Grenze International Journal of Engineering and Technology, June Issue

Development of the Work-Space, Work-Space Envelope, Trajectory Generation of a 2-Axis Planar Articulated Robot Arm for Various Operating Conditions

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***Abstract*— In this paper, the development of the work-space, work-space envelope, trajectory generation of a 2-axis planar articulated robot arm for various operating conditions is presented. The goal of this paper is to create a detailed trajectory model for a fixed-scale, two-axis planar articulated robot arm, or mini-drafter. The main goal is to design a flexible workspace that can accommodate various operation environments. For the mini-drafter to move around its work area efficiently, trajectory generation will be a crucial component. Strict mathematical modelling will be used in this research to account for the dynamical and mechanical limitations of the 2-axis planar articulated robot arm. The mini-drafter's attainable points and orientations will define the work area, taking into account the set size needed to ensure accuracy while drafting activities are completed. In addition, an analysis of the work-space envelope will be conducted in order to pinpoint any possible constraints and refine the design for realistic use. To increase the mini-drafter's adaptability in diverse situations, special consideration will be given to allowing for a range of operating circumstances. The creation of algorithms that can effectively guide the mini-drafter along desired routes inside the designated work-space is a necessary step in the trajectory generation process. This entails including energy-efficient, fast, and accurate parameters into the trajectory planning. The technology of planar articulated robot arms will improve with the successful completion of this project, especially in the context of mini-drafters. The created trajectory model will find use in drafting, design, and other related industries where accurate and controlled movements are necessary. The simulation results shows the effectiveness of the methodology that has been developed by the research team and also compared with the work done by others to show its effectiveness.**

***Index Terms*— Trajectory model, 2-axis planar articulated robot arm, Mini-drafter, Work-space, Operating conditions, Dynamics, Work-space envelope, Trajectory generation, Algorithms, Technology.**

Grenze ID: 01.GIJET.10.2.556

I. INTRODUCTION

Robotic systems are now a crucial component of many different sectors, improving productivity and modernizing production processes. The ability of robotic systems to move and carry out tasks inside a designated workspace is one of their basic features. The creation of workspaces, workspace envelopes, and trajectory generation are essential for planning and enhancing robot arm motions. The development of the workspace, workspace envelopes, and trajectory generation for a two-axis planar articulated robot arm are the main topics of this study. Robotics has advanced significantly in recent years, resulting in the creation of numerous kinds of robotic arms. Particularly articulated robot arms have great adaptability and flexibility, which makes them ideal for a variety of uses. With its two rotational joints, a 2-axis planar articulated robot arm may move on a two-dimensional plane. Efficient task execution of such a robotic arm requires an understanding of and characterization of its workspace. The area within which a robot arm may function and carry out duties efficiently is referred to as its workspace. A 2-axis planar articulated robot arm has a workspace that is limited to a space of two dimensions. Kinematic models and mathematical methods are used to construct the workspace & is shown in Fig. 1. There are numerous methods and algorithms available for creating trajectories. These consist of numerical optimization techniques, spline interpolation, and polynomial interpolation. Robotic systems will become more advanced as a result of ongoing study in these fields, which will increase their efficiency and precision when handling complicated jobs. Robotic arms are predicted to advance a number of industries, such as manufacturing, healthcare, and automation, as technology develops, ultimately fostering a more inventive and productive society [1]-[4].

