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Presentation An Approach Based on Control Systems To Purpose Control Simultaneous Vibrations And Maneuver the Arm Robotic With two Degree of freedom

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ABSTRACT

In recent times, the field of robotics and its applications have become increasingly attractive for researchers, particularly in the context of industrial control and automation. However, the approach predominant in the design and construction of robots until not too long ago favored solidity over flexibility. The primary rationale behind this inclination was the perceived weakness associated with highly flexible robots. While flexibility is deemed acceptable for certain purposes, the tendency was to prioritize simplicity and control, leading to the widespread adoption of rigid robotic structures. The drawback of this rigid approach became apparent as achieving control in highly rigid robots posed challenges. Such robots were often heavy, voluminous, and possessed a high weight-to-tolerance ratio, resulting in substantial energy consumption. The lack of adaptability and flexibility at joints further compounded these issues. The assumption that rigidity simplifies control was a guiding principle in designing robots. However, the contemporary consensus is that a rigid-centric methodology does not meet all the control needs in robotics. There is a growing recognition of the importance of flexibility and adaptability in robotic joints. This shift in perspective is driven by the understanding that not every joint in a robot needs to be rigid. Accepting flexibility in joints is based on the assumption that simplicity in control can still be achieved without rigid constraints. In the present era, it is acknowledged that a rigid-centric approach does not provide a comprehensive solution for the diverse requirements of robotic control. The acceptance of flexibility and adaptability in robotic systems has gained momentum. This change in attitude is evident in the emphasis on speed and adaptability in flexible robotic systems, leading to increased research efforts in control methodologies that embrace flexibility in the design and operation of robots.
Keywords: arm robotic, System control, Vibrations

1. Introduction

In the ever-evolving landscape of industries and technology, the ubiquity of robots has expanded across diverse sectors, including healthcare, automotive, aerospace, and more. The continual progress in this field has given rise to heightened expectations and demands for enhanced robotic capabilities. Particularly, robotic arms, frequently employed for repetitive tasks, stand to benefit significantly from incremental performance improvements, translating into substantial economic gains. Many contemporary industrial arms, tailored to meet stringent precision and repeatability standards, are characterized by robust yet heavy components. The inherent high inertia of these components necessitates considerable time for movement, resulting in elevated power consumption.

In response to these challenges, the global recognition of flexible jointed arms as a pragmatic problem-solving approach and a viable experimental model has

gained prominence. The incorporation of flexibility into these models is achieved by introducing specific stiffness springs as connection points between flexible arm segments. The flexibility inherent in these springs can be harnessed for rotational or translational movements within the system. In structural flexible systems, each component can be segmented into rigid bodies and elastic springs. Given the absence of constraints on the relative motion of robot components, a discrete coordinate approach proves advantageous for maneuvers involving substantial rotational angles. This hybrid motion comprises rigid (positional) components resulting from connections and flexible arm movements.

The unique model presented here utilizes equations for rigid body motion with point connections in a discrete coordinate system. Notably, none of the defined degrees of freedom correspond to actual deformations of the system. While this coordinate system allows for the modeling of large deformations, significant challenges arise in accurately representing stiffness and damping at connection points, especially beyond their linear behavior.

This article delves into the concurrent control of vibrations and maneuvering in a flexible two-link arm during single-axis maneuvers. It explores the synergistic effects of these two controllers on the arm's oscillatory behavior and targeting accuracy. The control of the flexible component involves the utilization of smart piezoelectric hinges, while arm maneuvering considers actuators applied to the arm connections. Through this exploration, we aim to contribute insights into optimizing the performance of flexible robotic arms in real-world applications

Innovation in Dynamic Modeling and Vibration Control:

This article represents a pioneering advancement in the realm of robotic systems by introducing a revolutionary paradigm shift in dynamic modeling and vibration control. Departing from conventional methodologies, our innovative approach challenges existing norms, introducing novel concepts and equations that redefine precision, adaptability, and efficiency in robotics. A key departure from traditional models is our emphasis on generalized coordinates, redefining their role in specifying particle positions within robotic systems. What distinguishes our research is the introduction of generalized forces associated with each coordinate, extending beyond classical Newtonian mechanics. Addressing the real-world presence of non-conservative forces, such as friction, our comprehensive framework offers insights into the intricate dynamic behaviors of robotic systems.

The integration of Hamiltonian principles plays a central role, providing a holistic representation through the sum of kinetic and potential energy. This innovative integration not only refines the accuracy of equations of motion but also opens avenues for unparalleled control and adaptability in robotic functionalities.

Another noteworthy innovation lies in the dynamic modeling section, where Lagrangian equations are employed to capture both conservative and non-conservative forces. The application of iterative learning methods enhances the understanding and control of the robotic arm's behavior, contributing to the adaptability of the control system for real-world applications.

Acknowledging the complexity of the derived equations and potential computational challenges, the study proposes a practical solution using fuzzy logic for inverse kinematics. This recommendation aims to streamline the implementation process, especially in scenarios where extensive calculations might hinder the operational efficiency of the robot.

In summary, this paper introduces a novel approach to controlling flexible robotic arms, addressing inherent challenges with practical solutions. The synergistic integration of smart materials, advanced control strategies, and fuzzy logic offers a comprehensive and adaptable framework for controlling flexible robotic systems, ushering in a new era of precision and efficiency.

modeling dynamic and Vibrations Robots:

In this article, we delve into dynamic modeling and vibrations of robots through the application of specific motion equations, which will be briefly discussed.

