

## Editorial

# Editorial for Special Issue of Motion Planning and Advanced Control for Robotics

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Advancements in robotics are increasingly essential in addressing complex challenges associated with motion planning and control, particularly in environments that require physical interaction with various elements. The contributions presented in this editorial reflect the latest developments in path planning, machine learning, task planning, and robotic navigation, which are crucial for enhancing the efficiency, autonomy, and integration of robots in human environments.

As robotics technology evolves, the need for innovative solutions to trajectory and path planning becomes paramount. Achieving optimal motion in robotic applications entails designing sophisticated models that account for dynamic interactions, environmental uncertainties, and the intricate requirements of various tasks. For instance, several contributions explore the integration of advanced sensing and perception techniques to improve the reliability of navigation systems in both indoor and outdoor environments. These approaches utilize algorithms that combine object detection and human pose recognition, thereby enabling robots to adapt their movements based on real-time environmental data.

The interplay between perception and action in robotic systems is a key focus of recent research. Machine vision plays a vital role in environment classification and obstacle detection, allowing robots to navigate and interact effectively in real-world settings. The integration of visual data with advanced control methodologies is a recurring theme across multiple contributions. In particular, the use of hybrid trajectory tracking algorithms demonstrates how combining different control strategies can yield superior performance, especially in the presence of uncertainties and external disturbances.

Furthermore, the contributions highlight the importance of addressing the challenges posed by hyper-redundant manipulators and mobile robotic platforms. The application of novel control schemes, such as the Sliding Mode Higher-Order Extended State Observer, exemplifies how advanced methodologies can enhance the robustness and precision of robotic movements in complex scenarios. Additionally, the development of systems capable of dynamic disturbance rejection shows promise for improving overall system stability, thereby expanding the range of tasks robots can undertake autonomously.

This Special Issue aims to encompass these relevant topics, offering insights into how new technologies and methods can be harnessed to solve the critical problems of motion and interaction in robotics. By bridging areas such as mechanical engineering, computer science, and systems control, the contributions collectively emphasize the multidisciplinary nature of the field and the necessity for integrated solutions to meet the demands of challenges in modern robotics.

In the context of Industry 4.0, collaborative robots (cobots) have gained significant relevance, particularly in welding and adhesive applications where speed, efficiency, and precision are crucial. As human operators struggle to maintain these conditions consistently, robots present a more suitable alternative. However, programming the required trajectories



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can be a lengthy and costly process due to the high costs of specialized software. In the current book, the first study presents a work that proposes an open-source Computer-Aided Manufacturing (CAM) software that automates trajectory generation for welding and adhesive applications (contribution 1). The process begins with the selection of the surface to be treated, which determines the trajectory model, followed by feeding a processing system with individual trajectory points selected in a CAD model. The system generates a program in URScript<sup>®</sup> that can be uploaded and executed on the robot.

Initial results demonstrate that the low-cost trajectory generator enables users to develop trajectories on both 2D and 3D surfaces, with 2D trajectories yielding better results due to their lower computational complexity. However, areas for improvement have been identified, including optimizing the number of waypoints and the mesh resolution for 3D trajectories, as well as unifying the solution into a single platform, with a suggestion for using ROS as an alternative simulation environment. Future enhancements are expected to foster a community dedicated to maintaining and improving this platform.

The next work suggests that the identification of location is essential in advanced navigation systems for mobile robots, as it facilitates meaningful connections between objects, spaces, and human actions. This work (contribution 2) introduces an innovative observation-based approach that integrates object detection algorithms, human pose detection, and machine learning techniques to learn and recognize human actions in domestic environments. The methodology focuses on training machine learning models using a dataset derived from the interaction between human pose detection and object detection, significantly enhancing classification performance.