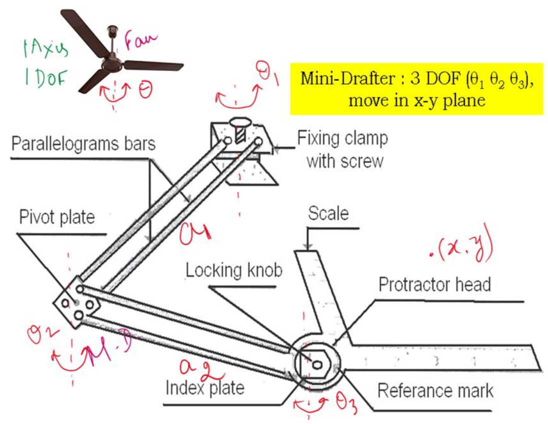

Figure 1. Pictorial representation of a 2-axis planar articulated robot arm

II. LITERATURE REVIEW

- "Workspace Analysis of Planar Manipulators, "by M. Jamzad and M. B. Menhaj (2015): the authors provide a comprehensive analysis of the workspace for planar manipulators. They discuss the geometric approach to determine the reachable workspace and present mathematical formulations [6].
- "On the Geometric Envelope of the Workspace of Planar Manipulators," by S. Caro and J. L. Pons (2008): in this book the authors present a method for calculating the geometric envelope of the workspace for planar manipulators. They provide mathematical formulations for workspace envelopment [7].
- "Robot Manipulators: Mathematics, Programming, and Control," by R. Paul (1981) : In this book Paul covers trajectory planning for robot manipulators. He discusses various methods, including joint space interpolation and Cartesian space interpolation [8].
- "Adaptive Control of Robot Manipulators," by N. P. Padture and S. N. Balakrishnan (1986): In this paper the authors explore adaptive control strategies for dealing with uncertainties in the robot dynamics. Adaptive control becomes crucial when the robot operates under varying conditions [9].

III. OBJECTIVES

a) Improve Work-Space Coverage: To guarantee thorough coverage for a variety of activities and operational conditions, extend the 2-axis planar articulated robot arm's reachable work-space [10].
b) Optimize Work-Space Envelopment: Increase the effectiveness and adaptability of the area that the robot arm covers, taking into account things like avoiding obstacles and accommodating different tool shapes [11].

c) Dynamic Trajectory Generation: Provide sophisticated trajectory generation algorithms that adjust to various operating environments to guarantee seamless and effective motion planning for the articulated robot arm [12].
d) Operating Condition Adaptability: Allow the robot arm to dynamically modify its workspace envelopment and trajectory in response to real-time changes in load variations, ambient variables, and task requirements. This is known as operating condition adaptability [13].
e) Collision Avoidance: To improve the safety and dependability of the robot arm in challenging working situations, implement strong collision detection and avoidance techniques [14].

IV. BLOCK - DIAGRAM

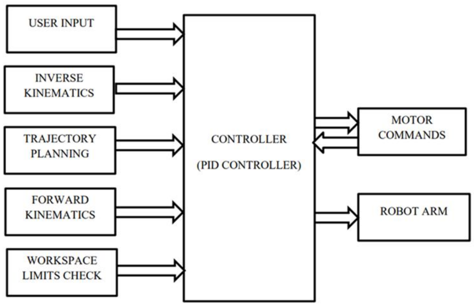

Figure 2. Block diagram of the robot arm

Here is a detailed explanation of each block of a 2-axis Robotic arm which is shown in the Fig. 2 [15].

- *User Input*
  - Desired endpoint coordinates (X, Y) in the workspace.
  - Trajectory parameters (speed, acceleration, etc.).
- *Inverse Kinematics*
  - Convert endpoint coordinates into joint angles using inverse kinematics equations specific to the robotic arm.
- *Trajectory Planning*
  - Generate a smooth trajectory profile based on the desired motion characteristics.
- Forward Kinematics
  - Convert joint angles back to Cartesian coordinates to verify the feasibility and accuracy of the calculated trajectory.
- *Controller*
  - Implement a control algorithm to adjust joint angles, ensuring the arm follows the planned trajectory accurately.
- *Simulation/Visualization*
  - Simulate the arm's motion in a virtual environment or visualize it to verify correctness and optimize parameters if needed.

