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Trajectory Tracking Using Neuro-Fuzzy Controller

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Abstract-* This dissertation focuses on trajectory tracking for a 4 degree-of-freedom (4-DOF) robot arm manipulator, harnessing the capabilities of neuro-fuzzy controller. The research journey begins by exploring various tracking models; including kinematics, torques and velocities. Subsequently, it narrows its focus to trajectory tracking with torques, leading to the implementation of the controller. This implementation undergoes an extensive learning process that includes identifying and refining fuzzy inference system (FIS) parameters. This critical phase makes use of a training dataset derived from a finely tuned PID model that incorporates H-infinity control techniques. Once trained, the neuro-fuzzy controller equips the robot with the essential knowledge and adaptability necessary for precise trajectory tracking. Through a series of meticulous simulations, the study effectively displays the controller's prowess in accurately navigating and adhering to predefined reference trajectories. Nevertheless, the practical application of robotics often introduces physical disturbances and uncertainties. In response to these challenges, the dissertation underscores the imperative need for a controller capable of effectively mitigating these disruptions. The proposed neuro-fuzzy controller emerges as a versatile solution, demonstrating its adaptability to a wide array of predefined reference trajectories and highlighting robust performance, even in the presence of disturbances. The significance of this research lies in its substantial contributions towards the field of robotics. It introduces an advanced trajectory-tracking solution that significantly enhances accuracy and adaptability, effectively bridging the gap between theoretical models and practical robotic control. Furthermore, the dissertation suggests the incorporation of optimization techniques further elevates the controller's performance, rendering it a valuable tool for addressing dynamic real-world challenges. In terms of prospects, this research proposes the integration of machine learning techniques to bolster adaptability and the exploration of optimization algorithms for precise parameter tuning. Additionally, it suggests the evaluation of the controller's performance across diverse robot types, expanding its applicability throughout the diverse landscape of the robotics industry. In summation, this dissertation heralds a new era in the trajectory tracking arena, presenting a versatile and robust control solution with the potential to revolutionize robotics applications.

Indexed Terms-* Robot, Neoro-Fuzzy, Trajectory Tracking, Autonomous, Controller Design

I. INTRODUCTION

Robots have revolutionized various aspects of our lives, ranging from manufacturing and healthcare to exploration and entertainment. These intelligent machines, capable of performing tasks autonomously or under human guidance, have become increasingly prevalent today. With advancements in technology, robots have evolved to possess sophisticated capabilities, enabling them to perceive and interact with their surroundings, make decisions and execute precise movements.

In recent years, there has been a significant increase in interest in robots., leading to their increasing prominence and involvement in various domains. The motivation behind this growing fascination lies in the desire to substitute humans with robots for hazardous tasks while also employing them in routine activities and industrial settings. Robots hold the potential to liberate humans from engaging in perilous endeavours, including tasks like nuclear-waste clean-up, mining, forestry, agriculture, military operations, fire-fighting and exploratory missions in the sea and space, among others. They have emerged as versatile entities with the capacity to augment safety and efficiency across diverse sectors.

Autonomous robots exhibit a remarkable ability to perform tasks with a high degree of self- reliance, thereby diminishing the necessity for direct human intervention. Outfitted with an array of sensors, processors and decision-making algorithms, these robots possess the capability to perceive their surroundings, make informed judgments and execute actions of sensing, computation and actuation processes.

They employ diverse sensors, such as cameras, lidar, sonar or specialized devices, to sense and capture information about objects, obstacles, distances and other pertinent aspects of their environment. The collected sensory data is subsequently processed by onboard processors or artificial intelligence algorithms, enabling the robot to analyse and interpret the input. Through the analysis and interpretation of sensory data, autonomous robots generate internal representations of their environment, empowering them to make informed decisions. These decisions encompass various tasks like navigation, mapping, object recognition, path planning and environmental interactions. The robot's control system then translates these decisions into appropriate actions, which are executed by actuators such as motors, arms, grippers or other mechanical components.