Generalized Coordinates: The position of a particle in space can be defined using three coordinate systems: Cartesian, spherical, and cylindrical. Alternatively, any three suitable parameters can be chosen. If the particle is constrained to move on a fixed plane, only two coordinates are necessary to specify its position. However, if the particle moves along a straight line or a fixed curve, specifying one coordinate becomes sufficient. In the case of a system composed of N particles, N^3 coordinates would be needed to simultaneously determine the positions of all particles.

When constraints are applied to the system, the number of coordinates required to specify the configuration becomes less than N^3. For example, if the system represents a rigid body, only the spatial position of a reference point on the body (e.g., center of mass) and its orientation are essential. Therefore, a minimum of n coordinates is generally required to specify the configuration of a specific system, and these coordinates are termed generalized coordinates.

In the generalized coordinate system, unlike the forces commonly seen in classical Newtonian mechanics, a force associated with each coordinate is defined,

known as the generalized force. This quantity, determined using the work definition, is dimensionally equivalent to work when multiplied by the generalized coordinate. Consequently, if the generalized coordinate has distance dimensions, the quantity becomes force, and if it is angular in nature, the quantity transforms into torque. The Hamiltonian, which is the sum of kinetic and potential energy of the system, is employed to accurately define the equations of motion.

Subsequently, these values are incorporated into the equation known as the Lagrangian equation of motion. The Lagrangian equation is expressed in terms of derivatives of the Lagrangian function concerning generalized coordinates and the time derivatives of the Lagrangian function regarding generalized speeds. In other words, denoting the Lagrangian function as L, the generalized coordinates as qk, and the generalized speeds as q̇k (where the dot denotes the time derivative of the generalized coordinate qk), the Lagrangian equations take the following form:

$$\frac{d}{dt}\frac{L}{q_k} - \frac{L}{q_k} = 0 \quad (1)$$

If the forces within the system are not entirely conservative, indicating the presence of a non-conservative force such as friction, in such instances, the Lagrangian equations on the right-hand side incorporate an additional term, Qk. This term represents the non-conservative generalized force.

$$\frac{d}{dt}\frac{L}{q_k} - \frac{L}{q_k} = Q_k \quad (2)$$

The Lagrangian equations exhibit uniformity across all coordinates, offering a systematic methodology for deriving the differential equations of motion in diverse systems. An alternative means of obtaining Lagrangian equations involves employing the principle of Hamiltonian variations. As previously mentioned, the Hamiltonian function, representing the cumulative kinetic and potential energy of a system, is defined within this approach.

In the context of Hamiltonian variations, an assumption is made about the existence of a potential function, signifying the conservative nature of the considered system. However, when non-conservative forces are present, similar to the Lagrangian equations, the impact of these forces is accounted for independently.

In such instances, the Hamiltonian function becomes the sum of kinetic energy and the work done by all forces, encompassing both conservative and non-conservative elements. This method provides an alternative viewpoint for formulating equations of motion in dynamic systems, placing emphasis on the collective energy and work contributions from all forces.

Hamilton Equations

The Hamiltonian equations consist of n² first-order differential equations, expressed in terms of generalized momentum and its derivatives. The generalized momentum is defined as the derivatives of the Lagrangian function concerning the generalized velocities. Consequently, these equations can be formulated as follows:

$$\frac{H}{p_k} = q_k$$

And,

$$\frac{H}{q_k} = P_k$$

In the given expression, qk denotes the generalized velocity, and the dot above pk (generalized momentum) signifies the time derivative. Upon comparing the Hamiltonian equations with the Lagrangian equations, it becomes evident that the former comprises a higher number of first-order equations. Specifically, in a system with N generalized coordinates, the Hamiltonian equations consist of n² first-order differential equations, while the Lagrangian equations consist of n second-order differential equations. Consequently, working with Hamiltonian equations is generally deemed more straightforward, and they find more frequent use in quantum mechanics and analytical mechanics.

Previous Studies:

A range of studies have explored the control of robotic arms with two degrees of freedom. Vorob'ev (2020) introduced a technique for coordinating the movements of the arms. This article proposes a technique for coordinating the movements of operating links of two-armed robotic systems with six degrees of freedom. The technique is based on introducing relative positioning matrices for the output links of the mechanical arms and solving reverse problems of the relative manipulator positioning. Manipulators with three degrees of freedom are viewed as mechanical arms. The reverse problems of manipulator positioning are solved, whic allow making output manipulator links carry out preset relative movements as solid bodies.

Efafi (2022) further enhanced this by proposing a feedback linearization controller to simultaneously control the main degrees of freedom and reduce vibration. In this paper, 3D dynamic modeling and robust control of a flexible robotic arm are performed with considering nonlinear effects. The simplifying assumptions such as linear vibration or 2D dynamic modeling of the arm significantly affect the accuracy of the arm dynamics. Thus, in this paper, a special

robotic arm is modeled using the 3D Euler–Bernoulli model considering the nonlinear effects of the beam. The Lagrange approach is used to extract the dynamic equations of motion and the coupled states of slow dynamics of the robotic degrees of freedom together with the fast dynamics of beam vibration is considered simultaneously. In order to control the main DOFs of the system and decrease the vibrating response of the system simultaneously, a feedback linearization controller equipped with the input shaping method is proposed through which all of the coupled states of the system can be controlled at the same time. It is shown that the response of the proposed model is closer to a real flexible robotics arm and the designed controller can successfully control all of the rigid and vibrating states of the system.

