actuators

Editorial

New Control Schemes for Actuators

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An actuator is a device that moves or controls a mechanism, by turning a control signal into mechanical action, such as in an electric motor. Actuators may be hydraulic, pneumatic, electric, thermal or mechanical, and they may be powered by electric current, hydraulic fluid or pneumatic pressure. However, increasingly, these systems are being driven by software, with the control signal originating from a microcontroller programmed by software. Therefore, an element key to increasing the reliability and performance of these actuators is the control system. The limitations of traditional control techniques when coping with real control problems have motivated the invention of new and advanced control schemes, in order to improve actuator performance and reliability and to reduce the non-linear dynamics and uncertainties usually present in actuators. Control schemes refer to the strategies and methods used to regulate and manipulate the behavior of a system or process. These schemes are crucial in various fields, including engineering, automation and robotics, to achieve desired outcomes, improve performance and maintain stability [1–3].

In this sense, the objective of the control scheme is to drive the system outputs toward a desired state, while minimizing any steady-state errors, overshoot and delays. Moreover, the control scheme should ensure the stability of the controls, as well as optimizing them as far as possible.

Several types of control systems date back to ancient times. However, a more formal analysis of the field began with a dynamic analysis of the centrifugal governor (used to regulate speed), which was conducted by physicist James Clerk Maxwell in 1868 and titled On Governors.

However, modern control theory was not developed until the 1960s, which heralded the introduction of new mathematical tools and techniques for analyzing and designing new control systems. This theory was based in the state space and could deal with multiple-input and multiple-output (MIMO) systems. This overcame the limitations of using classical control theory for more sophisticated design problems, such as fighter aircraft control; however, there was a limitation, in that no frequency domain analysis was possible. In modern control theory, a system is represented as a set of first order differential equations, defined using state space variables. Under this new approach, many new control schemes were developed, including non-linear, multivariable, adaptive and robust control schemes, among others [4,5].

More recently, in the mid-20th century, the advent of computers paved the way for digital control systems. Digital controllers offered greater flexibility and precision, as well as the ability to implement complex algorithms. Since that point, the field of control schemes has continued to evolve, with ongoing advancements in areas such as artificial intelligence, machine learning and quantum control [6–8].

The most common control scheme used in industry currently is the traditional PID control. However, advancements in technology continually drive the development of new control schemes for actuators, which play a crucial role in various industries, ranging from manufacturing to robotics, and are essential for the precise and efficient control of motion and force [9–11].

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Citation: Barambones, O.; Cortajarena, J.A.; Alkorta, P. New Control Schemes for Actuators. *Actuators* **2024**, *13*, 99. https://doi.org/10.3390/act13030099

Received: 19 February 2024
Accepted: 28 February 2024
Published: 1 March 2024

Below is a brief summary of some advanced control techniques currently under development, in order to improve actuator performance, as follows [12–15]:

Model Predictive Control (MPC): Uses a dynamic model of the system to predict future behavior and optimize control inputs over a specified prediction horizon. MPC is effective for systems with constraints and varying operating conditions.

Fuzzy Logic Control: Utilizes fuzzy sets and linguistic variables to create rules for decision-making. Fuzzy logic is especially useful when dealing with systems that deal with uncertain or imprecise information.

Model Reference Adaptive Control (MRAC): adjusts the controller parameters based on the difference between the system's actual and desired responses, adapting to changes in system dynamics.

Self-Tuning Adaptive Control: automatically adjusts controller parameters in real time, based on changes in the system or operating conditions.

Optimal Control: Utilizes optimization techniques to find the best control inputs that minimize a cost function, considering system dynamics and constraints. Model Predictive Control (MPC) is a type of optimal control.

Robust Control: Focuses on maintaining stable performance in the presence of uncertainties and variations in system parameters. Robust control techniques provide a margin of safety against disturbances.

Sliding Mode Control: Applies a discontinuous control law to drive the system along a sliding surface, ensuring rapid convergence to the desired state. Sliding mode control is robust against uncertainties and disturbances.

Neural Network Control: Integrates artificial neural networks in the control scheme, to learn and adapt to system dynamics. Neural network controllers are particularly useful for non-linear systems or those with complex and uncertain behaviors.

Reinforcement Learning (RL): RL algorithms can adapt and optimize control strategies based on feedback from the environment. This can be particularly useful in scenarios where the system dynamics are complex or change over time.

Redundancy-Based Control: actuators utilising this scheme are designed with redundant components, enabling them to adapt to component failures and thereby ensuring the system's continued operation.

