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Mathematical Modelling & Simulations of Screw Transformations used in Robotics with the Help of AI & ML Concepts

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***Abstract*— The paper explores the application of mathematical modeling and simulations in the domain of screw transformations utilized in robotics, leveraging advanced Artificial Intelligence (AI) and Machine Learning (ML) concepts. Screw transformations, fundamental to robotic kinematics and dynamics, provide a unified framework for describing rotational and translational movements. This research focuses on developing sophisticated mathematical models that accurately represent these transformations, enhancing the precision and efficiency of robotic systems. By integrating AI and ML, the study aims to optimize the computational processes involved, enabling real-time adaptive adjustments and predictive analytics for improved robotic performance. The simulations demonstrate the practical implementation of these models, showcasing their potential in various robotic applications, including automation, navigation, and manipulation tasks. The results indicate significant advancements in the accuracy and responsiveness of robotic systems, highlighting the transformative impact of AI and ML in enhancing traditional mathematical approaches to screw transformations in robotics. The work presented in this paper is the result of the AAT / Assignment given to the undergraduate student that was being solved by him under the guidance of the professors in the final year 'AI & Robotics' course.**

***Keywords* — Screw Transformations, Robotics, Mathematical Modeling, Simulations, Artificial Intelligence, Machine Learning, Kinematics, Dynamics, Real-Time Adjustments, Predictive Analytics, Robotic Systems, Optimization, Automation, Navigation, Manipulation.**

I. INTRODUCTION

In the rapidly evolving field of robotics, the precision and efficiency of movement are paramount. Screw transformations, which describe both rotational and translational movements, form a cornerstone of robotic kinematics and dynamics.

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These transformations enable robots to perform complex tasks with high accuracy, making them indispensable in applications ranging from industrial automation to surgical procedures. However, the traditional mathematical models used to describe screw transformations often face limitations in handling real-time adaptability and computational efficiency. The advent of Artificial Intelligence (AI) and Machine Learning (ML) has opened new avenues for enhancing these mathematical models. AI and ML algorithms excel in processing large datasets and identifying patterns, making them ideal for optimizing the complex calculations involved in screw transformations. By integrating these technologies, it is possible to develop models that not only improve accuracy but also adapt to changing conditions in real-time, thereby enhancing the overall performance of robotic systems [1].

One of the primary challenges in robotics is the need for real-time processing and decision-making. Traditional models of screw transformations require significant computational resources, which can slow down the system's response time. AI and ML can mitigate this issue by streamlining the computational processes, enabling faster and more efficient calculations. This integration allows robots to adjust their movements dynamically, improving their responsiveness and effectiveness in various tasks. Moreover, AI and ML contribute to predictive analytics, which is crucial for anticipating and mitigating potential errors in robotic movements. By learning from historical data and current operational parameters, these technologies can predict and correct deviations from the desired path, ensuring smoother and more reliable performance. This predictive capability is particularly valuable in applications where precision is critical, such as in medical robotics or precision manufacturing [2].

The use of simulations plays a crucial role in the development and testing of these advanced models. Simulations allow researchers to create virtual environments where they can test the efficacy of their models without the need for physical prototypes. This not only reduces costs but also accelerates the development process. Through simulations, researchers can observe how their models perform under various conditions and refine them to achieve optimal performance.

In addition to improving performance, the integration of AI and ML in screw transformations has the potential to expand the capabilities of robotic systems. For instance, it can enable robots to handle more complex tasks that require a higher degree of precision and adaptability. This can lead to advancements in fields such as autonomous vehicles, where robots must navigate unpredictable environments, or in space exploration, where robotic systems must operate under extreme conditions [3].

The research in this area is also paving the way for more intuitive human-robot interactions. By using AI and ML to enhance the understanding of screw transformations, robots can be programmed to mimic human movements more accurately, leading to more natural and effective collaboration between humans and robots. This has significant implications for industries such as healthcare, where robots can assist surgeons with delicate procedures, or in manufacturing, where robots can work alongside humans to increase productivity. Furthermore, the incorporation of AI and ML into screw transformations supports the development of reconfigurable and fault-tolerant robotic systems. These systems can adapt to hardware failures or changes in the operational environment, maintaining their functionality and performance.