Lima (2019) addressed the issue of overshoot in a robotic arm with flexible joints, using magnetorheological dampers and a state-dependent Riccati equation for feedback control. In recent years, the evolution of artificial intelligence techniques has widely grown such that it gives new ways to improve human life, not only at work but also living. Nowadays, to the human being, physical human-robot interactions (PHRIs) have been presented very important and present itself as a major challenge for the current engineering. Therefore, this work designs and analyses a two-degree-of-freedom robotic arm with flexible joints driven by a DC motor. Due to the interaction between the robot links and flexible joints, the arm may present overshoots when it is moved such that it becomes difficult to manipulate the arm. Therefore, Magnetorheological dampers (MR damper or MR brake) are attached to the links of the arm in order to control such overshoot and provide a way to adjust the mechanical limitations of the arm. The dynamics of the system will be investigated, showing the appearance of chaotic behavior due to the coupling of the manipulator to the motors. After that, the feedback control is obtained through the state-dependent Riccati equation (SDRE) aiming the control of the positioning of the manipulator and the torque applied on the MR damper. Numerical results showed that the proposed control using hybrid actuators, DC motor, and MR brake was effective to control the position and behavior of the flexible joints of the manipulators.

Gharab (2021) proposed a robust two degrees of freedom PID control system to address the challenges of controlling lightweight single link flexible robots. This system effectively removed actuator friction and link vibrations, and was robust to strain gauge sensor disturbances and payload changes. In this paper, a method to control one degree of freedom lightweight flexible manipulators is investigated. These robots have a single low-frequency and high amplitude vibration mode. They hold actuators with high friction, and sensors which are often strain gauges with offset and high-frequency noise. These problems reduce the motion's performance and the precision of the robot tip positioning. Moreover, since the carried payload changes in the different tasks, that vibration frequency also changes producing underdamped or even unstable time responses of the closed-loop control system. The actuator friction effect is removed by using a robust two degrees of freedom PID control system which feeds back the actuator position. This is called the inner loop. After, an outer loop is closed that removes the link vibrations and is designed based on the combination of the singular perturbation theory and the input-state linearization technique. A new controller is proposed for this outer loop that: (1) removes the strain gauge offset effects, (2) reduces the risk of saturating the actuator due to the high-frequency noise of strain gauges and (3) achieves high robustness to a change in the payload mass. This last feature prompted us to use a fractional-order PD controller. A procedure for tuning this controller is also proposed. Simulated and experimental results are presented that show that its performance overcomes those of PD controllers, which are the controllers usually employed in the input-state linearization of second-order systems.

Lin (2023) presented a vibration control method for a six-axis manipulator, using variational mode decomposition and the Hilbert–Huang transform to analyze and eliminate vibration, and a feedback controller and iterative learning controller to stabilize the system. This paper presents a vibration control method for the vibration suppression of a robotic arm. To understand the causes of the vibration in the six-axis manipulator and then eliminate the vibration through an effective control method, the vibration control structure can be divided into two parts. First, variational mode decomposition (VMD) and the Hilbert–Huang transform (HHT) algorithm are integrated to analyze the vibration signal and extract the vibration characteristics. Second, a smooth trajectory planning method is used to eliminate the residual vibration. Then, a feedback controller and iterative learning controller are used for controlling the vibration to stabilize the system while compensating for the torque of the elastic-joint model and repetitive errors caused by the vibration through the repeated operation of the arm. In addition, to improve the iterative learning control (ILC) performance, the integration of VMD and the HHT is used to distinguish useless information. The ILC is able to learn more quickly and compensate for the error caused by the vibration. The proposed VMD-HHT iterative learning control for the elastic joint (VH-ILC-EJ) method, along with a laboratory-developed six-axis degree-of-freedom (6-DOF) robotic arm, has been numerically and experimentally validated for vibration suppression.

Control System Description:

The control system employs the deviation of frequency from its designated value as a signal to excite the system, ensuring balance in vibrations and maintaining a constant natural frequency. Modern power systems are designed with high capacity for economic reasons. However, the considerable distance for power transmission to arms negatively impacts stability. It is crucial to note that while connecting smaller systems enhances stability against minor disturbances, introducing distortions in one system can affect others within the network.

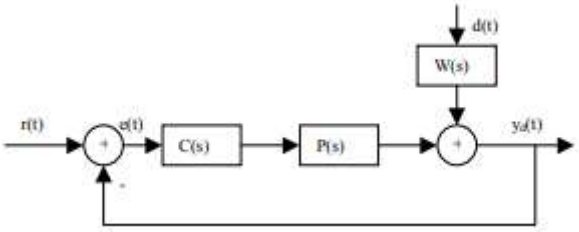


figure 1. Plan Control Feedback

The symbols employed in the aforementioned block diagram are explained as follows:

- *r*: Signal representing the reference entrance.
- *yd*: Output signal.
- *d*: Confusion signal.
- *e*: Signal representing the entrance error tracing.
- *P*: Variable for linear single output.
- *C*: Control time marker for linear single variable.
- *W*: Profile frequency signal for disorder.

In the context of a model based on recurrent fuzzy learning, aimed at overcoming challenges in position control, this study explores the utilization of the combined H2/Hinf controller method to achieve results comparable to a PID controller.

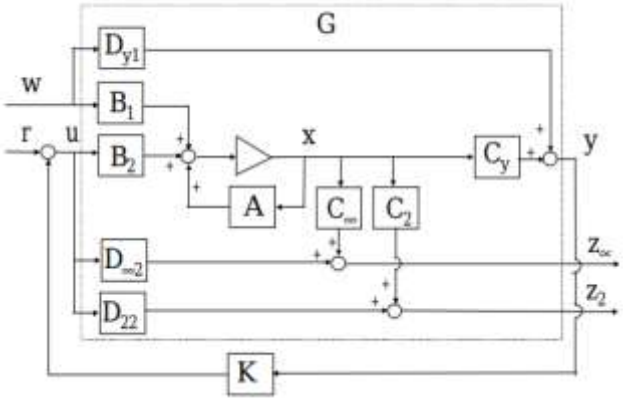


Figure 2. Closed-loop real system for H2/Hinf controller design.