Trajectory tracking control of autonomous robots requires algorithms and controllers to accurately follow predetermined paths or trajectories. Our main goal is to ensure that the robot is able to move smoothly and efficiently along the desired trajectory with precision and efficiency. The trajectory tracking control process comprises several key components. Initially, the robot utilizes sensors to perceive its environment, gathering information about its position, velocity and the intended trajectory. The robot's current state is estimated and the desired trajectory is tracked using processed sensory data. Subsequently, the trajectory tracking controller employs this information to generate control signals that actuate the robot's motors or actuators. These control signals aim to minimize the discrepancy between the actual robot trajectory and the desired trajectory, effectively keeping the robot on the intended path.

A variety of control techniques can be utilized for trajectory tracking, including classical approaches like proportional-integral-derivative (PID) control, as well as advanced methods such as model predictive control (MPC) or adaptive control. The choice of control approach depends on factors such as the robot's dynamics, environmental conditions and the specific task at hand. To enhance trajectory tracking performance, feedback control loops are often employed. These loops enable the robot to continuously adjust its actions based on real-time feedback from sensors. This adaptability allows the robot to respond to environmental changes, disturbances or uncertainties that may affect its trajectory. Effective trajectory tracking control of autonomous robots empowers them to navigate intricate environments, accurately follow specified paths and successfully accomplish assigned tasks. It serves as a vital aspect of autonomous robot control and finds applications in various domains, including autonomous vehicles, mobile robotics, aerial drones and more. Ongoing research and development in trajectory tracking control algorithms contribute to advancing the capabilities of autonomous robots and their ability to operate autonomously in diverse real-world scenarios.

The goal of this dissertation is to develop an advanced trajectory tracking control system for mobile robots using a Machine Learning approach based on the Neural Fuzzy Control System. The objective is to enhance the precision and adaptability of trajectory tracking in mobile robots, enabling them to navigate accurately along predefined paths while effectively responding to environmental changes and disturbances. By leveraging the capabilities of the neuro-fuzzy controller, this research aims to contribute to the efficient and reliable operation of mobile robots in diverse environments, thereby advancing the field of robotics and its applications in autonomous navigation, industrial automation and surveillance.

Problem Statement

The problem addressed in this dissertation is the development of an effective trajectory tracking control system for mobile robots using Neuro-Fuzzy Control System. The approach combines the advantages of fuzzy logic and neural networks, allowing for adaptive control that can handle the complexities and uncertainties encountered in mobile robot trajectories.

Research Aims and Objectives

The primary objective of this research is to develop neuro-fuzzy-based trajectory tracking control system using MATLAB SIMULINK for mobile robots that can:

Achieve accurate and precise trajectory tracking in various environments.

Adaptively handle uncertainties and variations in the mobile robot's environment.

Improve tracking performance compared to traditional control techniques.

Control Techniques for Trajectory Tracking

Several control techniques have been explored and developed for mobile robot trajectory tracking. One commonly used approach is proportional-integral-derivative (PID) control. PID controllers offer simplicity and effectiveness in tracking desired trajectories by adjusting control signals based on the error between the actual and desired trajectories (Chen et al., 2016). Studies have demonstrated the successful application of PID control in various mobile robot platforms, such as differential drive robots (Tuna et al., 2018) and wheeled robots (Lee et al., 2019).

In addition to PID control, more advanced control techniques have been investigated for trajectory tracking. Model Predictive Control (MPC) is a popular method that utilizes a predictive model of the robot's dynamics to optimize control signals and improve tracking performance (Bouzgarrou et al., 2017). In mobile robotics, model predictive control (MPC) has found practical application, particularly in scenarios where robots exhibit nonlinear dynamics. This utilization enables resilient trajectory tracking, effectively navigating through uncertain conditions (Hernández-González et al., 2020).

