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Editorial

Applications of Fractional-Order Calculus in Robotics

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1. Introduction

Fractional calculus, a branch of mathematical analysis, extends traditional calculus that encompasses integrals and derivatives of non-integer orders. This concept provides a robust framework for modelling complex systems, particularly in physics, engineering, and biology, where traditional calculus may fall short of capturing certain behaviours. Unlike integer-order operations in traditional calculus, fractional calculus enables differentiation and integration of arbitrary orders, offering flexibility in describing diverse physical phenomena [1]. The origins of fractional calculus can be traced back to the late 17th century, following the development of classical calculus by Leibniz and Newton. The concept was introduced in a letter from L'H ôpital to Leibniz in 1695, inquiring about the meaning of a half-order derivative. Leibniz's response hinted at the possibility of such an operation, setting the stage for further exploration [2,3]. Despite early interest, fractional calculus remained primarily a theoretical curiosity for over a century, exemplifying the depth and complexity of this mathematical concept. Significant advancements in the 19th century, led by mathematicians such as Liouville and Riemann, solidified the foundations of fractional calculus. Liouville formalized the concept by defining fractional integration and differentiation in terms of definite integrals, while Riemann expanded on these ideas through the Riemann-Liouville integral [4,5]. These pivotal works established a rigorous mathematical basis for fractional calculus, leading to its widespread applications across scientific disciplines today [6,7]. As a result, fractional calculus is now considered an essential mathematical tool, driving research and innovation in various fields [8–12].

The field of robotics has seen a revolutionary shift with the adoption of the fractional calculus framework, which has empowered researchers to develop more resilient and efficient control systems [13]. Conventional control methods often need help to address the intricacies and uncertainties present in robotic systems. Fractional calculus offers a refined approach to control and optimization thanks to its capacity to model systems with memory and hereditary properties [14]. This has led to substantial enhancements in robotics, particularly in motion planning, stability, and adaptive control. A significant advantage of fractional calculus in robotics is its ability to provide more precise descriptions of dynamic systems [15]. Robots frequently operate in environments with unforeseeable disturbances and fluctuating load conditions, where traditional integer-order models may fall short. However, fractional-order controllers deliver enhanced performance and reliability, such as fractional-order proportional integral derivative (FOPID) controllers [16,17]. They excel at managing system non-linearities and parameter variations, leading to smoother operations. Moreover, fractional calculus has ushered in progress in robotic path planning and trajectory optimization, enabling robots to manoeuvre more accurately through intricate and dynamic environments [18–20]. By integrating fractional-order models, researchers have developed algorithms that optimize paths more effectively, ensuring seamless transitions and reduced energy consumption. In conclusion, applying fractional calculus in robotics marks a

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significant leap forward, providing innovative solutions to persistent challenges and laying the groundwork for more advanced and autonomous robotic systems.

On this note, this Special Issue has captured the diversity of studies focusing on fractional calculus applications in various robotic systems. It contains nine articles and one review, which we will briefly describe in the next section. Please note that the purpose of this editorial is not to elaborate on each of the articles but rather to encourage the reader to explore them.

2. An Overview of Published Articles

Weidong Liu et al.'s article (contribution 1) introduces a fractional active disturbance rejection control scheme for remotely operated vehicles (ROVs). This scheme, which includes a double closed-loop fractional-order PID controller and model-assisted finite-time sliding-mode extended state observer, is more than just a theoretical concept. It has practical significance for ROV applications, as it demonstrates effective resistance to disturbances and independence from accurate model data, enabling high-precision tasks to be achieved despite disturbances and model uncertainties.

Likun Li et al.'s article (contribution 2) presents a novel approach to path planning for car-like mobile robots with suspension. Their fractional-order enhanced path planning method, which uses an improved ant colony optimization (ACO), is a unique solution. It aims to generate smooth and efficient paths in narrow and large-size scenes. It includes an accurate fractional-order-based kinematic modelling method and an improved ACO-based path planning method with dynamic angle constraints, adaptive pheromone adjustment, and fractional-order state-transfer models.

Bhukya Ramadevi et al. (contribution 3) propose a hybrid neural network model that has the potential to revolutionize wind power forecasting. Their model, which uses a long short-term memory model to forecast missing wind speed and direction data and a fractional-order neural network with a fractional arctan activation function to enhance wind power prediction, aims to improve wind power forecasting accuracy by addressing data gaps. The model has shown promising results in the field of wind power prediction.