Hierarchical Control: Organizes control tasks into a hierarchy of levels, with each level responsible for a specific aspect of the system. This structure simplifies complex systems and allows for a modular design.

Quantum Control: in emerging fields such as quantum computing, control schemes are designed to manipulate quantum states for specific applications, such as quantum information processing and quantum communication.

These control schemes represent a diverse range of approaches aimed at enhancing the efficiency, adaptability and reliability of actuators in different applications. The choice of a specific control scheme depends on the characteristics of the system, the desired performance of the actuator and the environmental conditions in which the actuator operates.

The Special Issue entitled "New Control Schemes for Actuators" was an opportunity to share knowledge, experience and information regarding the design and implementation of different control schemes. In this Special Issue, eleven original research papers were published. Within these papers, the authors analyzed different control schemes, such as Boundary Control, Disturbance Rejection Control, Fault-Tolerant Control, Adaptive Fuzzy Logic, Robust Control, Digital Twin Concept, Sliding Mode Control, Damping Passivity-Based Control and Adaptive Control. These works are summarized below.

In the first paper, Acho et al. [16] proposed a boundary controller based on a peak detector system, in order to reduce vibrations in the cable–tip–mass system. The control procedure was built upon a recent modification of the controller itself, incorporating a non-symmetric peak detector mechanism to enhance the robustness of the control design. The crucial element lay in the identification of peaks within the boundary input signal, which were then utilized to formulate the control scheme. Its mathematical representation relied on just two tunable parameters. Numerical experiments were conducted to assess the performance of this novel approach and to compare it to that of the boundary damper control; the results demonstrated that the novel approach showcased superior efficacy to the boundary damper control.

In the work of Zhang et al. [17], a friction feed-forward compensation method, based on an improved active disturbance rejection control (IADRC), was designed. A mathematical model of EMA was also developed, and the relationship between friction torque and torque current was derived. Furthermore, the compound ADRC method, utilizing a second-order speed loop and a position loop, was studied, and an IADRC method was proposed. A real EMA was developed, and the working principles of the EMA driving circuit and current sampling were analyzed. The three methods—PI, ADRC, and IADRC—were verified by conducting speed step experiments and sinusoidal tracking experiments. The integral values of time multiplied by the absolute error of the three control modes under the step speed mode were approximately 47.7, 32.1 and 15.5, respectively. Disregarding the inertia of the reducer and assuming that the torque during no-load operations equals the friction torque during constant motion, the findings indicate that, under a load purely driven by inertia, the IADRC method enhanced the tracking accuracy.

In the work of Wu et al. [18], a fuzzy linear active disturbance rejection control strategy (FLADRC) for absolute pressure piston manometers was proposed, to address the internal uncertainties and external disturbances of a pressure-measuring instrument. First, the characteristics of the main components were analyzed, according to the actual working principle of the system, to establish a theoretical model of the controlled system. Second, the corresponding linear active disturbance rejection controller (LADRC) was designed, according to the model. The principle of fuzzy control was introduced, in order to adaptively adjust the controller parameters of the LADRC in real time. The LADRC parameters have several disadvantages which are difficult to rectify, including a poor immunity to disturbances due to their fixed nature; adaptively adjusting these parameters subsequently demonstrated the stability of the control method. Finally, a simulation model was built in the Simulink environment in MATLAB, and three different pressure operating points were selected for the corresponding experiments, in order to comparatively analyze Kp, PID and LADRC. The results showed that FLADRC enabled the absolute pressure piston manometer, achieving better stability and a greater immunity to disturbances. This also verified the effectiveness and feasibility of the control strategy in practical engineering applications.

In the paper authored by Zhu et al. [19], the fault problem in distributed-four-wheel-drive electric vehicle drive systems was addressed. First, a fault-factor-based active fault diagnosis strategy was proposed. Second, a fault-tolerant controller was designed, to reconstruct motor drive torque based on vehicle stability. This controller ensured that the vehicle maintained stability by providing fault-free motor output torque based on the fault diagnosis results. To validate the effectiveness of the fault diagnosis and the fault-tolerant control, SIL simulations were conducted, using MATLAB/Simulink and CarSim. A hardware-in-the-loop (HIL) simulation platform, with the highest possible confidence level, was established, based on NI PXI and CarSim RT. Through the HIL simulation experiments, the proposed control strategy was shown to be able to accurately diagnose the operating state of the motor, rebuild the motor torque based on the stability of the system, and demonstrate robust stability when the drive system failed. Under various fault conditions, the maximum error in the vehicle lateral angular velocity was less than 0.017 rad/s, and the maximum deviation in the lateral direction was less than 0.7 m. These findings substantiated the highly robust stability of the proposed method.