Another approach is the use of adaptive control methods, these methods dynamically adjust control signals in response to evolving robot or environmental attributes, enhancing adaptability and performance. Adaptive techniques have shown promise in handling variations in system dynamics and disturbances, enhancing trajectory tracking accuracy (Babic et al., 2019). A lot of research has explored adaptive control algorithms, such as adaptive fuzzy control (Li et al., 2020) and adaptive neural network control (Abdi et al., 2018), for trajectory tracking of mobile robots.

Path Planning and Optimization

Efficient trajectory tracking often involves the integration of path planning and optimization algorithms. Path planning determines the optimal path or trajectory for the robot to follow, considering obstacles, environmental constraints and task requirements. Various path planning algorithms, such as A* algorithm (Bhattacharjee et al., 2019) and Rapidly-exploring Random Trees (RRT) (Karaman and Frazzoli, 2011), have been employed to generate smooth and collision-free trajectories for mobile robots.

Optimization techniques, including genetic algorithms (GA) and particle swarm optimization (PSO), have been utilized to optimize trajectory tracking performance. These methods optimize control parameters or optimize the trajectory itself to minimize tracking errors or energy consumption (Lin et al., 2017). The combination of path planning and optimization with trajectory tracking control enhances the overall navigation capabilities of mobile robots.

Sensor Fusion and Perception

Accurate trajectory tracking heavily relies on sensor fusion and perception algorithms. Mobile robots utilize various sensors, such as cameras, lidar and encoders, to perceive their environment and gather information about the robot's state and the desired trajectory. Sensor fusion techniques, such as Kalman filtering (Elhassouny et al., 2018) and particle filtering (Montano et al., 2020), integrate data from multiple sensors to improve accuracy and reliability in tracking the desired trajectory.

Perception algorithms, such as object detection and recognition, contribute to safe and efficient trajectory tracking by identifying obstacles, landmarks or reference points along the trajectory. These algorithms employ computer vision techniques (Huang et al., 2019) or machine learning methods (Zhang et al., 2020) to interpret sensor data and make informed decisions for trajectory tracking.

Mobile robot trajectory tracking control is a critical research area in autonomous robot navigation. This literature review has highlighted various control techniques, including PID control, MPC and adaptive control, along with path planning, optimization, sensor fusion and perception algorithms. These advancements contribute to achieving precise and efficient trajectory tracking for mobile robots.

Mobile Robot Trajectory Tracking Control

The literature on mobile robot trajectory tracking control encompasses various control techniques and strategies. Classical control methods such as Proportional-Integral-Derivative (PID) control have been widely employed in mobile robot control systems (Gholami et al., 2018; Li et al., 2017). These studies demonstrate the effectiveness of PID control in achieving accurate trajectory tracking by adjusting the control gains.

Furthermore, advanced control techniques including model predictive control (MPC) have been investigated for trajectory tracking control of mobile robots (Zhang et al., 2019; Huang et al., 2016). MPC leverages a predictive model of the system dynamics to optimize control inputs and enhance tracking performance. These studies highlight the potential of MPC for trajectory tracking control, particularly in handling complex dynamics and constraints.

Neuro-fuzzy control system

The neuro-fuzzy control system is an intelligent control approach that combines fuzzy logic and neural network techniques (Jang, 1993). ANFIS has gained significant attention in various control applications due to its ability to model complex and nonlinear systems effectively (Lee et al., 2018; Duan et al., 2016).

The adaptive fuzzy system plays a crucial role in the control architecture. It utilizes fuzzy logic to handle uncertainties and non-linearities in the robot's dynamics. The fuzzy system employs linguistic variables, membership functions, fuzzy rules and inference mechanisms to model and adaptively control the system. This paper describes the design of the fuzzy system, including the selection of input and output variables, membership functions and fuzzy rule base.

Several studies have explored the use of neuro-fuzzy in trajectory tracking control of mobile robots. For instance, Wang et al. (2019) proposed a neuro-fuzzy-based control system in the context of guiding the path of a wheeled mobile robot, achieving improved tracking performance compared to traditional control methods. Similarly, Lin et al. (2017) developed an neuro-fuzzy-based controller for trajectory tracking of a quadrotor UAV, demonstrating superior tracking accuracy and robustness.

