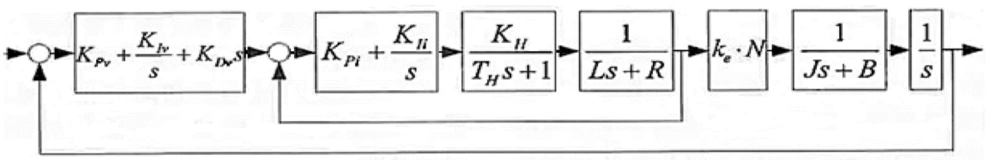


Figure 3 – Block diagram of the transfer function of a stepper motor system

The mechanical motion of the drivers refers to the physical movement and behavior of the mechanical components within the control system that are responsible for translating electrical signals into motion. These drivers play a critical role in controlling the movement of the load and managing the applied load torque.

The mechanics of the motion involve the interaction between the stepper motor, load, and the mechanisms that facilitate controlled motion. The mechanical motion of the drivers can be described as follows:

$$I\frac{d\omega}{dt} + B_{\omega} = T_e - T_L, \quad (1)$$

$$T_L = f(x_1 y) \rightarrow \text{var}, \quad (2)$$

$$Te = K_e i_q \text{ or } T_e = K_e N_2 i_q, \quad (3)$$

$$L\frac{di_q}{dt} + Ri_q = u, \quad (4)$$

$$T_H\frac{du}{dt} + u = K_H i_H, \quad (5)$$

$$K_{e_I}\int \Delta i\, dt + K_{P_I}\Delta i = i_H, \quad (6)$$

$$K_{D_\theta}\frac{d\Delta\theta}{dt} + K_{P_{\theta\Delta\theta}} = i_c. \quad (7)$$

Equations (1)-(7) provide a comprehensive mathematical model of the mechanical motion of the drivers, encompassing dynamics related to torque, electrical characteristics, H-bridge drive, and control mechanisms. These equations elucidate the interplay between electrical signals and mechanical motion, highlighting the complexities involved in achieving precise control over the parallel manipulator system.

The stepper motor orchestrates the coordinated motion of parallel actuators in the mechanical world, converting rotating power into linear motion via mechanical linkages. Parallel manipulators use complex equations, transformations, and optimization approaches to synchronize the movements of interconnected links and joints in the world of mathematics. The necessity to achieve harmonious motion in parallel configurations unites both domains while having different mechanisms and mathematical expressions, demonstrating the interplay between mechanical design and mathematical analysis. Therefore, a mathematical model of the system must be used to build a control system.

This paper aims to explore the application of Model Predictive Control to parallel manipulator, focusing on its design, dynamics, and control strategies. By investigating the interplay between parallel manipulator mechanisms and advanced control techniques, we seek to enhance the performance, accuracy, and versatility of these robotic systems. The integration of MPC into parallel manipulator control offers the potential to address challenges related to trajectory tracking, obstacle avoidance, and efficient energy utilization.

The mathematical model presents a systematic framework for understanding and controlling the motion of a parallel manipulator. It defines the mathematical relationships governing the movement of carriages based on input coordinates, providing equations that relate the coordinates (x, y) to the positions of the carriages S_1 and S_2. These equations establish the connection between input coordinates and carriage positions, laying the foundation for controlling the manipulator's motion [3].

$$x = \frac{1}{2} \cdot (S_2 - S_1) \cdot \sqrt{\frac{-(S_2 - S_1)^2 - 4 \cdot l^2 - d^2}{(S_2 - S_1)^2 + d^2}},$$
$$y = \frac{1}{2} \cdot \left(S_2 + S_1 - d \cdot \sqrt{\frac{-(S_2 - S_1)^2 + 4 \cdot l^2 - d^2}{(S_2 - S_1)^2 + d^2}} \right). \quad (8)$$

The transformation of angles into stepper motor motion outlines the process of converting abstract angular concepts into specific motor actions. This transformation is essential for translating desired angular adjustments into tangible motor movements, facilitating precise control over the manipulator's motion.