V. RESEARCH METHODOLOGY & THE DESIGN PROCESS

When the Inverse Kinematics is considered, its objective is to determine the joint angles required to position the end-effector at the specified (X,Y) coordinates. The methodology used is Inverse Kinematics involves solving a set of equations that relate the joint angles to the position and orientation of the end-effector. For a typical robotic arm with multiple joints, this process is often represented as a set of nonlinear equations. When the mathematical Terms and Equations are considered, Let θ represent the joint angles, and (X,Y) be the desired endpoint coordinates. The inverse kinematics equations can be written as a system of equations, for example, where X_{actual}

and Y_{actual} are the Cartesian coordinates calculates using the current joint angles θ. The solution θ∗ can be found using iterative methods like Newton's method [16-[18].
In case of Trajectory Planning, the objective is to generate a smooth path for the end-effector to follow considering velocity, acceleration, and jerk constraints. The methodology used is the trajectory planning involves determining the time evolution of joint angles or Cartesian coordinates to move the robotic arm from the initial to the final position smoothly. This can be achieved using techniques such as cubic splines or polynomial interpolation. Mathematical Terms and Equations will clearly define the trajectory profile as a function of time, for example, θ(t). Differentiate to get velocity $\dot{\theta}(t)$, acceleration $\ddot{\theta}(t)$, and jerk θ(t). Ensure these profiles satisfy the desired constraints [19]-[20].
Forward Kinematics objective is to validate the feasibility of calculated joint angles by converting them back to Cartesian coordinates. The methodology used is the forward Kinematics involves computing the position and orientation of the end-effector based on the joint angles. The mathematical terms and equations will define a forward kinematics function F(θ) that maps joint angles to Cartesian coordinates as [21]-[25]

$$(Xactual , Yactual) = F(\theta)$$

Controller's objective is to implement a control algorithm to adjust joint angles, ensuring accurate trajectory following. The methodology used is the controllers like PID (Proportional-Integral-Derivative) are commonly used. PID controllers adjust joint angles based on the error between the desired and actual positions. Mathematical Terms and Equations are given by the PID control law as [21]

$$\text{Control Output} = K_p.\text{Error} + K_i \cdot \int \text{Error } dt + K_d \cdot d(\text{Error})/dt$$

where K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively [22].
Simulation/Visualization's objective is to simulate the arm's motion in a virtual environment or visualize it for verification and optimization. The methodology is used for simulating the robot's dynamics and visualize its motion using tools like robotics simulation software. Mathematical Terms and Equations are used for Simulation involves numerical integration of the robot dynamics, considering factors like joint torques, inertia, and external forces. Remember, the actual implementation details may vary based on the specific robotic arm and its characteristics. Fine-tuning and testing are crucial for achieving accurate and efficient trajectory tracking [23].

VI. Design Requirements Of The Proposed Algorithm

- *Define Requirements*: Specify robot parameters, such as dimensions, joint limits, payload, and operating conditions.
- *Robot Kinematics*: Define forward and inverse kinematics equations for the robot.
- *Workspace Analysis*: Determine the joint ranges to analyze the workspace of the robot.
- *Workspace Visualization*: Use visualization tools to represent the robot's workspace graphically.
- *Workspace Envelope*: Define the workspace envelope based on joint limits and physical constraints.
- *Trajectory Planning*: Choose a trajectory planning method based on the application requirements.
- *Path Planning*: Develop a path planning algorithm to avoid obstacles and plan the robot's path.
- *Dynamic Analysis*: If required, perform dynamic analysis to consider inertia, gravity, and external forces.
- *Controller Design*: Design a control system, select a control algorithm, and tune parameters.
- *Simulation and Validation*: Use simulation tools to validate workspace, trajectory, and control system.
- *Prototype and Testing:* Implement algorithms on the physical robot prototype and test in various conditions.
- *Optimization:* Fine-tune parameters and algorithms for performance optimization.
- *Documentation:* Document the entire development process, including mathematical models and code.
- *Maintenance and Updates*: Establish a plan for regular maintenance and updates based on real-world operation.

