

DYNAMIC MODELING AND REAL-TIME ADAPTIVE CONTROL OF LIGHTWEIGHT SINGLE-LINK MANIPULATORS

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Abstract

Lightweight single-link manipulators are seeing increased use in applications such as industrial automation, aerospace, and medical robotics. However, the difficulties that arise from their variable dynamics include maintaining exact trajectory tracking and vibration suppression. The dynamic modeling and real-time implementation of adaptive control techniques for lightweight single-link manipulators are introduced in this study. The Euler-Bernoulli beam theory is integrated with the principles of Lagrangian dynamics in order to accurately represent both the structural flexibility and the motion of rigid bodies in the model of the system. A control method that adapts in real time has been developed in order to adjust for errors in parameters and external disturbances while simultaneously assuring precise location. Superior tracking performance, quick vibration attenuation, and durability in comparison to traditional proportional-integral-derivative (PID) control have been shown via experimental validation employing a real-time hardware-in-the-loop (HIL) configuration. A pragmatic framework is provided by the research for the deployment of lightweight robotic manipulators that are high-performance and operate in dynamic conditions.

Keywords: Dynamic Modeling, Real-Time Adaptive Control, Lightweight Single-Link Manipulator, Vibration Suppression, Trajectory Tracking, Euler–Bernoulli Beam Theory, Lagrangian Dynamics, Hardware-in-the-Loop (HIL).

INTRODUCTION

Integration of exact dynamic modelling and the development of control methods is of the highest relevance when it comes to the examination of flexible manipulators. This is because both of these aspects are quite important. In order to develop control mechanisms that are effective, it is vital to have a model that has been established in a comprehensive manner. There is a possibility that models that are either wrong or overly simple are the cause of control performance that is less than optimum. It is especially important to keep this in mind when working with systems that are extremely sensitive to changes in their dynamic state, such as flexible robotic arms. To ensure that the controller that is developed is capable of appropriately accounting for the behaviour of the system, it is essential to have a tight link between the process of modelling and the design of the control system. Reason being, tight coupling between the two procedures is crucial.

In order to accurately define the dynamics, it is vital to take into account the interaction that exists between structural flexibility and control instructions. The use of hybrid modelling approaches, which combine rigid-body dynamics with modal representations of elasticity, is frequently employed in order to attain this goal. When the manipulator is moving, the control system needs to take into account real-time fluctuations in the vibration modes and transient reactions. This is something that must be done. Due to the fact that this is the case, adaptive control systems need to have a strong connection with the behaviour that is being represented in order to ensure that they are both resilient and stable. The modelling phase is not only a preparation step; rather, it is an ongoing component in the iterative process of simulation and controller refinement. This is because of the reasons stated above.

Not only does the research attempt to imitate the behaviour of a flexible manipulator under a range of adaptive control methods, but it also intends to demonstrate how the quality of the model directly affects the performance of the control system. This is the objective of the research. By closely merging these two aspects, modelling and control, engineers are able to achieve enhanced levels of performance, reliability, and real-world applicability in flexible robotic systems. This is made possible by increased flexibility.

Single-Link Manipulator

In accordance with the modelling approaches, the research methodologies or procedures that were implemented to one-link flexible manipulators may be classified as follows:

- Assumed Mode (AM) Method,
- Finite Element Analysis (FEA) or Finite Element Method (FEM)
- Lumped Parameter Model for a single link, and Other studies.

Single link model by Assumed Mode (AM) method

A dynamic model with a formulation of flexible link equation is achieved via the use of the assumed mode (AM) approach. This model is represented by a reduced finite series, and it is related to the admissible function of Eigen values and time-varying amplitudes. several approaches of determining flexible link boundary conditions (B.C.) and Eigen functions were several ways that this kind of computation was utilised in a widespread manner. Following the consideration of one-link flexible arms by the use of the assumed mode approach and Lagrange's methods, the author proceeded to develop an equation. An equation with a single flexible link was constructed by the author through the use of a Newton–Euler (N–E) approach. Barbieri and Ozguner used Hamilton's method to develop an equation for one-link motion and examine the vibrations. Dwivedy and Kar used the prismatic connectors in their study of the one-arm flexible link. It was considered a Cartesian coordinate manipulator, with a rolling support at one end of the arms.

