applied sciences

MDPI

Editorial

Trajectory Planning for Intelligent Robotic and Mechatronic Systems

Lorenzo Scalera [1,*], Andrea Giusti [2] and Renato Vidoni [3]

1 Polytechnic Department of Engineering and Architecture, University of Udine, 33100 Udine, Italy
2 Robotics and Intelligent Systems Engineering, Fraunhofer Italia Research, 39100 Bolzano, Italy; andrea.giusti@fraunhofer.it
3 Faculty of Engineering, Free University of Bozen-Bolzano, 39100 Bolzano, Italy; renato.vidoni@unibz.it
* Correspondence: lorenzo.scalera@uniud.it

check for updates

Citation: Scalera, L.; Giusti, A.; Vidoni, R. Trajectory Planning for Intelligent Robotic and Mechatronic Systems. *Appl. Sci.* **2024**, *14*, 1179. https://doi.org/10.3390/app14031179

Received: 18 December 2023
Revised: 9 January 2024
Accepted: 28 January 2024
Published: 31 January 2024

1. Trajectory Planning for Intelligent Robotic and Mechatronic Systems

Trajectory planning is a crucial and challenging problem for research on intelligent robotic and mechatronic systems, which play a pivotal role in modern manufacturing processes, and especially within the framework of Industry 4.0 [1]. Indeed, in every robotic application, it is required to define not only a path, but also a motion law that can guarantee a feasible and safe operation of the system according to the requirements of the task and the limits of the robot [2]. Many approaches to the problem of trajectory planning have been developed and investigated in the literature, with applications that span from industrial, collaborative and, more in general, autonomous and intelligent robotic and mechatronic systems [3,4].

The motion law of a robotic system can be planned by considering different goals. The design of a proper motion law can be evaluated, for instance, in relation to the energy consumption of a robotic or mechatronic system, and, therefore, optimal trajectories can be determined based on the best performance of the robot in terms of time-energy consumption [5–7]. Another interesting field of application is that of vibration reduction. Indeed, many automatic machines and mechatronic applications require smooth and jerk-limited trajectories during the prescribed operation [8–10]. Moreover, emerging scenarios of industrial robotics, such as collaborative robotics and human–robot interaction, demand advanced strategies for the planning of robot trajectories to ensure smoothness, safety, and fluency during the execution of a task for a robot working alongside a human operator [11–13]. Finally, the trajectory planning for robotic and mechatronic systems is also tightly coupled with the motion control problem of such systems to guarantee high performance in the execution of the demanded motion law [14,15].

In this Special Issue, we invited researchers to contribute with original works and review articles related to trajectory planning for intelligent mechatronic systems, autonomous machines, industrial and collaborative manipulators, as well as mobile and reconfigurable robots. Original research papers on these themes have been sought, with a focus on both theoretical investigations and real-world applications on these topics.

Suitable topics included, but were not restricted to, the following: path and trajectory planning, dynamic modelling, energy efficiency, vibration suppression, smooth trajectories, motion profile optimization, motion control, intelligent robotic and mechatronic systems, collaborative robotics, and motion planning for human–robot interaction.

2. Special Issue

This Special Issue collects papers in open-access format on a broad number of aspects of trajectory planning for intelligent robotic and mechatronic systems introduced above. The call for the Special Issue "Trajectory Planning for Intelligent Robotic and Mechatronic Systems" received 15 manuscripts, 12 of which were accepted for publication. In most of the articles, numerical simulations are corroborated by experimental results. The contributions are listed below in order of publication.

Contribution 1 presents a research study on the trajectory and operational performance of a wheel loader automatic shoveling. A test platform for the operational performance of loaders is developed, and nine parallel shoveling trajectories of different depths are designed and compared in terms of total time, fuel and energy consumption, as well as operation resistance.

In Contribution 2, the authors describe the implementation and experimental validation of an obstacle avoidance algorithm using the UR5e robot. An error analysis of simulation and experiments allows one to conclude that the developed approach was effectively applied to a real collaborative robotic system, exhibiting behavior similar to what simulations predicted.

Another work dealing with a collaborative robotic application can be found in Contribution 3, where a bin-picking task is enhanced to achieve a successful and fluent collaboration between human and robot. Experimental results show that the use of a robot in collaboration with a human operator can be particularly useful to overcome typical bin picking failures and to improve the fault tolerance of the system, increasing its flexibility and reducing down times.

The authors of the paper in Contribution 4 illustrate the application of a motion profile with elliptic jerk to the Cartesian space position control of serial robots. A SCARA-like manipulator with four degrees of freedom (DOFs) and elastic balancing is considered, and both integer-order and fractional-order controllers are applied to simulate the behavior of the robot using the elliptic jerk profile.

The influence of joint stiffness and motion time on the trajectories of underactuated robots is analyzed in Contribution 5. More in detail, trajectories for a 3-DOF robot moving in the horizontal plane with two actuators and a torsional spring are planned, and combinations of torsional stiffness and motion time that minimize the motion torques or the swept area are discussed.