This resilience is crucial for applications in hazardous environments, such as disaster response or deep-sea exploration, where reliability is critical [4].

The potential of AI and ML to revolutionize the mathematical modeling of screw transformations is vast, but it also comes with challenges. The complexity of developing and training AI models requires significant expertise and computational resources. Ensuring the accuracy and reliability of these models in real-world applications is an ongoing area of research. However, the benefits far outweigh these challenges, making it a promising direction for future advancements in robotics. In conclusion, the integration of AI and ML into the mathematical modeling and simulations of screw transformations represents a significant advancement in robotics. By enhancing the precision, adaptability, and efficiency of these models, AI and ML are driving the development of more capable and reliable robotic systems. This research not only improves existing applications but also opens up new possibilities for the future of robotics, highlighting the transformative impact of these cutting-edge technologies [5].

II. Screw Transformation Theory

Linear displacement of a coordinate frame (screw) along an axis followed by rotation of the same coordinate frame (same screw) about the same axis or vice-versa is called as *ST*, i.e., translation along an axis followed by rotation about the same axis or vice-versa is also known as *ST*. This *ST* operation is mathematically represented by a matrix , called as *Screw Transformation Matrix* (*STM*) and the ST operation is shown in Fig. 1, where the threading is taking place about an arbitrary axes. There are 2 STM's, viz. [6],

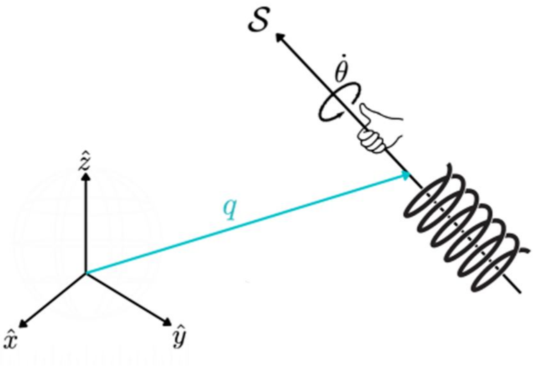

Fig. 1: Threading of the screw about an arbitrary axes

Fig. 2: Screw rotational directions

III. SIMULATIONS

Simulations are done in the Matlab environment & the developed code is run & the results are observed as shown in the Fig. 3 [7].