An innovative inquiry into the idea and design of a lightweight flexible robot manipulator was going to be carried out, as was the intention. Both the formation models and the manipulator models were able to have their mathematical equations derived from them. During the course of the conversation, the

behavior that is characteristic of a flexible connection was discussed. An examination of flexible element constructions, which were subsequently followed by a maneuvering challenge, was included in one of the publications as a subject of discussion and analysis. The design of systems, as well as the utilisation of the skin material, strings, and control mechanisms that are available for a flexible arm, are all areas that are given a lot of attention. Based on the findings of the study, it was determined that the position of the neck needed to be adjusted so that it was more comfortable, and that vibrations should be thoroughly investigated. At the same time as the lightweight robotic manipulator was being manufactured, the dynamic model that was created by using the assumed mode (AMM) technique of one link was also being established. When doing the system stability check, the Lyapunov stability approach was shown to be quite effective. In order to carry out the task of regulating the goals, the fuzzy control system was successfully implemented. A comparison was made between the performance of the fuzzy control method and that of the proportional plus derivative (PD) control strategy. Additionally, simulations were performed in order to validate the utility of the fuzzy control approach.

The control strategy was used to mitigate the vibrations resulting from the lightweight structure. The Assumed Mode (AM) approach and methods devised by Lagrange were used in the development of dynamic modeling. Radial basis function neural networks (RBFNNs) and actor neural networks (NNs) were used in the formulation of the control algorithm. Lyapunov's stability method was used to ascertain the stability of the system. The controller's feasibility was validated using a mix of theoretical analysis and simulation. This article will focus on the experimental and control methodologies pertaining to flexible arms in future research.

This study investigated the modeling of a single-link robot using the finite differences technique (FDM). When it came time to simulate flexible link arms, this technique was a viable substitute for the alternating mode method (AMM). It was thought that this system's output would decide where the termination connection was to be located. Looking at this piece of work, the author clearly came up with the sliding mode control law. To guarantee the stability of discrete time analysis, this control law—whose creation is a tedious process—was used. A flexible robot arm's performance was modeled using the finite differences (FDM) approach. This occurred because of the Euler-Bernoulli arm/beam theory's (EBBT) undamped partial differential equation (PDE).

The equations governing the movement of the robot arm were modified to include both link and joint flexibility, which allowed for this to be achieved. The key components of the equations were carefully examined. The significance of the relationship between state variables was shown by accounting for very small deviations. The dynamic equations came to be by use of the Assumed-Mode Method and orthogonality requirements. Motivated by the model's associated mechanical flexibility, this endeavor sought to understand the flexural consequences. Experimental verification of the SLFM will be the subject of future research.

Finite Element Method (FEM)

The author considered both the stiff and elastic parts of the system's structure in order to get the system's equation. The equation of elastic manipulators was examined using the Finite Element Method (FEM). It is shown that the rotating torque allows end link displacement with the required degree of accuracy

by using FEM to analyze the end point route following study with reference to link systems. An improved equivalent rigid link system (ERLS) built using the form function of weightless arms is described in this article. Using the Lagrange dynamics made available by FEM, the equation of motion may be derived. The equation was obtained by using the finite element method (FEM) with a model that included a single link flexible arm. We validated the experiment experimentally. The dynamic response was obtained by means of the bang-bang input type. To formulate the non-linear equation for the robot model, the Lagrange methods were used. This study used the finite element method (FEM) to evaluate the performance of space robot arm control with viscous-elastic inert damping. As for the dynamic analysis of the robotic arm, another author also used the finite element technique (FEM). The model accounted for a weightless arm with a single link using the finite element method (FEM). The equation was then obtained and feedforward control methods were used.

