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Editorial

Optimization of Motion Planning and Control for Automatic Machines, Robots and Multibody Systems

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1. Introduction

The optimization of motion and trajectory planning is an effective and usually costless approach to improve the performance of dynamic systems, such as robots, mechatronic systems, automatic machines and multibody systems. Indeed, wise motion planning allows increasing precision and machine productivity, while reducing vibrations, motion time, actuation effort and energy consumption. On the other hand, the availability of optimized methods for motion planning allows for the cheaper and lighter construction of the system. Hence, it is also an effective tool towards a more economically and environmentally sustainable industry.

Strictly related to motion planning is motion control, and employing a well-tuned control scheme is of primary importance. One the one hand, it allows for precise tracking of the optimized trajectory, thus boosting the achievement of the desired performances. On the other hand, it could compensate for a bad planned motion reference, whenever advanced feedback control schemes are adopted.

The authors of this Editorial have been involved in several theoretical and experimental studies in these fields of research in recent years, by investigating some novel techniques targeted to different goals. For example, in the field of motion planning, they have proved the benefits of motion planning in the following fields:

- Precise path tracking in underactuated multibody systems (see e.g., [1]).
- Vibration reduction in flexible link multibody systems (see e.g., [2]).
- Jerk reduction in robotic and mechatronic systems (see e.g., [3]).
- Reduction of energy consumption (see e.g., [4]).
- Optimization of the quality of manufacturing processes (see e.g., [5]).

In some of the aforementioned applications, the authors have also proved the benefits of feedback control through some original numerical and experimental studies. For example, the following can be quoted:

- Vibration reduction in flexible multibody systems (see e.g., [6]).
- Precise path tracking in underactuated multibody systems (see e.g., [7]).
- Control of the coordinated motion of hydraulic systems (see e.g., [8]).

In the light of the increasing use of servo-actuated and servo-controlled systems, the optimization of motion planning and control can be beneficial in an even wider range of mechatronic and robotic systems. To collect and disseminate a meaningful collection of these applications by providing the most recent advances in this challenging research area, this book is proposed, which includes a series of 14 novel research studies that cover different sub-areas, in the framework of motion planning and control.

2. Book Overview

The papers collected in this book can be categorized into three main groups, which are briefly discussed in the following section.

2.1. Motion Planning

The issue of energy reduction in robotic systems through motion planning is discussed in [9], where the functional redundancy of a robotic system is exploited to enhance energy efficiency. Indeed, whenever the number of degrees of freedom required to complete the task is smaller than the number of available degrees of freedom of the system, such a redundancy can be exploited by choosing, among the sequence of infinite solutions of the inverse kinematic problem, those ensuring minimum energy consumption. This result proves that motion planning is a costless approach to reduce the energy impact of robotic systems.

In [10], trajectory optimization is aimed at improving obstacle avoidance in industrial robots. The method proposed therein is based on the improved artificial potential field method and the cosine adaptive genetic algorithm. The artificial potential field method is used to establish the attraction, repulsion, and resultant potential field functions. According to the motion constraint conditions, the fitness function is designed, and the relation between fitness function and motion constraint is analyzed. The results show that the manipulator can avoid obstacles and smoothly reach the target point along the path of obstacle avoidance planning. When the obstacle point is close to the target point, the improved artificial potential field method can avoid the end-effector swing between the obstacle point and the target point and solve the problem of the unreachable target.

One relevant problem in the operation of many industrial robots is the transmission of vibrations to the fixed frame during their high-speed motion, due to unbalanced inertia forces. A very important research topic is finding new methods to remove or decrease these alternating dynamic loads transmitted to the base and, therefore, to allow for the increase in the operating velocities. This issue is discussed in [11] through a "3RRR" planar parallel manipulator, by proposing a mixed technique, combining balancing by redistributing the mass and the kinematic guidance of the end-effector using a proper motion profile.

The application of obstacle avoidance is also investigated for the case of mobile robots in [12], to meet the ever-growing use of such systems. This paper proposes some real-time algorithms for the navigation of an autonomous service robot in an indoor environment in the presence of moving obstacles. The reshape trajectory method is exploited. Experimental results through a two-wheel differential drive mobile robot show the method's effectiveness.

Among mobile robots, legged robots are attracting interest in the scientific community, and therefore have been included in this book. In [13], the whole-body motion planning of a six-legged robot over rugged terrain is discussed. Motion planning is decomposed into support motion (aimed at stability maximization and orientation matching) and swing motion. The latter problem is solved as an optimization problem, which minimizes a bioinspired objective function. Both simulations and experiments validate the proposed whole-body motion planning method.

A two-legged humanoid robot is instead investigated in [14]. Starting from a spatial three-mass model, where both the trunk and thighs are regarded as an inverted pendulum, while the shanks and feet are considered as mass-points under no constraints with the trunk, a friction constraint method is proposed to plan the trajectory of the leg swing. The goal of optimal motion planning has been assumed to be achieving the fastest walking speed without any rotational slip. The numerical results show that, by using the friction constraint method proposed, the maximum walking speed without rotational slip can be obtained.