Three experiments were conducted to evaluate the effectiveness of different data types in detecting areas within domestic settings. The first experiment assessed classification using only object data, where several machine learning algorithms, including Gradient Boosting (GB), Extreme Gradient Boosting (XGB), LightGBM (LGBM), and K-Nearest Neighbors (K-NN), were evaluated based solely on information from objects of interest. The GB model achieved the highest accuracy of 72.97%. The second experiment focused on classification using only human pose data, where the LGBM model showed the best performance with an accuracy of 97.86%. The third experiment highlighted the importance of integrating both object and human pose data, resulting in a notable accuracy increase to 98.66% with the LGBM model.

The study's conclusions underscore that combining object data with human pose data significantly improves classification results, though using a larger number of classes may not yield equally successful outcomes. Ultimately, the versatility of the system extends beyond single-person interactions and can adapt to multi-person scenarios, offering potential applications in various settings, including factories and shopping centers. The authors emphasize the advancement achieved by integrating information from both human pose detection and object detection for better understanding ongoing actions, which is beneficial for semantic navigation systems in mobile robots.

The next work (contribution 3) introduces a novel Sliding Mode Higher-Order Extended State Observer (SMHOESO) aimed at enhancing state estimation and disturbance monitoring in nonlinear dynamic systems. This innovative observer not only estimates state variables but also captures total disturbances, which include both internal and external influences affecting system performance. The approach is characterized by the incorporation of multiple augmented states and a nonlinear function designed to correct estimation errors, significantly improving the observer's ability to asymptotically monitor disturbances.

The authors conducted a rigorous analysis of the observer's convergence using the Lyapunov method, demonstrating its asymptotic stability and substantial error reduction in practical applications. The SMHOESO was then integrated into a modified Active Disturbance Rejection Control (ADRC) scheme, which combines a Nonlinear State Error Feedback (NLSEF) controller with a nonlinear tracking differentiator. The effectiveness of

the proposed SMHOESO-based ADRC was validated through numerical simulations on various nonlinear models, including a Differential Drive Mobile Robot (DDMR).

The results highlighted that the SMHOESO outperformed traditional Linear Extended State Observers (LESOs) by providing faster and more precise estimations of states and disturbances while also effectively mitigating the chattering issues typically associated with LESOs. Notably, the simulations demonstrated a significant reduction in the Integral of Time-weighted Absolute Error (ITAE) and the Integral of Squared Control Signal (ISU), confirming the advantages of the proposed method in terms of output response and control effort. The authors concluded that the SMHOESO offers a robust solution for state estimation in nonlinear systems, providing an essential tool for improving control strategies in complex robotic applications.

The next work (contribution 4) investigates a hybrid trajectory tracking control algorithm (HTCA) for robot manipulators (RMs) facing uncertain dynamics and external disturbances. The authors propose several strategies to meet control objectives. Firstly, they introduce a uniform second-order sliding mode disturbance observer (USOSMDO) that directly estimates lumped uncertainties without needing prior information about their upper bounds. Secondly, a fixed-time singularity-free terminal sliding surface (FxSTSS) is proposed to ensure fixed-time convergence of the tracking control error (TCE) without singularities in control input. The HTCA is developed based on the USOSMDO and FxSTSS, incorporating a fixed-time power rate reaching law (FxPRRL). This control proposal guarantees global fixed-time convergence, high tracking accuracy, and significantly minimizes the chattering problem.

In the experimental simulation, the authors compared the performance of the HTCA with conventional sliding mode control (SMC) and a newly published nonlinear fixed-time sliding mode control (NFTSMC) using a 3-degree-of-freedom (3-DOF) FARA-AT2 robot model. They constructed the mechanical model using SOLIDWORKS and export it to the MATLAB/SIMULINK environment for dynamic calculations. The simulation examined trajectory tracking under uncertain factors like external disturbances and internal frictions across all joints.

The results show that the proposed HTCA achieves the best performance among the three control methods in terms of tracking accuracy, with the smallest TCEs and fixed-time convergence. The chattering behavior in the control torque signal is also minimized due to the absence of a discontinuous control law. This combination of USOSMDO and FxPRRL effectively addresses the challenges posed by uncertainty and chattering.