Considering that the identification process and controller design are interconnected rather than independent, a systematic approach based on the iterative learning method is necessary to enhance the performance characteristics of the controlled system. This control method integrates the second-order H2 performance criterion for disturbance rejection with the Hinf performance criterion, aiming to achieve maximum robustness against uncertainty. The desired criterion is attained by tuning various design parameters within this scheme.

In each iteration, the control input undergoes correction based on a portion of the output error from the model. Theoretically, this correction allows the control signal to converge to a value that minimizes the output error of the actual plant. It's important to note that both strategies are developed without prior knowledge of the exact system models and differ in their application areas.

Cinematic Direction

The main goal in designing the dual-link robot is to trace a pre-defined path determined by the end of the second link, commonly known as the gripper. When both the path and the speed of traversal for the gripper are defined, the position of the gripper at any specific moment can be expressed in the global coordinate system. This representation is achieved using the following vector in Equation (20).

$$\boldsymbol{P(t) = u(t)i + v(t)j} \quad (20)$$

The ideal condition for traversing the path described in Equation (20) is predicated on the assumption of rigidity in the components. This implies that if the robot links under consideration lack flexibility, and the correct values of theta(i) are chosen, the robot precisely follows the specified path in Equation (20). However, in the real world, this matter is more complex due to the flexibility of gripper components, leading to oscillations around the desired path. The primary objective of this paper is to mitigate these oscillations, aiming to ensure that the actual gripper path closely conforms to the path outlined in Equation (20).

It's important to note that in this paper, the reduction of oscillations is achieved through the use of piezoelectric and the application of torques by motors. To initiate the analyses, the assumption is made that theta in the flexible state possesses values similar to those in the rigid state [14]. In other words, if theta has comparable values to the rigid state, the flexibility of the links only induces oscillations around the main path. For this purpose, utilizing Equations (2) and considering the assumption of rigidity, the position vectors of the endpoint of the second link are expressed as shown in Equation (21).

$$\begin{cases} \boldsymbol{u(t) = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)} \\ \boldsymbol{v(t) = \ L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)} \end{cases} \quad (21)$$

The system of nonlinear equations in Equation (21) can be represented using properties of trigonometric functions, as illustrated in Equation (22).

$$\begin{cases}[u(t) - L_1 \cos\theta_1]^2 + [v(t) - L_1 \sin\theta_1]^2 = L_2^2 \\ [u(t)]^2 + [v(t)]^2 = L_1^2 + L_2^2 + 2L_1L_2 \cos\theta_2\end{cases}$$

(22)

The notable characteristic of equations (22) is that, in contrast to equations (21) where both unknowns were interlinked, these two equations are independent of each other. This implies that they can be solved individually [15]. Recognizing this, the unknowns can be determined by utilizing equations derived from (22). It's important to note that in equations (22), in addition to θ, θ' is also unknown, and this will be further explained. If they are associated with s (in these equations, only θ is present), taking the derivative of equations (22) once will yield Equation (23):

(23)

$$\begin{cases}-L_1\dot{\theta}_1 \sin\theta_1 - L_2(\dot{\theta}_1 + \dot{\theta}_2)\sin(\theta_1 + \theta_2) = \dot{u} \\ L_1\dot{\theta}_1 \cos\theta_1 + L_2(\dot{\theta}_1 + \dot{\theta}_2)\cos(\theta_1 + \theta_2) = \dot{v}\end{cases}$$

It's worth mentioning that the relationship describing the absolute speed of the claw is given by Equation (24):

$$V(t) = \sqrt{(\dot{u})^2 + (\dot{v})^2}$$

(24)

Since the finger is expected to lift a load from one point at time t=0 and carry it to another point at time t=tf, the absolute velocity of the finger at these two instances must be zero. Mathematically, this can be expressed as:

$$\begin{cases}V(0) = 0 \\ V(t_f) = 0\end{cases}$$

(25)

The trajectory of the robot's finger motion has been approximated with a third-degree polynomial.

$$\theta_i(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

(26)

Differential Equations of the Motion System

The system is influenced by motors generating both single and double torques, leading to the emergence of external forces [9].

$$W = T_1(t)\theta_1 + T_2(t)\theta_2$$

(27)

In this equation, $T1(t)$ and $T2(t)$ denote the torques applied by motors one and two, respectively. In the formulation of the equations of motion, the assumed modes method is utilized, assuming that the lateral displacements of the links in the local coordinates of each link can be expressed as given in equation (28).

$$w_i(x_i, t) = \sum_{j=1}^{n} \phi_{ij}(x_i) q_{ij}(t)$$

In the given equation, the assumption of a cantilever beam with one end supported and the other end having mass leads to the expression for θ as a variable in the problem. Through the use of the assumed modes method, the partial differential equations are converted into ordinary differential equations. Subsequently, by defining the Lagrangian function as L=T−U, where T represents the kinetic energy and U denotes the potential energy, and incorporating the Euler-Lagrange equations alongside equation (28), the differential equations (29) can be derived.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \frac{\partial W}{\partial \theta_i} = T_i(t) \quad i = 1, 2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_{ij}}\right) - \frac{\partial L}{\partial q_{ij}} = \frac{\partial W}{\partial q_{ij}} = 0 \quad i = 1, 2$$

$$j = 1, 2, \dots, n$$

(29)