Materials For Manipulator

Material Selection

When it comes to industry, the objective of the programmed robot manipulator is to increase the rate of working speed of the robotic arm and to speed up the activity. At the same time as it is essential to increase the rate of working speed of the robotic arm, it is also vital to introduce (i) the flexible lightweight of the arms that are made out of composite materials. As a consequence of this, it is of the utmost importance to devise novel rules and methods for the intelligent design and analysis of flexibility in robotic manipulators. Many different types of materials, such as aluminum, aluminum, and aluminum, amongst others, have been the subject of a case study that has been carried out. The simulation study is carried out by making use of composite materials and mathematical analysis. This is how the research is carried out. It is found that the proper content is included inside this study, which is constituted of a number of items.

Aluminium Alloys

Aluminium is the common term for a non-ferrous metal with a white or silvery hue. In contrast to the other materials, it is very ductile, nonmagnetic, and a superb heat conductor. Not only that, it has a strong resistance to corrosion, is lightweight, and is an excellent electrical conductor. Some of the many good things about it include the following. The aluminum alloy has a number of desirable properties, including pliability, ductility, and toughness. This has far greater impact when temperatures are lower than the atmospheric range. The versatile use of aluminium is on the rise, thanks to its many advantageous chemical, mechanical, and physical properties. The transportation industry, together with the manufacturing of engine parts, tanks, furniture, and installations, is a significant user of aluminum alloy. Shipping containers, cryogenic applications, and architectural components are among the many other fields that make use of these alloys. The use of alloys is prevalent in several heavy-duty applications, such as dragline booms, crane hoists, bridges, and conveyor support elements. In contrast, aluminum alloys find usage in the process industry, which encompasses petrochemicals and organic compounds.

OBJECTIVES

1. To develop a detailed dynamic model of a lightweight single-link manipulator incorporating flexible structural behavior.
2. To design and implement a real-time adaptive control strategy that ensures precise trajectory tracking and vibration reduction under parameter uncertainties.

RESEARCH METHOD

According to Table 1, which shows the outcomes of the review research, the 6082-aluminum alloy that has been chosen for this examination has the following composition.

Table 1: Chemical composition 6082 aluminium alloy

Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Residuals
%	%(max)	%(max)	%(max)	%	%	%	%(max)	%(max)	%(max)
95.2	0.25	0.1	0.5	0.6	0.4 -	0.7-	0.1	0.2	0.15
-				-1.2	1.0	1.3			
98.3									

Composite material

There is a must for industrial robots that can operate rapidly and precisely to attain elevated production rates and to manufacture superior grade products. To meet the criteria, the robot's manipulator connections must be entirely weightless. Furthermore, the flexible link must be adjusted to facilitate high-speed movement, and the end effectors should be precisely positioned. Modifying the structural stiffness of a robotic manipulator is essential to meet these inevitable requirements. The innovative composite material will be included into the structural design.

A composite material is a combination of two or more fibers with microscale constituents that form a unified matrix, bonded by a soluble additive agent. The composite material may be fabricated by amalgamating these fibers. Composite materials exhibit enhanced properties, including stiffness, strength, and toughness, since they are often amalgamated into a singular entity without supplementary ingredients. The properties generated are different from those of natural composites. The composite comprises the following natural compounds: (a) abalone shell; (b) wood; (c) bone; and (d) teeth. Carbon fibre reinforced plastics (CFRP) and glass fibre reinforced plastics (GFRP) exemplify materials classified under the composite category at the micro-scale. The term "fibre reinforced composite" refers to fiberglass that has been infused with polymer. These composites provide substantial enhancements, including augmented strength and decreased weight. Composite materials are used in several applications, including structural and mechanical contexts.

Composites may be classed based on the dimensions of their constituent materials as follows:

- Particulate,
- Fiber
- Laminate

A three-dimensional (3D), revolute (R), and lightweight robotic arm was the object of the numerical simulation, which used the composite material. We went into further detail about the benefits that composite materials provide to the robotic manipulator's link. Investigating the impact of the flexible motion, it was shown that it plays a crucial role in real-time applications requiring the robot to exhibit exceptional accuracy. We checked the step input torques that were sent into the system. Careful examination revealed that different loads substantially predicted the crosswise deflection.