The next paper, authored by Sun et al. [20], aimed to highlight the critical role of robot manipulators in industrial applications and elucidate the challenges associated with achieving high-precision control. In particular, the detrimental effects of non-linear friction on manipulators were discussed. To overcome this challenge, a novel friction compensation controller (FCC), combining time delay estimation (TDE) and an adaptive fuzzy logic system (AFLS), was proposed in this paper. The friction compensation controller was designed to take advantage of the time delay estimation algorithm's strengths in eliminating and estimating the unknown dynamic functions of the system, using information from the previous sampling period. Simultaneously, the adaptive fuzzy logic system compensated for the hard non-linearities in the system and suppressed the errors generated by time delay estimation, thus improving the tracking accuracy of the robotic arm. The numerical experimental results demonstrated that the proposed friction compensation controller significantly enhanced the tracking accuracy of the robotic arm, and that the addition of the adaptive fuzzy logic system improved the performance of the time delay estimation by an average of 90.59.

In the work of Hashim et al. [21], two new versions of modified active disturbance rejection controls (MADRCs) were proposed, which aimed to stabilize a non-linear quadruple tank system and to control the water levels of the lower two tanks in the presence of exogenous disturbances, parameter uncertainties and parallel varying input set-points. The first proposed scheme was configured from the combination of a modified tracking differentiator (TD), a modified super twisting sliding mode (STC-SM) and a modified non-linear extended state observer (NLESO). The second proposed scheme was obtained by aggregating another modified TD, a modified non-linear state error feedback (MNLSEF) and a fal-function-based ESO. The MADRC schemes, with a non-linear quadruple tank system, were investigated by running simulations in the MATLAB/SIMULINK environment, and several comparison experiments were conducted, to validate the effectiveness of the proposed control schemes. Furthermore, a genetic algorithm (GA) was used as a tuning algorithm to parametrize the proposed MADRC schemes, with the integral time absolute error (ITAE), the integral square of the control signal (ISU) and the integral absolute of the control signal (IAU) as an output performance index (OPI). Finally, the simulation results showed the robustness of the proposed schemes, with a noticeable reduction in the OPI.

Chaiprabha et al. [22] proposed an advanced trajectory controller, based on a digital twin framework into which artificial intelligence (AI) was incorporated, which could effectively control a precision linear stage. A precision linear stage is an electro-mechanical system that includes a motor, electronics, flexible coupling, gear, ball screw and precision linear bearing. In these kind of systems, a tight fit can provide better precision but also generates a difficult-to-model friction that is highly non-linear and asymmetrical. This framework offered the following advantages: the detection of abnormalities, an estimation of performance and selective control over any situation. The digital twin was developed via Matlab's Simscape and ran concurrently, using a real-time controller.

In the work of Shiravani et al. [23], an enhanced integral sliding mode control (ISMC) for the mechanical speed of an induction motor (IM) was presented and experimentally validated. The design of the proposed controller was created in the DQ synchronous reference frame with indirect field-oriented control (FOC). Global asymptotic speed tracking, in the presence of model uncertainties and load torque variations, was guaranteed using an enhanced ISMC surface. Moreover, this controller provided a faster speed convergence rate than the conventional ISMC and proportional integral methods, and it eliminated the steady-state error. Furthermore, the chattering phenomenon was reduced through the use of a switching sigmoid function. The stability of the proposed controller under parameter uncertainties and load disturbances was proven, using the Lyapunov stability theory. Finally, the performance of this control method was verified through numerical simulations and experimental tests, achieving fast dynamics and good robustness for IM drives.

Montoya et al. [24] presented a paper describing the output voltage regulation control for an interleaved microgrid connected to a direct current (DC), which considered bidirectional current flows. The proposed controller was based on an interconnection and damping passivity-based control (IDA–PBC) approach, with integral action that regulated the output voltage profile at its assigned reference. These authors also designed a control law, using non-linear feedback, that ensured asymptotic stability in a closed loop, according to Lyapunov. Moreover, the IDA–PBC design added an integral gain to eliminate the tracking errors possible in steady-state conditions. Numerical simulations, carried out in the piecewise linear electrical circuit simulation (PLECS) package for MATLAB/Simulink, enabled the assessment of the effectiveness of the proposed controller and its comparison with a conventional proportional integral controller under different scenarios, considering strong variations in the current injected/absorbed by the DC microgrid.