It appears that the provided text might lack clarity. However, from the context, it seems that the Lagrangian function was derived using the assumed modes method and energy equations. Subsequently, this Lagrangian function was applied to the system equations (29), leading to a set of equations representing the motion of the system (equation (30)). If you have specific questions or if there's a particular aspect you'd like more clarification on, please let me know.

$$M\ddot{z} + v = f$$

(30)

Conditions border

It seems that the given text describes the boundary conditions and the methodology for determining the unknowns in the system. The approach involves introducing four hypothetical forces (F1, F2, F3, and F4) to the mechanism and applying them to establish the initial conditions (q(0)). These forces are assumed to act perpendicular to the respective links and in the positive local coordinate directions. The conditions are established by assuming the mechanism is in a state of static equilibrium under the influence of these hypothetical forces. The resulting displacements are then determined using Castigliano's theorem. If you have specific questions or need further clarification, feel free to ask.

$$M_{cb_1}^{in.} = \sum_{i=1}^{10} M_{1,i}^{in.}$$
$$M_{b_1}^{in.} = \sum_{i=1}^{8} M_{2,i}^{in.} \quad (31)$$

At Relationships Above $in.$ To floor the moment Beginning Move Is. also $M_{cb_1}^{in.}$ torque with came At Intermittent That Piezoelectric Existence has it And $M_{b_1}^{in.}$ To sign to give torque At Intermittent To Work may Process That Lacking Piezoelectric may to be also torques with came At Intermittent From link two That At it Piezoelectric Existence has it And At Intermittent That Lacking Piezoelectric Been particle for direct object may power To order To Description Under sign gave:

$$M_{cb_2}^{in.} = \sum_{i=1}^{5} M_{3,i}^{in.}$$
$$M_{b_2}^{in.} = \sum_{i=1}^{3} M_{4,i}^{in.} \quad (32)$$

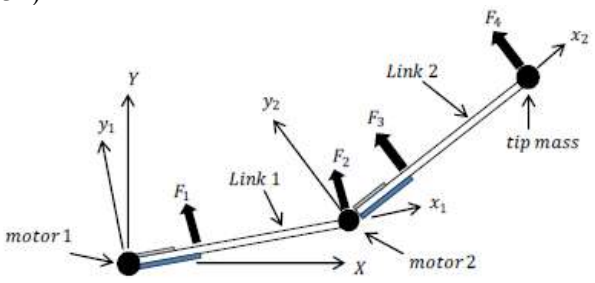


Figure 3 - Virtual Forces Acting on the Manipulator's Two Links

now With Attention To Relation (22), Energy Potential Store done At link particle for direct object may power To Shape Relation (34) wrote:

$$U_i^{sin.} = \frac{1}{2}\int_0^{l_{c_i}} \frac{\left(M_{cb_i}^{in.}\right)^2}{(EI)_{cb_i}} dx_i + \frac{1}{2}\int_{l_{c_i}}^{L_i} \frac{\left(M_{b_i}^{in.}\right)^2}{(EI)_{b_i}} dx_i \quad (34)$$

Pointed may to be That Target From actions loads virtual F_i Find Level Movement arrows, Location actions times Is That it particle for direct object may power With Use From The case Castigliano got brought In this way That Movement δ_i At Location actions Bar Fi from Relation (35) Following may slow [17]:

$$\delta_i = \frac{\partial U}{\partial F_i} \quad (35)$$

It is noteworthy that U represents the potential energy stored in the body, and delta(i) signifies the displacement in the direction of applying the load Fi. Since, in reality, the Fi forces do not exist externally and are only introduced into the problem to determine the displacement of the locations where these virtual loads are applied, their values should be set to zero after differentiation.

Importantly, q(0) remains unknown. To establish a connection between the outcomes derived from equation (34) and these unknown values, the displacement vector in the direction of applying virtual forces is initially expressed in the form of equation (36):

$$\begin{cases} \Delta_i = \delta_i j_1 & i = 1,2 \\ \Delta_j = \delta_j j_2 & j = 3,4 \end{cases} \quad (36)$$

Utilizing the relationship given in Equation (36) in conjunction with the relationship presented in Equation (28), a relationship to describe the shape is formulated, as expressed in Equation (37).

(37)

$$\begin{cases} \delta_1 = \phi_{11}(l_{c_1})q_{11}(0) + \phi_{12}(l_{c_1})q_{12}(0) \\ \delta_2 = \phi_{11}(L_1)q_{11}(0) + \phi_{12}(L_1)q_{12}(0) \end{cases}$$

In the relationships mentioned above, involving $\delta_1 = w_1(l_{c_1}, 0)$ and $\delta_2 = w_1(L_1, 0)$, conditions for computing q11(0) and q12(0) are established. This process is designed to fully prepare the formation. By employing this approach, the unknown q (0) for the two elements can be determined for future reference. A similar procedure is applied to the face, yielding:

$$\delta_3 = -L_1 \sin\theta_{20} + w_1(L_1, 0)\cos\theta_{20} + w_2(l_{c_2}, 0)$$
$$\delta_4 = -L_1 \sin\theta_{20} + w_1(L_1, 0)\cos\theta_{20} + w_2(L_2, 0)$$
$$\begin{cases} \delta_3 + L_1 \sin\theta_{20} - \delta_2 \cos\theta_{20} = \\ \phi_{21}(l_{c_2})q_{21}(0) + \phi_{22}(l_{c_2})q_{22}(0) \\ \delta_4 + L_1 \sin\theta_{20} - \delta_2 \cos\theta_{20} = \\ \phi_{21}(L_2)q_{21}(0) + \phi_{22}(L_2)q_{22}(0) \end{cases} \quad (38)$$

From these two relations, it is also possible to determine q21(0) and q22(0). By considering this order, the unknown q (0) can be fully known. Moreover, it is worth noting that taking q (0) into account, along with the primitive conditions of the robot, to solve the system of differential equations (Equation 31) will lead to further progress.