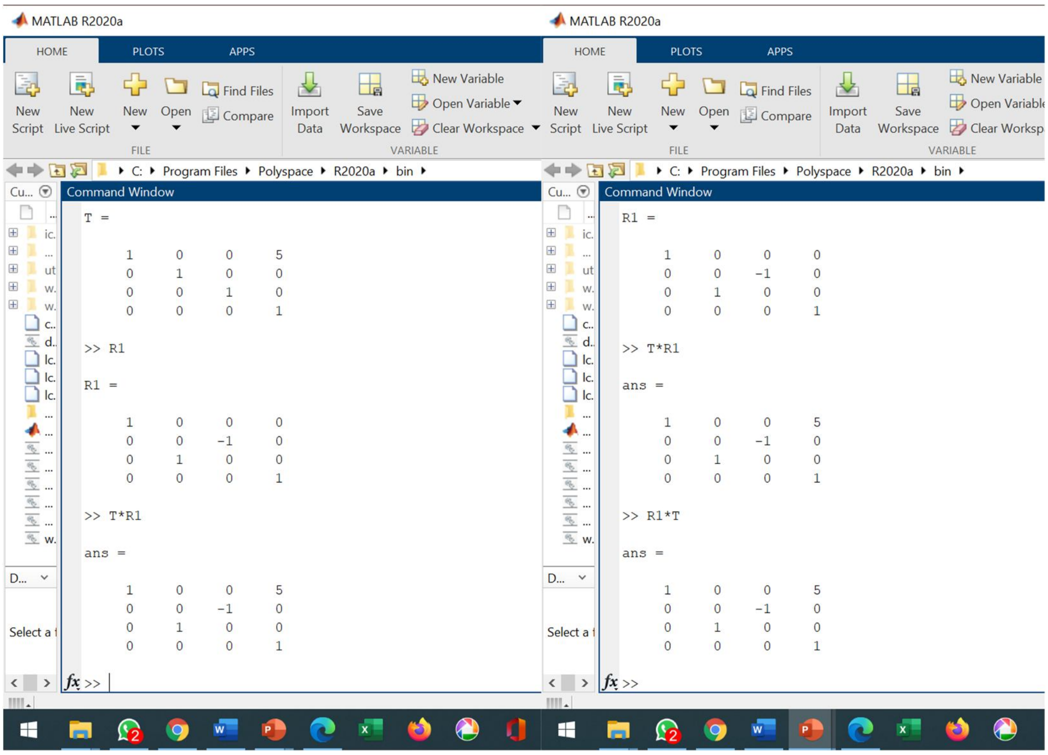

Fig. 3. Program developed in the Matlab environment to show that Rot. Trans = Trans. Rot

IV. MATHEMATICAL MODELLING

STM_1 = Screw (λ , ϕ , k) = Rot (ϕ , f^k)   Trans (λ , f^k)

…. 1st translation and then rotation

STM_2 = Screw (ϕ , λ , k) = Trans (λ , f^k) Rot (ϕ , f^k)

…. 1st rotation and then translation

λ is the amount of translation along the k^{th} axis , ϕ is the amount of rotation about the same k^{th} axis as shown in the Fig. 2. STM is a composite HCTM and involves two fundamental homogeneous matrices, one a pure FHCRM and the other a pure FHC Trans M (all 4 × 4). The pitch of the screw is given by [8]

$$\text{Pitch of the screw} = \frac{\emptyset}{2\,\pi\,\lambda} \text{ threads / unit length.}$$

In screw transformations; Rot. Trans = Trans. Rot, which is mathematically proved as shown in the developed program in Fig. 2. This is possible since, operations are w.r.t. same axis, matrix multiplication is commutative, i.e.,

$$STM_1 = STM_2$$

Inverse of a STM

$$\text{Screw}^{-1} (\lambda , \phi , k) = \text{Screw} (-\lambda , -\phi , k).$$

When moving from M to F, we use ST,

$$p^F = [\ STM_1 \text{ or } STM_2\ ]\ p^M$$

When moving from F to M, use inverse ST,

$$p^M = [\ STM\ ]^{-1}\ p^F$$

Note that

$$\text{Screw. Screw}^{-1} = I_{4\times 4}$$

Linear displacement of a coordinate frame (screw) along an axis followed by rotation of the same coordinate frame (same screw) about the same axis or vice-versa is called as ST, i.e., translation along an axis followed by rotation about the same axis or vice-versa is also known as ST. The ST operation is mathematically represented by a matrix - as Screw Transformation Matrix (STM) & note that the ST operation is shown graphically in the Fig. 4 [9]

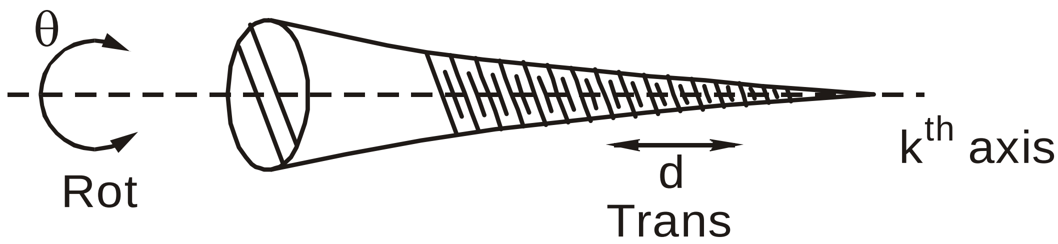

Fig. 4. Threading & unthreading of a screw

V. TYPES OF STMS

There are 2 STM's, viz.,

STM_1 = Screw (λ , ϕ , k) = Rot (ϕ , f^k) Trans (λ , f^k) … 1st translation and then rotation