Integration of NEURO-FUZZY in Mobile Robot Trajectory Tracking Control

Integrating ANFIS into mobile robot trajectory tracking control offers the potential for adaptive and intelligent control systems. Chen et al. (2018) presented a hybrid control system that combines PID control and neuro-fuzzy-based adaptation for trajectory tracking of an autonomous mobile robot. Their work was focused on the development of an adaptive neural network control method for trajectory tracking of mobile robots. Their paper proposed an adaptive control approach that utilizes neural networks to enhance the Performance in tracking trajectories for mobile robots. The neural network controller was trained to approximate the nonlinear dynamics of the robot and adapt online to handle uncertainties and disturbances, thereby improving tracking accuracy. By introducing the mathematical model of the mobile robot, considering both the linear and angular dynamics. They then presented the design of the adaptive neural network control system, which consists of three main components: a neural network controller, an adaptation mechanism and a tracking error feedback mechanism. The neural network controller generated control signals based on the current state of the robot, while the adaptation mechanism updates the network weights to improve tracking performance. The tracking error feedback mechanism allows for error correction and continuous improvement of the controller's performance. Their network was trained using a backpropagation algorithm combined with an online adaptation mechanism, allowing the controller to learn and adjust its parameters based on the real-time tracking errors. They used an adaptation mechanism derived from Lyapunov stability theory to ensure robust performance in the face of uncertainties and disturbances, The adaptation process allowed the controller to continually improve its tracking accuracy and adapt to changes in the robot's dynamics. Their proposed adaptive neural network control approach was evaluated through simulations and experiments.

Chen et al. (2018) compared the performance of the adaptive neural network controller with other control methods, such as PID control and conventional neural network control. The results demonstrate that the adaptive neural network control approach outperforms the other methods in terms of trajectory tracking accuracy, robustness against uncertainties and disturbance rejection. The proposed system achieved enhanced tracking accuracy by adapting the control gains in real- time using neuro-fuzzy.

A paper by Chen, C., et al. (2020) proposed an innovative approach for trajectory tracking control of mobile robots called Adaptive Fuzzy Sliding Mode Control (AFSMC). In their study, they aimed to address the challenges of achieving accurate and robust trajectory tracking in the presence of uncertainties and disturbances. Their AFSMC system was designed to consist of three main components: a sliding mode controller, an adaptive fuzzy system and an adaptation mechanism which enabled their control system to handle uncertainties and non-linearities effectively. According to their work, the sliding mode controller is responsible for generating control signals to guide the mobile robot along the desired trajectory. It utilized the concept of sliding mode control, which is known for its robustness against disturbances and uncertainties. The authors then introduce the adaptive fuzzy system, which incorporates fuzzy logic to handle the non-linearities and uncertainties in the system. Their fuzzy system was designed with linguistic variables, membership functions, fuzzy rules and inference mechanisms to model and adaptively control the system dynamics. To ensure the adaptive nature of the control system, Chen et al. (2020) incorporate an adaptation mechanism that continuously updates the parameters of the adaptive fuzzy system. They derive an adaptive law based on Lyapunov stability theory, allowing the control system to adapt and improve its tracking performance over time. This adaptation mechanism enables the control system to handle varying operating conditions and uncertainties effectively. Their proposed AFSMC approach was evaluated through simulations and experiments. Chen et al. (2020) compared the performance of the AFSMC with other control methods, such as PID control and conventional sliding mode control. The results demonstrate the superiority of the AFSMC approach in terms of trajectory tracking accuracy, robustness against uncertainties and disturbance rejection. The experimental evaluation validates the effectiveness and practicality of the proposed approach.