The loading torque of the stepper motors is a critical parameter influencing motor performance and behavior. Understanding loading torque is essential for ensuring the stepper motor operates effectively and reliably in different applications.

$$S_1\!: T_{L_1} = g_1(\theta_1, \theta_2), \quad S_2\!: T_{L_2} = g_2(\theta_1, \theta_2)\,. \quad (9)$$

Transforming the coordinates of a working point into the position of a stepper motor is a fundamental process in control systems and robotics. It involves converting abstract spatial coordinates into specific motor movements that drive the system to desired locations. This transformation bridges the gap between conceptual positions and actionable instructions for the stepper motor, enabling precise control over the manipulator's motion.

The control vector *u* is a multidimensional array of variables guiding the system's trajectory. Each element of the control vector corresponds to a distinct aspect of motion control, contributing to the overall control strategy for the system.

The state vector q comprises variables defining the current state of the system. These variables include angles, driver currents, and their derivatives, providing insight into the system's dynamics and behavior. A mathematical model in the form of a state space was obtained. It allows encapsulation of system dynamics and control inputs.

The Model Predictive Control (MPC) strategy outlined provides a robust framework for steering dynamic systems along precise trajectories by optimizing control inputs to minimize a quadratic cost function over a defined time horizon.

The objective is to minimize a quadratic cost over the time horizon, consisting of a state cost and a control input cost. The state cost represents deviations from a reference trajectory, while the control input cost penalizes deviations from reference inputs.

$$\begin{gathered} \min_{u_1 \dots u_6,} \int \left(\overrightarrow{\Delta q^T} Q \, \Delta \vec{q} + \overrightarrow{\Delta u^T} R \, \Delta \vec{u} \right) dt \ , \\ subj.to \dot{\vec{q}} = A\vec{q} + f(\vec{q}) + B\vec{u}, \\ \vec{y} = C\vec{q}, \\ 0 \le u_1, u_4 \le H, \\ |u_2, u_5| < V_{max}, \\ |u_3, u_6| < a_{\max} \ , \\ 0 \le q_1, q_5 \le H, \ q_2, q_6 \le i_{\text{driver max}} . \end{gathered} \tag{10}$$

The system dynamics are governed by a differential equations in state space.

$$\dot{\vec{q}} = A\vec{q} + f(\vec{q}) + B\vec{u}, \tag{11}$$

$$\vec{y} = C\vec{q}, \tag{12}$$

Constraints ensure the practicality of control inputs and state variables. Control inputs u_1 and u_4 are confined within the range $[0, H]$, while the rates of change in control inputs are bounded by V_{max} and a_{max}. State variables q_1 and q_5 are constrained within $[0, H]$, and q_2 and q_6 are limited by $i_{driver\ max}$.

The optimization problem is solved over a finite time horizon, predicting state and control input trajectories for a future period. Overall, MPC enables optimal decision-making and responsive control by leveraging predictive models and optimization techniques, making it applicable across a wide range of industries and applications. The mathematical model provides a rigorous framework for understanding and controlling the motion of parallel manipulators, laying the groundwork for further analysis and optimization.

In conclusion, the integration of Model Predictive Control (MPC) into parallel manipulator systems offers a promising avenue for advancing their control capabilities and performance across various applications. Through a comprehensive exploration of the fundamental principles underlying parallel manipulators and the predictive power of MPC, this paper has highlighted the potential benefits of merging these technologies.

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ПРОЕКТУВАННЯ СИСТЕМИ КЕРУВАННЯ З ПРОГНОЗУЮЧОЮ МОДЕЛЮ ДЛЯ ДВОПРИВОДНОГО МАНІПУЛЯТОРА ПАРАЛЕЛЬНОЇ СТРУКТУРИ

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Анотація. *Ця робота має на меті поповнити сукупність знань про паралельні маніпулятори та керування ними, використовуючи методи керування з прогнозуючою моделлю. Ми прагнемо детально дослідити кінематику, динаміку та стратегії керування паралельними маніпуляторами, щоб відкрити можливості для підвищення продуктивності, гнучкості та точності цих робототехнічних систем..*

Ключові слова: *каркасна установка, маніпулятор, прогнозуюча модель, паралельна структура, система керування.*

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