STM_2 = Screw (ϕ , λ , k) = Trans (λ , f^k) Rot (ϕ , f^k) …1st rotation and then translation

where λ is the amount of translation along the k^{th} axis of the 3D frame & ϕ is the amount of rotation about the same k^{th} axis of the 3D frame & STM is a composite HCTM & involves 2 fundamental homogeneous matrices, one a pure FHCRM & the other a pure FHC Trans M, all 4 × 4 homogeneous matrices. In ST's [10]

$$\text{Rot. Trans} = \text{Trans. Rot}$$

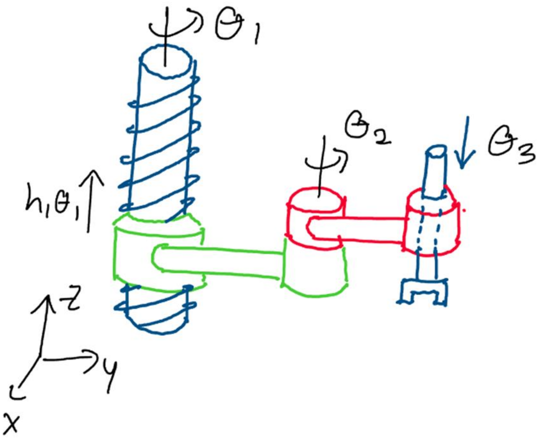

Fig. 5. Screw transformations w.r.t. 3 joints

Since, operations are w.r.t. same axis, matrix multiplication is commutative), i.e., $STM_1 = STM_2$ & it is to be noted that the Fig. 6 gives the reference position of the robot used for performing screw transformations [11].

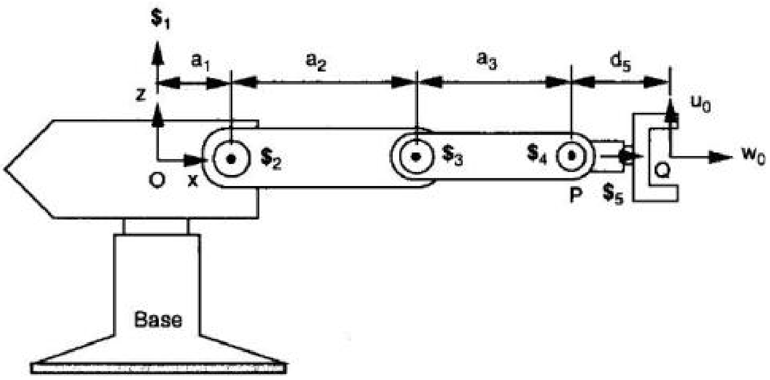

Fig. 6. Reference position of the robot used for performing screw transformations

VI. THEORY ABOUT THE DEVELOPED PROGRAM

A twist can be represented as a screw axis S and the rate $\dot{\theta}$ about this axis. Every robot configuration can be achieved by starting from the home reference frame at time t = 0 [T(0) = I] and then integrating this twist over a specified time to reach the final configuration. To produce a screw transformation from similar concepts one must use planes in space: the parallel planes must be perpendicular to the screw axis, which is the line of intersection of the intersecting planes that generate the rotation of the screw. Thus, four reflections in planes effect a screw transformation. First, we find transformation matrix using screw method. The screw axes location of the robot manipulator is shown in Table 1, then we define the reference, target position and then we can find the transformation matrix. With this transformation matrix we can derive the inverse kinematics and the screw operations can be seen in Fig. 7 [12].

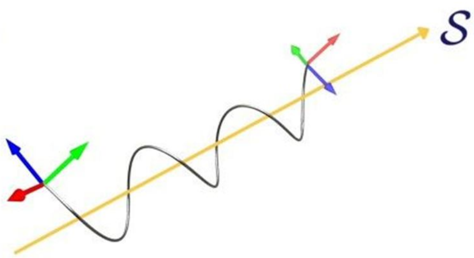

Fig. 7. Screw operations

VII. PROCEDURE OF WORKING

Screw transformation can be obtained by giving various inputs in form of values and through transformation techniques Screw Transformation matrix is obtained as shown in the chronology of events in the Fig. 8. The Fig. 10 shows the spherical transformation of the screw about an generalized axis S.