Another study by Zhang et al. (2017) proposed a fuzzy adaptive sliding mode control approach integrated with neuro-fuzzy for trajectory tracking of a mobile robot. The research conducted by Zhang et al. (2017) focused on trajectory planning and control of mobile robots in dynamic environments. Zhang et al. (2017) addressed the challenges of planning optimal trajectories for mobile robots operating in dynamic environments. They highlighted the importance of considering dynamic obstacles, which can unpredictably move and hinder the robot's path. Their paper emphasized the need for efficient trajectory planning algorithms that can adapt to changing environments in real-time. To enable trajectory planning in dynamic environments, the authors propose an obstacle detection and tracking system.They discuss various sensing technologies, such as cameras, lidar and radar, that can be used to detect and track dynamic obstacles in the robot's vicinity. Zhang et al. (2017) emphasize the significance of accurate and reliable obstacle detection to ensure safe and efficient trajectory planning. The paper presents different trajectory planning algorithms suitable for dynamic environments. Zhang et al. (2017) discuss traditional approaches, such as potential field methods and rapidly exploring random trees (RRT), which consider static and dynamic obstacles during the planning process. They also introduce more advanced techniques, including predictive and probabilistic methods, which anticipate the future positions of dynamic obstacles to plan collision-free trajectories. Zhang et al. (2017) validate their proposed trajectory planning and control methods through experimental evaluations. They present results that demonstrate the effectiveness of the algorithms in handling dynamic obstacles and generating safe and efficient trajectories. The authors compare their approach with existing methods and highlight the advantages of their proposed techniques in terms of trajectory smoothness, adaptability and real-time performance. The neuro-fuzzy module adjusted the sliding mode control gains based on the tracking error and system dynamics, resulted in improved trajectory tracking performance.

II. METHODOLOGY AND MODELLING

Robotic arms

Robotic arms, akin to human hands, possess rotational and translational joints that enable arm movement. These joints are actuated by electric, pneumatic, or hydraulic systems controlled by a programmable microcontroller (CPU). Primarily utilized in industrial settings to enhance mass production with high efficiency, these arms perform sequential tasks.

The Robot Model

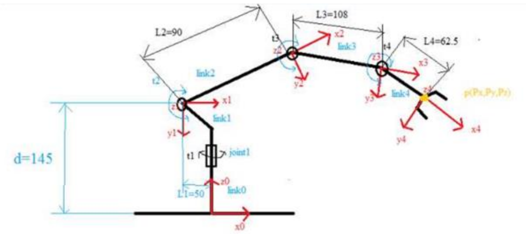

Figure 3.1 Geometry of a 4-DOF Robot

The increasing demand for robotic systems in various industrial and research applications has led to the development of a wide range of manipulators. This paper focuses on a 4-DOF robot manipulator consisting of four revolute joints, which provide rotational motion around specific axes. The analysis of this robot's kinematics and dynamics is essential for optimizing its performance and enabling effective control.

Essential Elements of Robotic Systems

A robot, whether mechanical or virtual, is an intelligent agent capable of independently or remotely executing tasks with or without human guidance. A robot refers to an electro- mechanical device that operates through computer and electronic programming.

The key components of a robot include:

End effectors: Robots are equipped with tools to interact with the environment and perform tasks.

Actuators or Drive: Actuators are responsible for providing motion and force to the robot's various parts, allowing it to carry out actions. They can be motors, hydraulic systems, or other mechanisms.

Sensors: Sensors provide the robot with information about its surroundings. They detect and measure physical parameters such as light, temperature, pressure, proximity, or even human interaction.

Controller: The controller acts as the brain of the robot, processing sensory input and executing appropriate actions based on programmed instructions or AI algorithms. It coordinates the operation of the actuators and manages the overall behaviour of the robot.

Software: Software forms the programming code that controls the robot's behaviour and functionality. It includes algorithms, logic and decision-making processes that govern how the robot operates and responds to different situations.