Presentation of Results:

In this section, the presentation of results will involve creating charts and visual representations. Initially, in Figure 4-3, the presentation of results related to the angles of the robot's links can be observed.

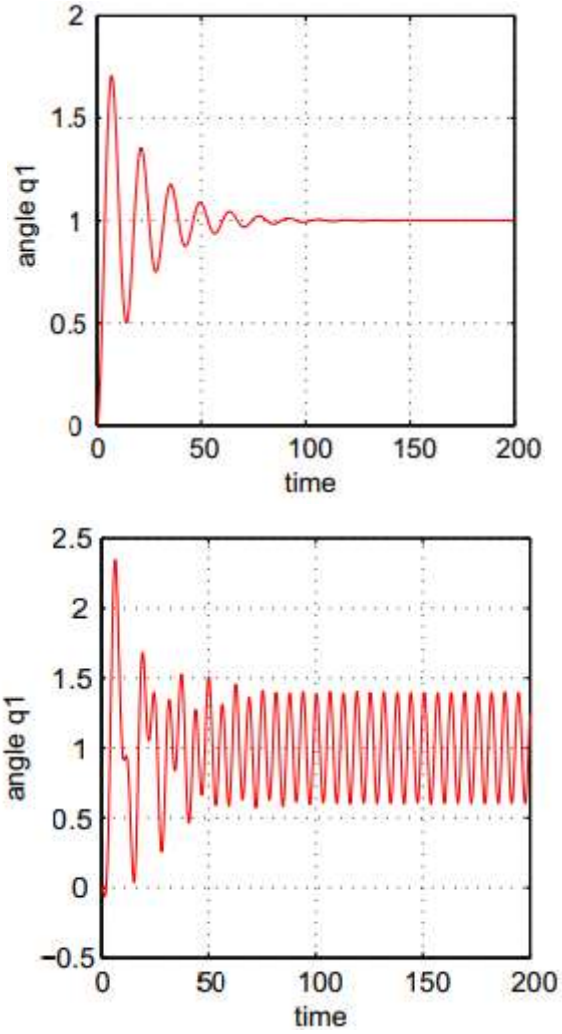


Figure 4: Diagram of the Angle of the First Link (Right side: Uncontrolled, Left side: Controlled)

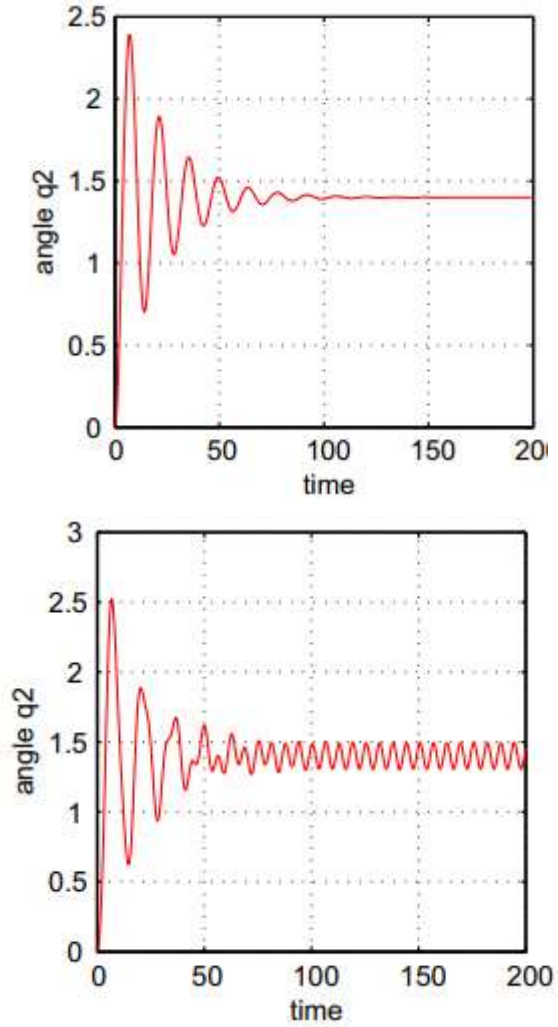


Figure 3: B - Diagram of the Angle of the Second Link (Right side: Uncontrolled, left side: Controlled)