Zhang et al. [25] derived a mathematical model of asymmetric thrust magnetic bearings for a cold compressor, and analyzed the changes in the system characteristics owing to changes in the equilibrium position. By constructing PID controllers associated with the structural parameters of the magnetic bearing, they realized the adaptive adjustment of the control parameters under different balanced position commands. The simulation and experimental results proved that the gain-scheduled control method proposed in this paper could achieve robust stability of the rotor, in the range of 50 to 350 μm, and not at the cost of the response speed, adjustment time and overshoot. These research results have significance for the structural design of asymmetric thrust magnetic bearings and play an important role in the commissioning and performance improvement of cold compressors.

In the last paper of this Special Issue, Chen et al. [26] proposed a Witty control system, using a revised recurrent Jacobi polynomial neural network (RRJPNN) control and two remunerated controls with an altered bat search algorithm (ABSA) method, in order to control the electromagnetic actuator systems employed in a rice milling machine system. The Witty control system, with a finer learning capability, could fulfil the RRJPNN control, which involved an attunement law, two remunerated controls, which also have two evaluation laws, and a dominator control. The aforementioned attunement and evaluation laws were derived from the Lyapunov stability principle. Moreover, the ABSA method could acquire adjustable learning rates, to quicken the convergence of the weights. Finally, the proposed control method exhibited a finer control performance, which was confirmed by the experimental results.

The number and the quality of the papers presented in this Special Issue have shown that the design and implementation of new control schemes for different actuators is an active research area that attracts the interest of the scientific community.

Finally, as the Guest Editors, we would like to thank all of the authors who submitted papers and, therefore, contributed to the success of this Special Issue. All the papers submitted were reviewed by experts in the field and I would like to extend my thanks to these reviewers; without their input, the Special Issue would not have been a success. We would also like to thank the Editorial Board for their assistance in managing this Special Issue.

Author Contributions: O.B., J.A.C. and P.A.: writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors wish to express their gratitude to the Basque Government through the project EKOHEGAZ II (ELKARTEK KK-2023/00051), to the Diputación Foral de Álava (DFA) through the project CONAVANTER, to the UPV/EHU through the project GIU23/002, and to the MobilityLab Foundation (CONV23/14, CONV23/12), for supporting this work.

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

References

1. Tan, C.; Lin, M.; Xia, H.; Zhao, B. Fault-tolerant tracking control for nonlinear systems with multiplicative actuator faults in view of zero-sum differential games. *Neurocomputing* **2024**, *567*, 127037. [CrossRef]
2. Li, A.; Qin, D.; Guo, Z.; Xia, Y.; Lv, C. Wet clutch pressure hysteresis compensation control under variable oil temperatures for electro-hydraulic actuators. *Control Eng. Pract.* **2023**, *141*, 105723. [CrossRef]