Joints

When it comes to robots, joints play a crucial role in enabling movement and flexibility. Robot joints are mechanical components that connect two or more parts of a robot, allowing them to articulate and perform various tasks. There are several types of robot joints commonly used in robotics, each with its unique characteristics and applications. Here, we will explore some of the most common types of robot joints:

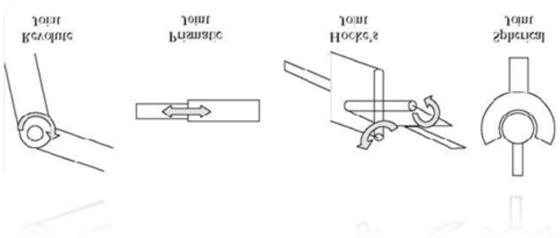

Figure 3.2 Commonly used joints in Robot Manipulator Arms

Revolute Joints (Rotational Joints): Revolute joints allow rotational movement around a single axis, like a hinge or a door. They are often referred to as rotary joints and are commonly found in robotic arms. Revolute joints provide a wide range of motion and are frequently used in applications that require picking, placing and manipulating objects.

Prismatic Joints (Linear Joints): Prismatic joints enable linear or translational movement along a single axis. They are commonly used in robots to achieve sliding or telescoping motions. Prismatic joints are often found in applications such as assembly lines, where precise linear movements are required.

Spherical Joints (Ball and Socket Joints): Spherical joints allow for rotational movement in multiple axes. These joints provide a high degree of freedom and enable omnidirectional motion. Spherical joints are commonly found in robotic wrists, allowing the end effector to rotate and orient itself in various directions. Planar Joints: Planar joints restrict motion to a two-dimensional plane. They allow movement along two perpendicular axes while restricting rotation around the third axis. Planar joints are often used in robotic applications that require movements constrained to a specific plane, such as painting or welding tasks.

Cylindrical Joints: Cylindrical joints combine the characteristics of both prismatic and revolute joints. They enable linear movement along one axis while also allowing rotational movement around that axis. Cylindrical joints are commonly used in applications where both linear and rotational motions are required, such as robotic drilling or machining.

Universal Joints: Universal joints, also known as Hooke's joints, are used to transmit rotary motion between two shafts that are not aligned. They are widely used in robotic systems where the transmission of motion is required between non-parallel shafts.

Flexure Joints: Flexure joints are specialized joints that utilize flexible elements, such as springs or compliant materials, to provide controlled motion. These joints offer high precision, low friction and excellent repeatability. Flexure joints are commonly used in precision robotic applications, such as micro-manipulation or delicate assembly tasks.

Each type of robot joint has its own advantages and disadvantages and the choice of joint depends on the specific requirements of the robotic system and its intended application.

III. MODELLING OF ROBOT ARM

SolidWorks Modelling

SolidWorks is widely used for modelling mechanical systems, including robotic arms, as it is a powerful computer-aided design (CAD) software. The conceptual design phase involves defining the robotic arm's structure, links and joints, considering factors like payload capacity and workspace. In SolidWorks, individual links and joints are designed, considering material properties and structural strength. Kinematic constraints are added to replicate real-world limitations. Joint angles and lengths are determined using inverse kinematics. Once optimized, the design is documented for manufacturing. Iterative improvements are made based on results and feedback, resulting in a well-designed robotic arm ready for MATLAB control system development and real-world implementation.

Simulation and Validation

This research involves the simulation and validation of a robotic arm using integrated SolidWorks-MATLAB techniques. The robotic arm's 3D model is designed in SolidWorks and imported into MATLAB for dynamic analysis. Various tasks, including pick-and-place operations and pattern drawing, are simulated to evaluate accuracy, repeatability and response time. Performance metrics, such as position errors and settling time, are measured and compared against design specifications. Practical validation is achieved using a physical robotic arm with sensors and encoders, comparing experimental results with simulations. Iterative improvements are made based on the outcomes, ensuring an accurate, efficient and reliable robotic arm for real-world applications.

This section outlines the process of modelling a robotic arm, starting with its design in SolidWorks to ensure it meets the specified design requirements. Subsequently, the SolidWorks model is imported into MATLAB, where it becomes accessible for simulation purposes using the Robotics Toolbox.

rol signals. Consequently, it effectively manages the fourth joint of the robotic arm.