The study affirms that the HTCA significantly improves tracking performance for robot manipulators under uncertain conditions. The authors intend to further apply this method to a real FARA-AT2 robot in future research to validate its practical applicability.

The next paper (contribution 5) proposes a Slope-Adaptability Model Predictive Control (SAMPC) algorithm for quadruped robots to enable stable walking on unknown, sloped terrains without the need for external vision sensors. The SAMPC algorithm estimates the slope's orientation and inclination using data from joint position sensors and an Inertial Measurement Unit (IMU). To ensure stability, it adapts the robot's posture and the touchdown point of its swing leg. A nonlinear control law is incorporated to adjust the friction factor based on slope inclination, reducing the risk of slipping.

In simulations, the SAMPC showed significant improvements over a standard Model Predictive Control (MPC) on sloped terrains. While the original MPC maintained good tracking performance on flat surfaces, it failed to adapt to inclined slopes, leading to instability. However, the SAMPC maintained the robot's body parallel to the slope, ensuring better balance and effective weight distribution. Slope estimation accuracy was validated through various tests, showing a steady-state estimation error of only 6.7% for a 30° slope. Moreover, the SAMPC enabled omnidirectional walking on a 35° slope and achieved a maximum climbing angle of 42.4° by mimicking the lateral climbing strategy of blue sheep.

The SAMPC framework provides adaptability for quadruped robots on unknown sloped terrains by estimating slope parameters and dynamically adjusting the robot's

stance and friction factor. This approach allows for smooth transitions between flat and inclined surfaces and facilitates omnidirectional movement on slopes. Future work will focus on deploying SAMPC on a physical quadruped platform and enhancing the friction factor optimization. Expanding adaptability to more complex terrain using external sensors will also be explored to further improve environmental interaction. The study lays a foundation for robust slope navigation in scenarios where visual sensors may be useless due to environmental conditions.

The next work (contribution 6) presents a novel Robotic Multi-Model Perception (RMMP) system designed to improve efficiency and automation in 3D scanning and reconstruction of complex environments. The system integrates a mobile platform, a manipulator, and a custom-designed scanner equipped with multiple sensors, including cameras, LiDAR, and a depth camera. The primary goal is to overcome limitations in traditional scanning methods, such as heavy manual input and insufficient compatibility with varying object sizes.

The RMMP system utilizes a path planning approach under photogrammetric and kinematic constraints to ensure optimal scanning coverage. It autonomously determines the ideal scanner poses to reduce image distortion and resolution loss, while optimizing path efficiency. The system can switch between different sensor configurations based on the size of the objects, enhancing its versatility. Through experimental validation, the RMMP system showed significant advantages over traditional approaches in both automation and adaptability to different scanning scenarios.

Future work will aim to further enhance its automation capabilities and explore its application in larger and more complex scenes.

Finally, a novel approach to solving inverse kinematics (IK) for hyper-redundant manipulators (HRMs) is introduced (contribution 7), addressing challenges such as obstacle avoidance and the need for minimal joint angle adjustments. The proposed Variable Dimension Scaling Method (VDSM) adjusts the end-effector's path based on the obstacle's position while maintaining proportional scaling, resulting in efficient and simplified path planning.

The method was tested in various environments (obstacle-free and with three different obstacles). In all scenarios, the VDSM enabled the manipulator to avoid obstacles and maintain a smooth, non-repeating path for the end-effector. In scenarios with obstacles, the VDSM adjusted the path while maintaining joint center relationships, ensuring collision avoidance.

The authors analyzed link angles, confirming that minimal changes were required for path adherence. They also validated distance calculations to prevent collisions and monitored driving cable lengths, which showed stability during movements. Experimental validation further corroborated simulation results, as the HRM accurately executed planned paths while avoiding obstacles, guided by a PID control system. The findings affirm that the VDSM enhances HRM operational capabilities in complex environments, offering potential for future exploration in dynamic obstacle avoidance.

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