Mohamed Naji Muftah et al.'s article (contribution 4) focused on enhancing the performance of a pneumatic positioning system by developing a control system based on fuzzy fractional-order proportional integral derivative controllers. The controllers were optimized using a particle swarm optimization algorithm, and real-time experimental results showed improved rapidity, stability, and precision compared to a fuzzy PID controller. The proposed control system effectively controlled a pneumatically actuated ball and beam system.

Banu Ataşlar-Ayyıldız (contribution 5) proposed a fractional-order proportional-tilt integral-derivative controller for a serial robotic manipulator. The controller was designed to achieve high-accuracy trajectory tracking and reduce the impact of disturbances and uncertainties. The controller parameters were optimized using a hybrid Gray Wolf and particle swarm optimization algorithm, demonstrating superior trajectory tracking and increased robustness compared to other controllers. Additionally, it showed reduced energy consumption, confirming its robustness and stability against continuous disturbances.

Xuan Liu et al.'s article (contribution 6) introduces a framework for implementing digital twins in industrial robots to facilitate real-time monitoring and performance optimization. This framework incorporates multi-domain modelling, behavioural matching, control optimization, and parameter updating. A fractional-order controller based on an enhanced particle swarm optimization algorithm improves the system's control performance. Experimental validation demonstrates substantial enhancements in time-domain performance, including reduced overshoot, decreased peak time, and improved settling time.

Dora Morar et al.'s article (contribution 7) introduces two controller design procedures for a mechatronic system. The first method formulates an optimization problem using linear matrix inequalities to determine closed-loop poles and address model uncertainties

using linear differential inclusions. The second method involves a cascade controller with an inner P controller and an outer fractional-order FO-ID controller. Both methods offer four degrees of freedom for each axis. The article includes a numerical example and a comparison of performance metrics for the positioning system.

The article by Timi Karner et al. (contribution 8) discusses the use of dielectric elastomer actuators in soft robotics, noting their viscoelastic behaviour. They derived a fully fractional generalized Maxwell model using the Laplace transform to capture this behaviour. Based on the experimental results, they utilized the Pattern Search global optimization procedure to determine the model's optimal parameters and number of branches. This model can be implemented to control dielectric elastomer actuators and applied to various viscoelastic materials in simulations.

Yixiao Ding et al.'s article (contribution 9) introduces a fractional-order impedance controller for robot manipulators. Unlike traditional models, this method employs fractional calculus to describe damping forces more accurately. A systematic tuning procedure is developed based on frequency design, and comparisons with integer-order controllers show the fractional-order controller's superior step response and anti-disturbance performance.

The tenth article by Kishore Bingi et al. (contribution 10) reviews state-of-the-art fractional-order modelling and control strategies for robotic manipulators. Robotic manipulators are crucial in various fields, especially where human access is limited or hazardous. These highly complex systems require effective modelling and robust controllers to handle uncertainties. The review paper presents comprehensive research on modelling and control, aiming to provide the control engineering community with a better understanding and up-to-date knowledge in this area. The paper includes a summary of around 95 related works, focusing on modelling, control strategies, and future research directions.

3. Conclusions

In conclusion, this special issue, "Applications of Fractional-Order Calculus in Robotics", has successfully highlighted fractional calculus's expansive and varied applications in enhancing robotic systems, demonstrating its critical role in modern robotics research and development. By incorporating fractional calculus into their methodologies, researchers have addressed complex problems with greater precision and efficiency, showcasing the versatility and robustness of this mathematical approach. The articles within this issue cover diverse topics, from improving control accuracy and optimizing path planning to enhancing system robustness against disturbances and uncertainties.

The nine articles and one comprehensive review article in this special issue encapsulate various innovative approaches and novel methodologies. These contributions push the boundaries of robotics, emphasizing theoretical advancements and practical implementations. Each article presents unique solutions to longstanding challenges in robotics, highlighting the potential of fractional calculus to revolutionize various aspects of robotic technology. In summary, this special issue collectively underscores the significant impact of fractional calculus in advancing robotic technology and encourages further exploration and development in this promising study area.

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List of Contributions

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