Speed angles connections

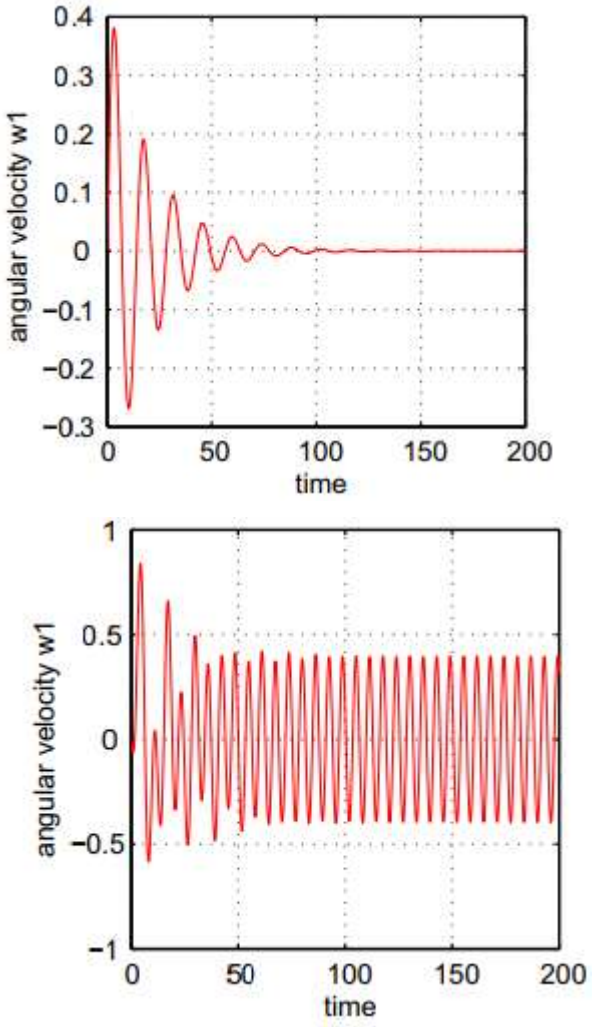


Figure 5: A - Angular Speed of Connection for the First Link (Right side: Non-control, left side: Controlled)

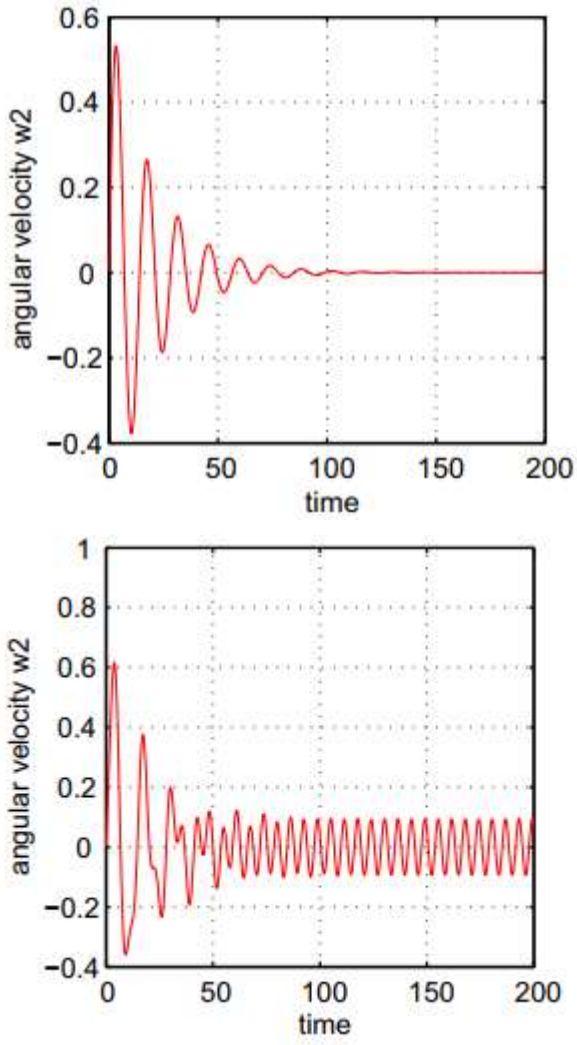


Figure 5: B - Angular Speed of Connection for the Second Link (Right side: Non-control, left side: Controlled)

Theoretical framework

Traditionally, the preference in the design and construction of robots has been for rigid structures rather than flexible ones. The choice was based on the notion that sturdy and inflexible designs would streamline control and improve durability. The perception of flexibility as a possible vulnerability has resulted in the general acceptance of inflexible robotic systems. Nevertheless, with the progress of robotics, namely in the realm of industrial control and automation, there has been a notable change in viewpoint. Researchers increasingly acknowledge the significance of integrating flexibility to enhance adaptability and efficiency in many applications.

The use of inflexible robotic systems poses several difficulties, especially in terms of control and efficiency. Stiff robots often possess a considerable weight and size, rendering them challenging to navigate and leading to increased energy consumption as a consequence of their big mass. Moreover, these robots exhibit a deficiency in flexibility due to the constraints imposed by their rigid joints, which restrict

their capacity to carry out a wide array of jobs. The inflexible characteristics of these robots also impede their ability to quickly adapt to changing settings, resulting in reduced versatility and efficiency while dealing with changeable situations and jobs. Flexible robotic systems have several benefits, beginning with their high energy efficiency. Flexible robots, being typically lighter than rigid robots, need less energy for operation. The decreased weight of these objects also enhances their flexibility and versatility, enabling them to carry out a wider array of duties. Moreover, flexibility might enhance the management of some applications by enabling robots to effectively adapt to disruptions and changes in their surroundings. The enhanced control capacity enhances the efficiency and effectiveness of versatile robots in diverse environments.

Effective control of flexible robots involves advanced methodologies that account for their dynamic nature. State-space representation is a key mathematical model used to describe the robot's dynamics, capturing the relationships between position, velocity, and control inputs. An example equation, $\dot{x} = Ax + Bu$, represents how the robot's state changes over time. Control techniques like PID (Proportional-Integral-Derivative) control, state feedback control, and Model Predictive Control (MPC) are commonly employed. PID control adjusts the control input based on the current error, its integral, and its derivative, offering a balanced approach to error correction. State feedback control uses the full state vector for precise control, with methods like LQR optimizing performance and energy use. Adaptive and learning-based methods, including machine learning, further enhance control by enabling the robot to learn and adapt to its behavior over time. This equation provides a framework for understanding how the robot's state evolves over time based on its current state and the control inputs. Control techniques like PID (Proportional-Integral-Derivative) control are widely used due to their simplicity and effectiveness. The PID control law is given by:

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \quad (39)$$

u(t) is the control input at time t, e(t) is the error (difference between desired and actual value) at time t. K_p, K_i, K_d denote the proportional, integral, and derivative gains, respectively.