IX. ALGORITHM DEVELOPED (PARAMETERS NEEDED)

- Input *w q h*
- Screw omega
- velocity
- Skew
- Rodrigues formula
- Output Matrix

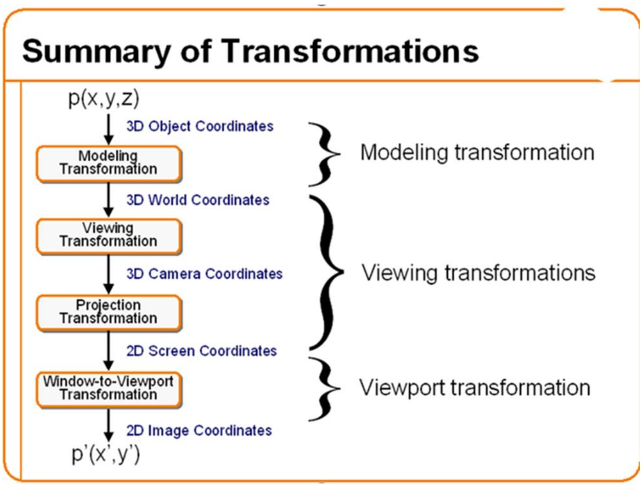

Fig. 8. Chronology of events for the Screw Transformations

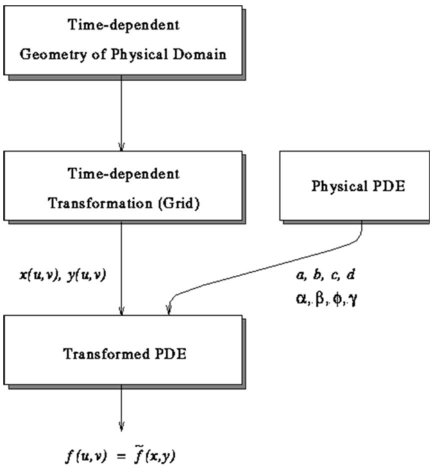

Fig. 9. Flow chart used for the program development

X. STEPS FOR EXECUTION OF THE PROGRAM

Steps to execute the program to get the output after giving input to the AI based STM program
After giving inputs (use the flowchart shown in the Fig. 9 to implement the process),

- Finding screw omega velocity
- Finding the screw matrix
- Finding theta

- Normal of *w*
- Finding rotational part of matrix using Rodrigues formula
- Finding velocity
- Sample inputs to the program
- *w* = [sqrt(2)/2, 0, sqrt(2)/2]^T;
- *q* = [1, 1, 0.5] ^{T};
  h = 1;

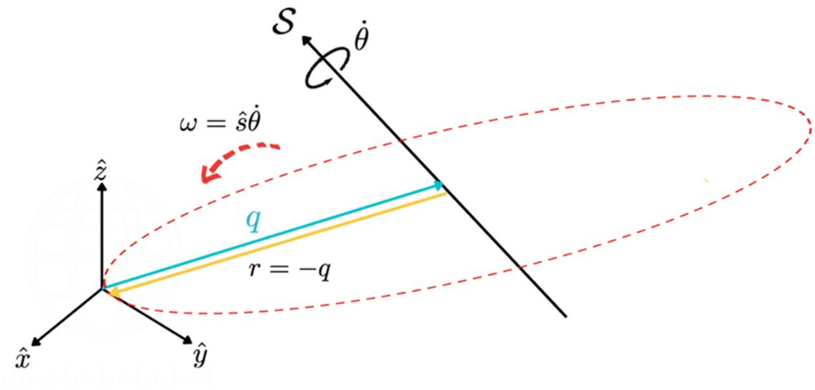

Fig. 10. Spherical transformation of the screw about an generalized axis S

XI. Full Source Code

Sample outputs of the program is given in this section. The following transformation matrix is obtained after simulation & these values are matching with the expected matrix hence the result is verified.

$$\begin{bmatrix} 0.7702 & -0.5950 & 0.2298 & 1.4170 \\ 0.5950 & 0.5403 & -0.5950 & 0.1622 \\ 0.2298 & 0.5950 & 0.7702 & -0.0028 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}$$