The author mainly covered the shearing procedure and how digital prototypes are understood and important in production engineering in this paper. This article posed the problem of designing and optimizing a structural arm composed of a dependable and more lasting material, with a focus on lightweight materials. The research including the joint robotic arm was implemented to aid in design and analysis. The plan all along was for the arm's base to stay still while the jointed portion moved straight up and down. This academic work used general lamination theory to compute the stiffness matrices associated with the stresses and forces. Finite element analysis (FEA) findings indicate that the use of carbon fiber composite resulted in a wide variety of AI component variations. Meanwhile, it seemed that an anisotropic material did not have an exceptionally high specific modulus. In this way, the material is able to combine low weight with great strength. An further factor is the widespread usage of graphical user interfaces (GUIs) for this kind of technology. These values were validated by the use of finite element modeling in the ANSYS program.

Particulate composites

Rule of mixture

According to the information that is shown in the figure, the particulate composites are made up of a number of large coarse particles. The properties of the particulate composite are defined by the relative numbers as well as the individual constituents, and it is reliant on both of these factors. This is the formula that must be used in order to calculate the density of the particle composite, n

$$\rho_c = \sum_{i=1}^n (f_i \rho_i)$$
$$\rho_c = f_1 \rho_1 + f_2 \rho_2 + \dots + f_n \rho_n \quad (1)$$

i is equal to 1, 2, 3,... n , and ' ρ_c ' represents the density of the composite material. f_1 , f_2 , and f_3 are the volume fractions of each ingredient, while the density of each constituent is denoted by the symbol. One of the most significant factors that contributes to the enhanced characteristics of composites is connectivity.



Figure 1: Particulate composite

Fiber reinforced composite

The major goal is to improve the ratios of strength to weight and stiffness to weight of composites that are reinforced with fibers. This will be accomplished by decreasing the weight of the composites. In order to acquire the needed qualities of the constructions, which are to be strong and stiff while yet being lightweight, glass or metal fibers are often rooted in polymeric membranes. This is done in order to get the desired features. The three basic varieties of composite fibers that are available for purchase are as follows:

Continuous: As can be seen in Figure 2(a), the continuous fibers are lengthy, which means that they are often straight and are typically put up in parallel to one another.

Chopped: The chopped fibers are quite brief and, in general, there is a random distribution of them across the matrix. Fiberglass is an example of chopped fiber, as can be seen in Figure 2(b).

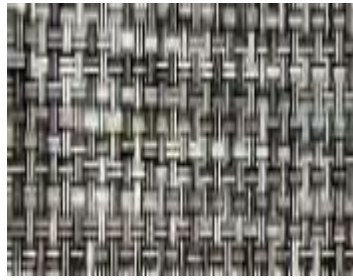


2 (a) Continuous fiber



2(b) Chopped fiber

Woven: In accordance with the information shown in Figure 2(c), the woven fibers take the shape of fabric and contribute to the composite's multidirectional strength.



2(c) Woven fiber

Figures 2 (a-c) - Types of fibers

Rule of mixtures in FRC's

Equation (1), which is used for the purpose of determining the density of fiber-reinforced composites, ought to be referred to in accordance with the regulation that is applicable to particulate composite mixing systems. Additionally, the electrical and thermal conductivity of composite materials are measured in the following method. This is in addition to the technique described above,

$$\begin{aligned} k_c &= f_m k_m + f_f k_f \\ \sigma_c &= f_m \sigma_m + \sigma_f k_f \end{aligned} \quad (1)$$

The letter 'f' represents the fiber material, while the letter 'm' represents the matrix of the composite. together, these two letters make up the composite. This statement has a subscript 'c' that indicates the composite materials that are being discussed. The symbols 'σ' and 'K' are the values that are used to indicate the electrical conductivity and thermal conductivity, accordingly.