PID control modulates the control input by considering the present error, its accumulated integral, and its derivative, providing a well-balanced method for error correction.

State feedback control is an advanced approach that utilizes the whole state vector to compute the control input. The control legislation governing state feedback is as follows: u=−Kx

K is the gain matrix that determines how the state variables influence the control input. A specific example of state feedback control is the Linear Quadratic Regulator (LQR), which optimizes control performance by minimizing a cost function that balances performance and energy use. The LQR control law is derived by solving the Riccati equation to find the optimal gain matrix K. Adaptive and learning-based methods, including machine learning, further enhance control by enabling the robot to learn and adapt to its behavior over time. These methods use data-driven approaches to improve control precision and adaptability in dynamic environments.

Result

Upon reviewing the outcomes of inverse kinematics, it reveals both advantages and disadvantages, summarized as follows:

- The equations in this section are intricate, leading to time-consuming calculations.
- The robot necessitates the utilization of direct and inverse kinematic relations to position each foot accurately.
- These non-linear relations, especially for a mobile system with a single leg, are cumbersome. Given that the processor unit must be embedded within the robot and faces processing speed limitations, these relations are better suited for mechanical simulation rather than as a suitable method for controlling the robot independently.
- The presence of an exact solution in these relations implies that the control system built on this foundation is expected to exhibit zero steady-state error and achieve a very short time to reach the steady state.

In practical implementation, the routine steps of this robot should not involve extensive calculations. Hence, fuzzy logic is suggested. In the fuzzy logic approach to inverse kinematics – akin to what insects, including the discussed insect, employ – there is no requirement for an exact solution. Instead, utilizing the differentials of joint vectors and employing fuzzy logic facilitates the implementation of inverse kinematics.

Furthermore, based on the results, it is noted that when exploring the foot space within the robot's width, achieving a better and faster outcome is preferable when the position is closer to the obtained angle.

The field of robotics has undergone significant evolution, particularly in the context of industrial control and automation. Traditionally, robot design has favored rigidity over flexibility due to the perception that flexible robots were inherently weaker. The rationale behind this preference was that rigid structures simplified control, despite the drawbacks of increased weight, volume, and energy consumption. These rigid robots were often characterized by their

high weight-to-tolerance ratios and lack of adaptability at the joints, leading to inefficient energy usage and limited functionality in dynamic environments.

However, the limitations of a rigid-centric approach have become increasingly apparent. Controlling highly rigid robots is complex and often impractical for applications requiring adaptability and precision. Consequently, the contemporary consensus in robotics is shifting towards incorporating flexibility and adaptability into robotic joints. This paradigm shift is driven by the recognition that not all joints need to be rigid to achieve effective control. Flexible joints can provide the necessary simplicity in control without the constraints imposed by rigidity. Modern robotic research emphasizes the benefits of flexible and adaptive systems. These systems are designed to be more efficient, faster, and capable of handling a broader range of tasks. The focus on flexibility has spurred increased research into control methodologies that accommodate and leverage adaptable joints. This shift acknowledges that rigid-centric designs do not adequately address the diverse and evolving requirements of robotic control. By embracing flexibility, researchers aim to create more versatile and efficient robotic systems that can meet the demands of contemporary industrial applications. The results obtained in the work can be validated by comparing our findings with the previous ones given in the recent years. For example, S. Dhifaoui,et al. [19] have discussed that in vibration isolation systems, vibration suppression and platform positioning were both critical. The author also presented, absolute velocity feedback caused difficulties in achieving these goals simultaneously; hence, this paper proposed an H_∞ control strategy based on sensor fusion feedback. Signals from inertial and displacement sensors were combined using complementary filters, allowing effective control of both vibration and position. This method also reduced noise levels in the fusion signals, maximizing system damping and bandwidth to improve performance. The effectiveness of the proposed strategy was demonstrated by comparing it with conventional absolute velocity feedback on a 3-DOF isolator. M. I. Azeez , et al. [20] have aimed to enhance the performance of a nonlinear three-rigid-link maneuver (RLM) in terms of trajectory tracking, disturbance and noise cancellation, and adaptability to joint flexibility. An optimized sliding mode controller with a proportional integral derivative surface (SMC-PID) was employed, optimized using a multi-elite guidance artificial bee colony algorithm (MGABC). The MGABC algorithm was selected for its efficient exploration and exploitation, resulting in optimal controller parameters. The optimized SMC-PID system have showen superior performance by reducing tracking error, eliminating chattering, and demonstrating robustness against disturbances, noise, and variations in payload mass. However, such papers did not succeed to give the novelty presented in the current work.

5. Conclusions

In conclusion, this article marks a significant stride in the field of robotic systems, particularly in dynamic modeling and vibration control. The innovative approach outlined in this study not only challenges traditional methods but also introduces novel concepts and equations that redefine the precision, adaptability, and efficiency of robotic systems. The emphasis on generalized coordinates, with associated forces, provides a fresh perspective, extending beyond classical Newtonian mechanics and addressing real-world challenges such as non-conservative forces. The incorporation of Hamiltonian principles enhances the accuracy of equations of motion, paving the way for unprecedented control and adaptability in robotic functionalities. The application of Lagrangian equations and iterative learning methods in dynamic modeling contributes to a deeper understanding and effective control of robotic arm behavior, making the proposed approach well-suited for practical applications. Furthermore, the suggestion of using fuzzy logic for inverse kinematics presents a practical solution to streamline implementation, especially in scenarios where computational challenges may impact operational efficiency.

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