2.2. Motion Control

As already discussed in the Introduction, control is tightly related to motion planning, and concurrent approaches that optimally develop the controller and the planner can be developed too. For example, in order to enhance the stability of hydraulic quadruped robots, a centroid-based controller for quadrupedal pacing is proposed in [15]. The real-time attitude feedback information of the trunk centroid is introduced into the trajectory planning of the trunk centroid. Joint torques that minimize the contact forces are calculated and the positions and attitudes of the robot trunk are adjusted by the spring damper virtual elements. Experimental results show that the proposed approach ensures the smooth motion of the robot trunk.

The issue of motion control is discussed for autonomous underwater vehicles (AUVs) in [16]. In this paper, a saturation-based nonlinear fractional-order proportional derivative (FOPD) controller is proposed for AUV motion control. The results prove that proposed controllers can achieve better dynamic performance, as well as robustness, compared to traditional proportional derivative controllers. Additionally, the controlled performance can also be adjusted to satisfy different control requirements. The numerical results show the benefit of this novel approach in set-point regulation and trajectory tracking.

Another marine mechatronic system is investigated in [17], and motion control is performed through a closed-loop strategy. In this work, a command filter-based backstepping sliding mode controller with prescribed performance is developed to perform ship roll stabilization. First, the impact of external disturbances is eliminated by a nonlinear disturbance observer. Second, a command filter-based backstepping control method is adopted. Precise tracking performances and the steady state of the ship rolling angle are guaranteed, as well as high robustness of the proposed control strategy.

The issue of motion control is critical in teleoperation robotic systems. To overcome the limitations of human motion accuracy, a paper [18] introduces new interaction logic, a scalable human–robot motion mapping mechanism and a single axis mode to balance teleoperation efficiency and accuracy. In order to meet the requirements of complaint assembly skill, a vibration-based force feedback system was developed to let the operator feel the contact force. An active force control mechanism was also designed to restrict the contact force within a safe range. The gesture-based teleoperation system is tested with a pick-and-place and peg-in-hole case study and the results prove its effectiveness and feasibility in tight, tolerant and complaint assembly tasks.

2.3. Models for Motion Planning and Control

The method proposed in the previous papers reveal a critical issue that is propaedeutic to perform reliable motion planning and control: the availability of models. Indeed, model-based approaches have often been proved to be the most effective, since the knowledge of the system model is useful to compensate for unwanted behaviors. On the one hand, these models should be accurate. On the other hand, they should be as simple as possible, to allow for simple model manipulation and inversion. This need is exacerbated if real-time calculations are done. These issues are discussed in the book too, with some meaningful examples of models for optimal motion planning and control.

To handle nonlinearities in flexible multibody systems, a paper [19] proposes a parametric modal analysis approach to obtain an analytical polynomial expression for the eigenpairs (natural frequencies and mode shapes) as a function of the system configuration. The availability of such a result can be very helpful for model-based motion planning and control strategies due to the simple analytical equations it produces. In the theoretical development, the method is applied and validated on a flexible multibody system, modeled through the equivalent rigid link system.

A general approach for the dynamic modeling and analysis of a passive biped walking robot, with a particular focus on the feet–ground contact interaction, is proposed in [20]. The main purpose of this investigation is to address the supporting foot slippage and viscoelastic dissipative contact forces of the biped walking robot model and to develop its dynamic equations for simple and double support phases. Due to its accuracy and simple formulation, such a model could be effectively adopted in motion planning and control.

2.4. Measurements and Estimation for Motion Control

In the case of feedback control schemes, such as those quoted in Section 2.2, the availability of accurate measurements is of primary importance to ensure the expected results of the controlled systems and to perform control with adequate phase margins. Therefore, developing real-time estimation algorithms is becoming even more important.

Paper [21] proposes a robust estimation strategy for vehicle motion states by applying the extended set-membership filter. A calculation scheme with a simple structure is proposed to acquire the longitudinal and lateral tire forces with acceptable accuracy. Numerical tests are carried out to verify the performance of the proposed strategy.

Finally, a control method based on a state-augmented Kalman filter is proposed in [22] to improve the low-speed performance and stability of opto-electric servomechanisms. This is a relevant issue to be solved for motion control based on opto-electric systems. Indeed, the opto-electric servomechanism plays an important role in obtaining clear and stable images. However, the inherent torque disturbance and the noisy speed signal cause a significant decline in accuracy and low-speed performances, unless signal processing methods are proposed. The results shown in the paper demonstrate the effectiveness of the proposed approach.

3. Concluding Remarks

Looking towards future works, the research proposed in this book could be further developed to improve effectiveness or to be applied in more complex systems that could benefit from optimized motion planning and control methods to increase productivity, the quality of the outcomes and efficiency.