1.1 The MATLAB Simulink block diagram to Control our 4-dof robot

The Simulink block diagram in MATLAB for controlling our 4-DOF robot is depicted in Figure 5.20 below.

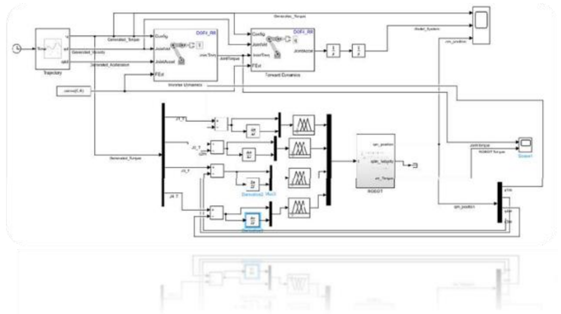

Figure 5.32 The Simulink block diagram in MATLAB for controlling our 4-DOF robot

As originally designed, the trajectory generator produced signals representing the joint angles for our 4-DOF robot. These signals were then directed to the inverse dynamics block and subsequently to the forward dynamics block to trace the intended trajectory. Figure xxx illustrates this process. However, when the same trajectory was applied to the physically modelled robot system, it failed to replicate the trajectory displayed in the scope by the tracking model.

To address this discrepancy, we underwent a tuning process and trained the dynamic model using a fuzzy controller. This controller takes the generated torque as input and calculates the error by subtracting the measured positions (feedback) from the desired trajectory as the first input and the derivative of the error change as the second input. The fuzzy controller then determines the consequences (output) for the path navigation.

It is worth noting that this model or system is versatile and can be applied to other introduced tracking models, whether we choose to track using Kinematics, Velocity, or Torques.

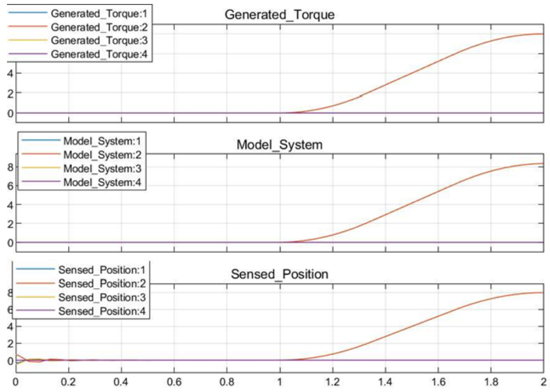

Figure 5.33 Simulation Result with Fuzzy logic Controller

The figure above displays the robot's trajectory with desired reference trajectories. The simulation results serve as a testament to the efficacy of the proposed algorithm, affirming its capability to achieve accurate tracking outcomes.

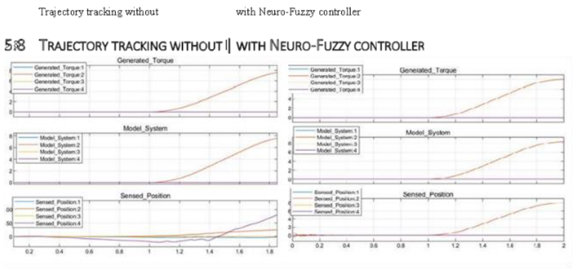

Figure 5.34 Trajectory Tracking Without Controller Vs Tracking with Neuro-Fuzzy Controller

The initial graph provides a visual representation of the response of a physical robot when subjected to predefined trajectories. In contrast, the second graph vividly illustrates the improved trajectory tracking achieved by the robot, thanks to the implementation of the neuro- fuzzy controller.

CONCLUSIONS | RECOMMENDATIONS AND FUTURE WORKS

Summary

A trajectory tracking system has been developed and simulated for a 4-DOF robot, with the simulation results demonstrating the enhanced precision in trajectory tracking achieved through the utilization of fuzzy logic controllers.