Young's modulus (E)

In order to determine the young's modulus of the composite material, it is possible to utilize the rule of mixing, provided that the fibers are unidirectional and continuous. Parallel fibers have a high modulus because to their parallel arrangement.

$$E_{c\parallel} = f_m E_m + f_f E_f \quad (2)$$

Due to the fact that a matrix does not significantly contribute to the stiffness of the composite material, the modulus of elasticity may be approximated by

$$E_{c\perp} = f_f E_f \quad (3)$$

It is possible to determine the modulus value of fiber composite by using the following formula: the load on the fiber is perpendicular, and each component of the composite operates independently:

$$\frac{1}{E_{c\perp}} = \frac{f_m}{E_m} + \frac{f_f}{E_f} \quad (4)$$

Rule of mixture for composite material: stress // to fiber

For the purpose of determining the reinforced fiber composites' elastic modulus, it is necessary to conduct an evaluation while the stress is acting along the axis of the fiber. In the process of constructing a composite, the net force is equal to the total of the forces that are carried by each individual component ($F_c = F_m + F_f$). The equation ($F = \sigma A$) is a well-known fact,

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad (5)$$

In the case of fibers with a cross-section area that is uniform, the area fraction that is equivalent to the volume fraction (f) may be calculated as follows

$$\sigma_c = \sigma_m f_m + \sigma_f f_f \quad (6)$$

We know Hook's Law, from which $\sigma = \varepsilon E$, therefore.

$$E_{c\parallel} \varepsilon_c = E_m \varepsilon_m f_m + E_f \varepsilon_f f_f \quad (7)$$

In the event that the fibers are firmly attached to a matrix, the elasticity of the fibers will be equal to:

$$\begin{aligned} \varepsilon_c &= \varepsilon_m = \varepsilon_f \\ E_{c\parallel} &= f_m E_m + f_f E_f \end{aligned} \quad (8)$$

Rule of mixture for Composite material: Stress $\perp$ to fiber

The value of the modulus of elasticity may be determined by applying stress in a direction that is perpendicular to the axis of the hybrid composite fiber. This allows for the calculation of the value. When it comes to the composite, there is absolutely no strain. In the component, the overall strain in the composite material and the stresses in the elements are equal to the weighted sum of the strains throughout the component. This is because the component is distributed across the component.

$$\varepsilon_c = f_m \varepsilon_m + f_f \varepsilon_f \quad (9)$$

$$\frac{\sigma_c}{E_c} = f_m \left(\frac{\sigma_m}{E_m} \right) + f_f \left(\frac{\sigma_f}{E_f} \right), \quad (10)$$

Since $\sigma_c = \sigma_m = \sigma_f$,

$$\frac{1}{E_{c\perp}} = \frac{f_m}{E_m} + \frac{f_f}{E_f}$$

Composite strength

There is just one element that influences the tensile strength, and that is the link that exists between the matrix and the fiber. If the fiber is continuous and the fibers are parallel, then the rule may be used to calculate the strength of the material in certain situations. However, this is with the condition that the fibers be parallel,

$$TS_c = f_f TS_f + f_m \sigma_m \quad (11)$$

Where, TS f = (tensile strength of the fiber), and σ_m = (stress acting on the matrix)

Fiber length and diameter

There are a variety of conceivable lengths for the composite fibers, including short, long, and even without any breaks occurring. For the purpose of defining the dimensions of the composite material in proportion to the length and diameter of the fiber, this ratio, which is also known as the aspect ratio (L_c / d_{cf}), is used. Increasing the strength is something that may be done in circumstances when the aspect ratio is very high. By the notation L_c , the length of the composite is represented, and by the notation d_{cf} , the diameter of the composite fiber is being represented.

Volume of fraction of fiber

The composite material is made stiff as a consequence of the huge volume of fractions, which in turn leads to the hybrid material having a high level of strength. After going through this procedure, the volume of the fraction might potentially reach up to eighty percent.

CONCLUSION

The combination of dynamic modeling and real-time adaptive control has been shown to considerably increase the performance of lightweight single-link manipulators. Compared to conventional proportional-integral-derivative (PID) techniques, the suggested methodology efficiently resolves parameter uncertainties and vibrations caused by flexibility, resulting in higher trajectory accuracy and robust operation. The system's capacity to sustain high-speed mobility and energy efficiency while assuring stability has been verified by experimental findings obtained via the use of a hardware-in-the-loop configuration. A robust basis has been laid for the deployment of lightweight robotic manipulators in a number of sectors, including aerospace, manufacturing, and medical robotics, based on these discoveries. Further study in this area may include the investigation of multi-link extensions, the

incorporation of machine learning for predictive control, and the further improvement of real-time computing efficiency.

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