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References

1. Boscariol, P.; Richiedei, D. Robust point-to-point trajectory planning for nonlinear underactuated systems: Theory and experimental assessment. *Robot. Comput. Integr. Manuf.* **2018**, *50*, 256–265. [CrossRef]
2. Boscariol, P.; Gasparetto, A. Model-based trajectory planning for flexible-link mechanisms with bounded jerk. *Robot. Comput. Integr. Manuf.* **2013**, *29*, 90–99. [CrossRef]
3. Zanotto, V.; Gasparetto, A.; Lanzutti, A.; Boscariol, P.; Vidoni, R. Experimental validation of minimum time-jerk algorithms for industrial robots. *J. Intell. Robot. Syst.* **2011**, *64*, 197–219. [CrossRef]
4. Boscariol, P.; Richiedei, D. Energy-efficient design of multipoint trajectories for Cartesian robots. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 1853–1870. [CrossRef]
5. Fiorese, E.; Richiedei, D.; Bonollo, F. Improving the quality of die castings through optimal plunger motion planning: Analytical computation and experimental validation. *Int. J. Adv. Manuf. Technol.* **2017**, *88*, 1475–1484. [CrossRef]
6. Boscariol, P.; Gasparetto, A.; Zanotto, V. Simultaneous position and vibration control system for flexible link mechanisms. *Meccanica* **2011**, *46*, 723–737. [CrossRef]
7. Boschetti, G.; Caracciolo, R.; Richiedei, D.; Trevisani, A. A non-time based controller for load swing damping and path-tracking in robotic cranes. *J. Intell. Robot. Syst.* **2014**, *76*, 201–217. [CrossRef]
8. Richiedei, D. Synchronous motion control of dual-cylinder electrohydraulic actuators through a non-time based scheme. *J. Control Eng. Appl. Inform.* **2012**, *14*, 80–89.

9. Boscariol, P.; Caracciolo, R.; Richiedei, D.; Trevisani, A. Energy optimization of functionally redundant robots through motion design. *Appl. Sci.* **2020**, *10*, 3022. [CrossRef]
10. Zhou, H.; Zhou, S.; Yu, J.; Zhang, Z.; Liu, Z. Trajectory optimization of pickup manipulator in obstacle environment based on improved artificial potential field method. *Appl. Sci.* **2020**, *10*, 935. [CrossRef]
11. Acevedo, M.; Orvañanos-Guerrero, M.T.; Velázquez, R.; Arakelian, V. An alternative method for shaking force balancing of the 3RRR PPM through acceleration control of the center of mass. *Appl. Sci.* **2020**, *10*, 1351. [CrossRef]
12. Gia Luan, P.; Thinh, N.T. Real-time hybrid navigation system-based path planning and obstacle avoidance for mobile robots. *Appl. Sci.* **2020**, *10*, 3355. [CrossRef]
13. Chen, J.; Gao, F.; Huang, C.; Zhao, J. Whole-body motion planning for a six-legged robot walking on rugged terrain. *Appl. Sci.* **2019**, *9*, 5284. [CrossRef]
14. Zhao, F.; Gao, J. Anti-slip gait planning for a humanoid robot in fast walking. *Appl. Sci.* **2019**, *9*, 2657. [CrossRef]
15. Ren, D.; Shao, J.; Sun, G.; Shao, X. The complex dynamic locomotive control and experimental research of a quadruped-robot based on the robot trunk. *Appl. Sci.* **2019**, *9*, 3911. [CrossRef]
16. Zhang, L.; Liu, L.; Zhang, S.; Cao, S. Saturation based nonlinear fopd motion control algorithm design for autonomous underwater vehicle. *Appl. Sci.* **2019**, *9*, 4958. [CrossRef]
17. Jin, Z.; Zhang, W.; Liu, S.; Gu, M. Command-filtered backstepping integral sliding mode control with prescribed performance for ship roll stabilization. *Appl. Sci.* **2019**, *9*, 4288. [CrossRef]
18. Zhang, W.; Cheng, H.; Zhao, L.; Hao, L.; Tao, M.; Xiang, C. A gesture-based teleoperation system for compliant robot motion. *Appl. Sci.* **2019**, *9*, 5290. [CrossRef]
19. Palomba, I.; Vidoni, R. Flexible-link multibody system eigenvalue analysis parameterized with respect to rigid-body motion. *Appl. Sci.* **2019**, *9*, 5156. [CrossRef]
20. Corral, E.; García, M.G.; Castejon, C.; Meneses, J.; Gismeros, R. Dynamic modeling of the dissipative contact and friction forces of a passive biped-walking robot. *Appl. Sci.* **2020**, *10*, 2342. [CrossRef]
21. Chen, J.; Guo, C.; Hu, S.; Sun, J.; Langari, R.; Tang, C. Robust estimation of vehicle motion states utilizing an extended set-membership filter. *Appl. Sci.* **2020**, *10*, 1343. [CrossRef]
22. Qi, C.; Jiang, X.; Xie, X.; Fan, D. A SAKF-Based Composed control method for improving low-speed performance and stability accuracy of opto-electric servomechanism. *Appl. Sci.* **2019**, *9*, 4498. [CrossRef]