The paper in Contribution 6 provides a comprehensive review on use of reinforcement learning for dynamic obstacle avoidance and path planning algorithms. Publications from the last 5 years (2018–2022) are collected and analyzed to evaluate the latest trends in mobile robotics using reinforcement learning, including a discussion on performance metrics and research gaps in this field.

In Contribution 7, an approach for frame-based slip detection for an underactuated robotic gripper for assistance of users with disabilities is presented. The proposed method effectively handles common issues associated with purely vision-based slip detection methods, such as optical path occlusion or compliant objects, showing high performance in terms of accuracy and robustness against changes of the environment.

Contribution 8 proposes a technique for positioning applications that involves employing a platform subjected to planar oscillations along circular, elliptical, and complex trajectories. Dynamic and mathematical models of the motion of a small object on the platform were developed to investigate the motion characteristics of the part by controlling frequency and amplitude of the excitation force.

In Contribution 9, different learning methods based on artificial neural networks are examined to replace the default speed controller for high-precision position control and drift attenuation in robotic manipulators. Experimental tests on a UR5 robot yield to comparable results with respect to the classical controller, showing the feasibility of the proposed approach without the need for tuning the controller parameters.

Furthermore, in Contribution 10 a virtual force control for a six-axis robotic arm is developed using both traditional mathematical modeling and machine learning techniques in the implementation of the dynamic model of the manipulator. The proposed position and force hybrid controller is based on a Raspberry Pi board with a real-time kernel, demonstrating the fulfillment of the motion control requirements with a low-cost device. The virtual force sensor is also used to detect collisions with the human operator.

The work in Contribution 11 aims at developing a trajectory planning approach to avoid collisions for a SCARA robotic manipulator in the context of collaborative robotics. The authors show that the proposed approach based on topological path planning is a collision-free, deterministic, and predictable route planning method with superior performance with respect to alternative approaches, e.g., based on probabilistic roadmap methods or on generalized Voronoi diagrams.

Finally, in Contribution 12 the authors propose a novel method for designing motion profiles utilizing a sinusoidal jerk model to generate fast and smooth trajectories characterized by low vibrations. Differently from previous studies, an analytical optimization procedure for the profile parameters is introduced to minimize both the motion duration and the excitation frequency contents. Numerical and experimental results on a linear axis show the effectiveness of the proposed method in comparison with alternative strategies in terms of smoothness and vibration attenuation.

The presented contributions collectively explore diverse dimensions of trajectory planning for intelligent robotic and mechatronic systems. To summarize, Contributions 1, 4 and 5 delve into trajectory planning and control strategies for robotic manipulators, emphasizing factors like operational performance, motion profiles, and joint stiffness influences. Contributions 2 and 11 address the challenges of obstacle avoidance and collision-free trajectory planning in collaborative robotic applications. In the same context, the virtual force sensor presented in Contribution 10 is used to detect collision with the body of the human operator working alongside the robot. Contributions 3 and 7 focus on enhancing collaboration between humans and robots in specific tasks, such as bin-picking and slip detection for a robotic gripper. Contributions 6 and 9 explore the integration of artificial intelligence, with a focus on reinforcement learning and artificial neural networks, to improve dynamic obstacle avoidance, path planning, and position control in robotic systems. Finally, Contributions 8 and 12 explore the effects of motion design on mechanical vibrations.

3. Final Remarks

As technology advances, the vision for trajectory planning in intelligent robotic and mechatronic systems is evolving towards more sophisticated and adaptive solutions. The integration of artificial intelligence and machine learning techniques opens new avenues for optimizing trajectory planning algorithms. Future developments may emphasize real-time adaptability to dynamic environments, enhanced collision avoidance strategies, and improved coordination in multi-robot systems. The trajectory planning field aims to create frameworks that not only ensure precision and efficiency, but also consider the inherent complexities of real-world scenarios. With the continued integration of cutting-edge technologies, the trajectory planning field will play a pivotal role in the advancement of autonomous robotics and mechatronic applications.

This Special Issue contains valuable research works focused on the trajectory planning for intelligent mechatronic and robotic systems, covering a wide area of applications. This collection demonstrates the high level of research interest in these topics, as well as the potential for future developments. We sincerely hope that this Special Issue on "Trajectory Planning for Intelligent Robotic and Mechatronic Systems" will be a useful resource for academics and researchers working on these topics.

Author Contributions: Conceptualization, L.S., A.G. and R.V.; writing–original draft preparation, L.S.; writing–review and editing, L.S., A.G. and R.V.; supervision, project administration, R.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