3. Li, J.; Lu, Y.; He, F.; Miao, L. Motion control of hydraulic actuators with nonlinear friction compensation: Applied to variable valve systems of diesel engine. *ISA Trans.* **2023**, *137*, 561–573. [CrossRef]
4. Liu, Y.; Chen, X.; Yu, Z.; Yu, H.; Meng, L.; Yokoi, H. High-precision dynamic torque control of high stiffness actuator for humanoids. *ISA Trans.* **2023**, *141*, 401–413. [CrossRef]
5. Sai, H.; Xu, Z.; He, S.; Zhang, E.; Zhu, L. Adaptive nonsingular fixed-time sliding mode control for uncertain robotic manipulators under actuator saturation. *ISA Trans.* **2022**, *123*, 46–60. [CrossRef]
6. Ding, S.; Zhao, T.; Zhang, W.; Gao, F.; Zhu, B.; Tang, Z. Motion-inhibition control of a multi-robot mooring system using an actuating force fuzzy control method. *Ocean Eng.* **2023**, *267*, 113236. [CrossRef]
7. Fan, Y.; Shi, Y.; Mu, D.; Liu, J.; Li, Z. Global fixed-time adaptive fuzzy path following control for unmanned surface vehicles subject to lumped uncertainties and actuator saturation. *Ocean Eng.* **2023**, *286*, 115533. [CrossRef]
8. Yan, S.; Qian, H.; Ding, P.; Chu, S.; Wang, H. Finite-time tolerant containment control for IT2 T-S fuzzy network multi-agent systems with actuator faults, packet dropouts and DoS attacks. *ISA Trans.* **2023**, *137*, 199–209. [CrossRef]
9. Ziaei, A.; Sinafar, B.; Kharrati, H.; Rahimi, A. Concurrent-learning-based event-triggered fault tolerant attitude control for spacecraft with actuator faults. *Adv. Space Res.* **2024**, *73*, 95–107. [CrossRef]
10. Lázaro, R.P.S.; Fuentes-Aguilar, R.; Chairez, I. Trajectory tracking control with state restricted gains for a magnetic pendulum using electromagnetic actuators. *ISA Trans.* **2023**, *139*, 475–483. [CrossRef]
11. Wang, W.; Wen, T.; He, X.; Xu, G. Robust trajectory tracking and control allocation of X-rudder AUV with actuator uncertainty. *Control Eng. Pract.* **2023**, *136*, 105535. [CrossRef]
12. Wan, Q.; Cao, L.; Pan, Y.; Lin, W. Improved prescribed performance fuzzy control for nonlinear multiagent systems with actuator faults and dual input saturations. *Eur. J. Control* **2024**, *75*, 100937. [CrossRef]
13. Liu, A.; Lai, G.; Xiao, H.; Liu, Z.; Zhang, Y.; Chen, C.P. Resilient adaptive trajectory tracking control for uncalibrated visual servoing systems with unknown actuator failures. *J. Frankl. Inst.* **2024**, *361*, 526–542. [CrossRef]
14. Tang, L.; Liu, J.; Wang, L.; Wang, Y. Robust fixed-time trajectory tracking control of the dynamic positioning ship with actuator saturation. *Ocean Eng.* **2023**, *284*, 115199. [CrossRef]
15. Khan, A.M.; Kim, Y.; Shin, B.; Moghadam, M.H.; Mansour, N.A. Modeling and control analysis of an arc-shaped SMA actuator using PID, sliding and integral sliding mode controllers. *Sens. Actuators A Phys.* **2022**, *340*, 113523. [CrossRef]
16. Acho, L.; Pujol-Vázquez, G. Enhancing Vibration Control in Cable-Tip-Mass Systems Using Asymmetric Peak Detector Boundary Control. *Actuators* **2023**, *12*, 463. [CrossRef]
17. Zhang, P.; Shi, Z.; Yu, B. Research on Friction Compensation Method of Electromechanical Actuator Based on Improved Active Disturbance Rejection Control. *Actuators* **2023**, *12*, 445. [CrossRef]
18. Wu, H.; Zhai, X.; Gao, T.; Wang, N.; Zhao, Z.; Pang, G. Balancing Control of an Absolute Pressure Piston Manometer Based on Fuzzy Linear Active Disturbance Rejection Control. *Actuators* **2023**, *12*, 275. [CrossRef]
19. Zhu, S.; Li, H.; Wang, G.; Kuang, C.; Chen, H.; Gao, J.; Xie, W. Research on Fault-Tolerant Control of Distributed-Drive Electric Vehicles Based on Fuzzy Fault Diagnosis. *Actuators* **2023**, *12*, 246. [CrossRef]
20. Sun, Y.; Liang, X.; Wan, Y. Tracking Control of Robot Manipulator with Friction Compensation Using Time-Delay Control and an Adaptive Fuzzy Logic System. *Actuators* **2023**, *12*, 184. [CrossRef]
21. Hashim, Z.S.; Khani, H.I.; Azar, A.T.; Khan, Z.I.; Smait, D.A.; Abdulwahab, A.; Zalzala, A.M.; Jawad, A.J.M.; Ahmed, S.; Ibraheem, I.K.; et al. Robust Liquid Level Control of Quadruple Tank System: A Nonlinear Model-Free Approach. *Actuators* **2023**, *12*, 119. [CrossRef]
22. Chaiprabha, K.; Chancharoen, R. A Deep Trajectory Controller for a Mechanical Linear Stage Using Digital Twin Concept. *Actuators* **2023**, *12*, 91. [CrossRef]
23. Shiravani, F.; Alkorta, P.; Cortajarena, J.A.; Barambones, O. An Enhanced Sliding Mode Speed Control for Induction Motor Drives. *Actuators* **2022**, *11*, 18. [CrossRef]
24. Montoya, O.D.; Serra, F.M.; Gil-González, W.; Asensio, E.M.; Bosso, J.E. An IDA-PBC Design with Integral Action for Output Voltage Regulation in an Interleaved Boost Converter for DC Microgrid Applications. *Actuators* **2022**, *11*, 5. [CrossRef]
25. Zhang, S.; Wu, J. Gain-Scheduled Control of Asymmetric Thrust Magnetic Bearing. *Actuators* **2021**, *10*, 329. [CrossRef]
26. Chen, D.F.; Chiu, S.P.C.; Cheng, A.B.; Ting, J.C. Electromagnetic Actuator System Using Witty Control System. *Actuators* **2021**, *10*, 65. [CrossRef]