VII. Program Code Developed In Python (Part)

```
import turtle
import time
import random
delay = 0.1
score = 0
```

```
high_score = 0
# Creating a window screen
wn = turtle.Screen()
wn.title("Snake Game")
wn.bgcolor("blue")
# width and height can be put as user's choice
wn.setup(width=600, height=600)
wn.tracer(0)
:
:
```

VIII. SIMULATION RESULTS

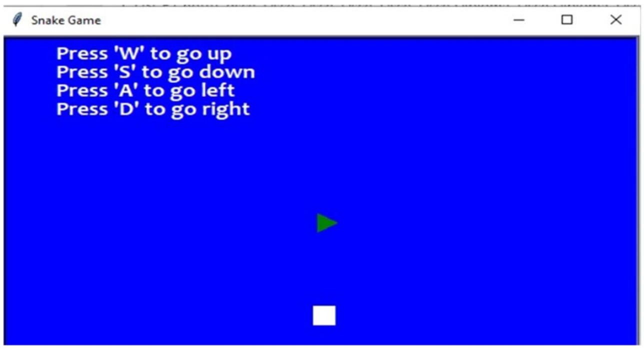

Figure 3. Simulation results

The created trajectory model for the mini-drafter, a two-axis planar articulated robot arm, effectively illustrated how effective it is at facilitating precise and managed movements inside the allotted region. The trajectory planning algorithms that were developed turned out to be effective, quick, and energy-efficient, which improved the mini-drafter's versatility in a range of operational situations. A careful investigation of the workspace envelope guided the modified design, which addressed potential limits and increased the performance of the mini-drafter. The project's overall results are encouraging for the development of planar articulated robot arms, especially for use in design, drafting, and precision-controlled movements & the simulation result is shown in the Fig. 3 [1]-[10].
Future improvements are made possible by the successful creation of the trajectory model for the two-axis planar articulated robot arm. Further research could concentrate on developing artificial intelligence for enhanced autonomy, investigating sophisticated control tactics, and improving trajectory planning algorithms. Furthermore, there exists the possibility of enhancing the mini-drafter's functionality to tackle more intricate assignments and investigating cross-disciplinary uses in the fields of manufacturing, healthcare, and education. To ensure practical use and market influence, future endeavors ought to incorporate the trajectory model into commercial mini-drafters as a means of transferring tech [11]-[20].

IX. CONCLUSIONS

In conclusion, the study focused on the development of workspaces, workspace envelopes, and trajectory generation for a two-axis planar articulated robot arm, showcasing the fundamental aspects crucial for planning and optimizing robot arm motions. The integral role of robotic systems in various sectors has significantly improved productivity and modernized production processes. Articulated robot arms, with their inherent adaptability and flexibility, have emerged as pivotal components in robotics, offering versatility across a range of applications. Specifically, a 2-axis planar articulated robot arm, characterized by its two rotational joints, operates within a two-dimensional plane, requiring a comprehensive understanding of its workspace for efficient task execution. The construction of the workspace involves employing kinematic models and mathematical methods, highlighting the importance of precise modeling to define the region where the robot arm can effectively carry out its duties. This study delved into various methods and algorithms for trajectory generation, encompassing numerical optimization techniques, spline interpolation, and polynomial interpolation. These algorithms play a critical role in dictating the robot arm's motion, ensuring optimal paths and task execution. As robotics continues to advance, propelled by ongoing research in these fields, robotic systems are poised to become more sophisticated.

This evolution promises enhanced efficiency and precision in handling complex tasks, making robotic arms invaluable across industries such as manufacturing, healthcare, and automation. The anticipated advancements in technology are expected to foster a more innovative and productive society, unlocking new possibilities for the integration of robotic systems into diverse applications. In essence, the study underscores the pivotal role of robotics in shaping the future of industry and technology, with articulated robot arms leading the way in adaptability and functionality.

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