List of Contributions

1. Chen, Y.; Jiang, H.; Shi, G.; Zheng, T. Research on the Trajectory and Operational Performance of Wheel Loader Automatic Shoveling. *Appl. Sci.* **2022**, *12*, 12919.
2. Neri, F.; Forlini, M.; Scoccia, C.; Palmieri, G.; Callegari, M. Experimental evaluation of collision avoidance techniques for collaborative robots. *Appl. Sci.* **2023**, *13*, 2944.
3. Boschetti, G.; Sinico, T.; Trevisani, A. Improving Robotic Bin-Picking Performances through Human–Robot Collaboration. *Appl. Sci.* **2023**, *13*, 5429.
4. Bruzzone, L.; Stretti, D. Application of Elliptic Jerk Motion Profile to Cartesian Space Position Control of a Serial Robot. *Appl. Sci.* **2023**, *13*, 5601.
5. Tonan, M.; Doria, A.; Bottin, M.; Rosati, G. Influence of Joint Stiffness and Motion Time on the Trajectories of Underactuated Robots. *Appl. Sci.* **2023**, *13*, 6939.
6. Almazrouei, K.; Kamel, I.; Rabie, T. Dynamic Obstacle Avoidance and Path Planning through Reinforcement Learning. *Appl. Sci.* **2023**, *13*, 8174.
7. Marx, L.; Pálsdóttir, Á.A.; Andreasen Struijk, L.N. Frame-Based Slip Detection for an Underactuated Robotic Gripper for Assistance of Users with Disabilities. *Appl. Sci.* **2023**, *13*, 8620.
8. Kilikevičius, S.; Liutkauskienė, K.; Česnavičius, R.; Keršys, A.; Makaras, R. Investigation of the Motion Characteristics of Parts on a Platform Subjected to Planar Oscillations. *Appl. Sci.* **2023**, *13*, 9576.
9. Mystkowski, A.; Wolniakowski, A.; Kadri, N.; Sewiolo, M.; Scalera, L. Neural Network Learning Algorithms for High-Precision Position Control and Drift Attenuation in Robotic Manipulators. *Appl. Sci.* **2023**, *13*, 10854.
10. Hung, C.W.; Jiang, G.Y. Application of External Torque Observer and Virtual Force Sensor for a 6-DOF Robot. *Appl. Sci.* **2023**, *13*, 10917.
11. Batista, J.G.; Ramalho, G.L.; Torres, M.A.; Oliveira, A.L.; Ferreira, D.S. Collision Avoidance for a Selective Compliance Assembly Robot Arm Manipulator Using Topological Path Planning. *Appl. Sci.* **2023**, *13*, 11642.
12. Fang, Y.; Zhu, G.N.; Zhao, Y.Z.; Gu, C. Design Procedure of Motion Profiles with Sinusoidal Jerk for Vibration Reduction. *Appl. Sci.* **2023**, *13*, 13320.

References

1. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R. Substantial capabilities of robotics in enhancing Industry 4.0 implementation. *Cogn. Robot.* **2021**, *1*, 58–75. [CrossRef]
2. Biagiotti, L.; Melchiorri, C. *Trajectory Planning for Automatic Machines and Robots*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008.
3. Siciliano, B.; Khatib, O.; Kröger, T. *Springer Handbook of Robotics*; Springer: Berlin/Heidelberg, Germany, 2008; Volume 200.
4. Corke, P.I.; Jachimczyk, W.; Pillat, R. *Robotics, Vision and Control: Fundamental Algorithms in MATLAB*; Springer: Berlin/Heidelberg, Germany, 2011; Volume 73.
5. Paes, K.; Dewulf, W.; Vander Elst, K.; Kellens, K.; Slaets, P. Energy efficient trajectories for an industrial ABB robot. *Procedia Cirp* **2014**, *15*, 105–110. [CrossRef]
6. Carabin, G.; Scalera, L. On the trajectory planning for energy efficiency in industrial robotic systems. *Robotics* **2020**, *9*, 89. [CrossRef]
7. Boscariol, P.; Richiedei, D. Energy-efficient design of multipoint trajectories for Cartesian robots. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 1853–1870. [CrossRef]
8. Gasparetto, A.; Zanotto, V. A new method for smooth trajectory planning of robot manipulators. *Mech. Mach. Theory* **2007**, *42*, 455–471. [CrossRef]
9. Haschke, R.; Weitnauer, E.; Ritter, H. On-line planning of time-optimal, jerk-limited trajectories. In Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France, 22–26 September 2008; pp. 3248–3253.
10. Bianco, C.G.L.; Ghilardelli, F. A scaling algorithm for the generation of jerk-limited trajectories in the operational space. *Robot. Comput.-Integr. Manuf.* **2017**, *44*, 284–295. [CrossRef]
11. Vicentini, F. Collaborative robotics: A survey. *J. Mech. Des.* **2021**, *143*, 040802. [CrossRef]
12. Scalera, L.; Vidoni, R.; Giusti, A. Optimal scaling of dynamic safety zones for collaborative robotics. In Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA), Xi'an, China, 30 May–5 June 2021; pp. 3822–3828.
13. Scalera, L.; Giusti, A.; Vidoni, R.; Gasparetto, A. Enhancing fluency and productivity in human-robot collaboration through online scaling of dynamic safety zones. *Int. J. Adv. Manuf. Technol.* **2022**, *121*, 6783–6798. [CrossRef]

14. Brady, M. *Robot Motion: Planning and Control*; MIT Press: Cambridge, MA, USA, 1982.
15. De Luca, A.; Oriolo, G. Trajectory planning and control for planar robots with passive last joint. *Int. J. Robot. Res.* **2002**, *21*, 575–590. [CrossRef]