Discussion

This thesis has explored the trajectory tracking of a 4-DOF robot using a neuro-fuzzy controller. The controller was employed to acquire knowledge within a Fuzzy Inference System (FIS) and to iteratively adjust various parameters, including membership functions and fuzzy rules, using training dataset values obtained from a tuned PID controller designed with an H- infinity approach. The current controller effectively learned and developed the necessary information to enable the robot to accurately track a desired trajectory.

Numerous simulation experiments were conducted to display the trajectory controller's capabilities. The neuro-fuzzy controller facilitates the tracking of predefined reference trajectories. When we compare the results displayed in figure 5.34, it becomes evident that certain physical disturbances affecting the robot, such as (wear and tear, gravity variations, obstacles, external forces, etc), necessitate the use of a controller to manage these disturbances. The proposed adaptive neuro-fuzzy controller proves adaptable to various predefined reference trajectories and exhibits robust performance, akin to other conventional controllers.

While this dissertation has demonstrated the capability to track a predefined robot trajectory successfully, it's important to highlight a limitation. In real-time trajectory tracking, the neuro- fuzzy controller exhibits a significant drawback it struggles to track trajectories it hasn't been specifically trained for. To enhance the efficiency of fuzzy logic in robot systems, it is advisable to utilize it primarily for assessing linguistic parameters related to a particular robot design. This assessment can be conducted in conjunction with a robust controller that possesses the ability to track trajectories in real-time. Controllers such as computed torque or adaptive controllers are better suited for this purpose, ensuring more versatile and adaptable performance in dynamic environments.

Contributions

This dissertation presents an innovative trajectory tracking control approach designed to enhance the performance of trajectory tracking in robots. This advanced method leverages the Neuro-Fuzzy controller System, highlighting its efficacy in significantly improving the accuracy of trajectory tracking. This innovation holds great promise in the field of mobile robotics, offering a more precise and adaptable approach to path following.

Moreover, the research also demonstrates the robustness of the proposed neuro-fuzzy controller in the face of physical disturbances. These disturbances are a common challenge encountered in real-world applications. The controller's adaptability to various predefined reference trajectories, even in the presence of disruptive factors, underscores its practical relevance. This robustness is a critical attribute for ensuring the dependable operation of mobile robots in dynamic and unpredictable environments.

Significance

This dissertation carries substantial significance within the realm of advancing autonomous systems, primarily by empowering robots to function with heightened efficacy within intricate and ever-changing environments. It markedly curtails the necessity for human intervention across an array of applications. By enhancing a robot's capacity to independently navigate complex scenarios, it not only bolsters efficiency but also augments safety and resource utilization in sectors such as manufacturing, healthcare and exploration.

Furthermore, this research marks a pivotal shift in the trajectory tracking domain, ushering in a novel paradigm defined by the integration of neuro-fuzzy-based control. This transformative approach offers a heightened degree of adaptability and versatility when juxtaposed with traditional control methods. This paradigm shift holds the potential to spearhead a wave of innovations and breakthroughs in the trajectory tracking field, potentially revolutionizing how robots and autonomous systems interact with and adapt to their surroundings.

Future Work

In the context of future research, several promising avenues emerge from the findings and achievements of this study:

- Further research could explore deeper integration of machine learning techniques to enhance the neuro-fuzzy controller's adaptive capabilities and improve its performance in dynamic environments.

- Investigate methods to improve the neuro-fuzzy controller's ability to track unforeseen trajectories in real-time scenarios.
- Consider integrating fuzzy logic to evaluate linguistic parameters specific to individual robot designs while coupling it with a real-time tracking controller for enhanced performance.
- Assess the suitability of alternative controllers such as computed torque or adaptive controllers for real-time trajectory tracking in various robot systems
- Extending the research to real-world robotic platforms and conducting experiments in diverse, unstructured environments would provide valuable insights into the practicality and robustness of the proposed control system.
- Exploring optimization algorithms to fine-tune Neuro-Fuzzy Controller parameters for even better trajectory tracking performance and faster learning.
- Assessing the adaptability and performance of the neuro-fuzzy-based controller on several types of robots beyond the 4-DOF manipulator studied in this dissertation.

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