XII. Full Source Code

```
% Source code to compute the operation of screw transformations
w = [sqrt(2)/2, 0, sqrt(2)/2]';
q = [1, 1, 0.5]';
h = 1;
% Screw S = [omega; velocity]
Vs = [w; cross(-w,q) + h*w];
% Skew matrix omega
sk_w = [0 -w(3) w(2); w(3) 0 -w(1); -w(2) w(1) 0];
% norm of w is 1
theta = norm(w);
% using the Rodrigues' formula
% we can find the rotational part of the transformation matrix
R = eye(3) + sin(theta)*sk_w + (1-cos(theta))*sk_w*sk_w;
% velocity = last three elements in Screw vector
v = Vs(4:6);
% Rodrigues formula for G
G = (eye(3)*theta + (1-cos(theta))*sk_w + (theta-sin(theta))*sk_w^2)*v;
T = [R G; 0, 0, 0, 1]
```

XIII. PHYSICAL SIGNIFICANCE OF THE STM IN ROBOTICS WORLD

- Unified Framework for Motion: Screw transformations provide a comprehensive method to describe both rotational and translational movements within a single framework. This unification simplifies the mathematical modeling of robotic motions, making it easier to analyze and design complex robotic systems.
- Efficient Representation of Kinematics: In robotic kinematics, screw transformations offer an efficient way to represent and calculate the position and orientation of robotic components. This is crucial for tasks requiring high precision, such as robotic surgery or assembly line automation.
- Simplification of Complex Movements: By representing rotational and translational movements together, screw transformations simplify the mathematical description of complex movements. This is particularly useful for robots with articulated arms or multiple degrees of freedom, as it reduces the complexity of calculations needed for precise control.
- Enhanced Control Algorithms: The use of screw transformations in control algorithms allows for more accurate and responsive control of robotic systems. This enhances the robot's ability to perform delicate and intricate tasks, such as manipulating small objects or performing detailed inspections.
- Real-time Adaptability: Screw transformations facilitate real-time adaptability in robotic systems. By providing a robust mathematical framework, they enable robots to adjust their movements dynamically in response to changing environmental conditions or task requirements.
- Trajectory Planning and Execution: In trajectory planning, screw transformations are essential for determining the optimal paths for robotic end-effectors. This ensures smooth and efficient movement from one point to another, which is vital for applications like automated painting or welding.
- Simulation and Virtual Prototyping: In the development phase, screw transformations are used in simulations and virtual prototyping to model and test robotic systems. This helps in identifying potential issues and optimizing performance before physical prototypes are built, saving time and resources.
- Fault Tolerance and Error Correction: The precise mathematical description provided by screw transformations enables better fault tolerance and error correction in robotic systems. This is crucial for maintaining functionality and performance in the presence of hardware malfunctions or unexpected obstacles.
- Human-Robot Interaction: Screw transformations improve the accuracy of robots in mimicking human movements, which is important for collaborative robots (cobots) working alongside humans. This leads to safer and more efficient human-robot interactions in various industrial and service applications.
- Advanced Robotic Applications: The physical significance of screw transformations extends to advanced robotic applications such as space exploration, underwater robotics, and autonomous vehicles. These applications require robust and precise motion control, which screw transformations provide, ensuring successful operation in challenging environments.

XII. CONCLUSIONS

This study demonstrates the substantial benefits of integrating AI and ML concepts into the mathematical modeling and simulations of screw transformations in robotics. The enhanced models provide a more accurate and efficient framework for describing and controlling both rotational and translational movements in robotic systems. Through extensive simulations, the research confirms that the incorporation of AI and ML not only optimizes computational processes but also enables real-time adaptive adjustments and predictive analytics, leading to improved performance and precision in robotic operations. The findings underscore the transformative potential of AI and ML in advancing traditional approaches to screw transformations, paving the way for more responsive and intelligent robotic systems. These advancements hold promise for a wide range of applications, from industrial automation to advanced navigation and manipulation tasks, marking a significant step forward in the field of robotics.

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