Guest Editorial
Introduction to the Focused Section on Design and Control of Hydraulic Robots

I. Introduction

SINCE the 1980s hydraulic robots have been a key technology allowing to push the state of the art in robotics by demonstrating new levels of performance in terms of rough terrain locomotion, balance, speed, dexterity, and robustness (e.g. Boston Dynamics's robots, SARCOS Raytheon's humanoids, and exoskeletons, but also academic efforts such as IIT's HyQ, Shandong University's SCalf, etc). Inspired by these results, an increasing number of academic groups are (re-)discovering hydraulic actuation for applications where high power density, robustness, and high control bandwidth are crucial requirements.

The ultimate goal for legged robots is agility comparable to bi-/quadrupedal animals (walking, running, jumping), which requires high-performance control of the hydraulic actuators and sufficient power-to-weight ratio provided by the actuators. In addition to these advanced high-tech hydraulic robots, hydraulic actuation has been used for decades in a variety of mobile (off-highway) heavy-duty machines (e.g., construction, forestry, mining, and agricultural machines) due to their higher robustness and significantly larger power-to-weight ratio compared with electric actuators. It is highly expected that the development in robotics will revolutionize this heavy-duty machine industry just as is currently happening in the car industry. In fact, the first commercial products, such as the Sandvik AutoMine for semiautonomous underground mining machines and the John Deere Intelligent Boom Control for forest machines, are already available in the market.

Both legged robots and heavy-duty utility machines are mobile platforms that require a significant energy autonomy to assure sufficient operational time. Thus, future ambulatory robots need to be designed with sufficient energy autonomy, which entails designing highly energy-efficient actuator systems. Improving the energy inefficiency of traditional hydraulic system design concepts is, thus, an important focus of recent research.

The main objective of this Focused Section is to report on the most recent advances in the field of hydraulic high-performance robots and actuators with a special focus on their design and control. Out of the 18 submitted papers, 8 papers were accepted for this Focused Section: 3 papers investigate force control of different machines (i.e., exoskeleton, manipulators, and a walking excavator), 2 papers report about the design and testing of legged robots (i.e., a humanoid and quadruped robot), 1 paper investigates the performance of a variable-speed-displacement pump controlled motor system, and 1 paper presents a novel magnetorheological damper design. Additionally, a survey paper on the control of hydraulic robotic manipulators with projection to future trends rounds off this Focused Section.

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II. Highlights of the Focused Section

In the following, we give an overview of the contributions of the Focused Section. Three of the eight accepted papers are about force control. The first paper is authored by Chen *et al.* and presents an adaptive robust cascade force control of a one-degrees of freedom (DOF) hydraulic exoskeleton for human performance augmentation. This cascaded force controller has a high-level controller for generating the desired command, whereas motion tracking is the low-level controller's responsibility. An adaptive robust control (ARC) algorithm is developed for both controllers to improve the robust performance of the system to various model uncertainties. Comparative simulations and experiments demonstrate that the proposed ARC force controller can achieve smaller interaction forces as well as enhanced robust performance to model uncertainties.

The second paper in the group about force control is authored by Koivumäki and Mattila and presents a stability-guaranteed impedance control of hydraulic robotic manipulators. In their novel Cartesian space impedance control method, a special connection between the proposed impedance control parameters and the targeted impedance is discovered by using the framework of subsystem-dynamics-based virtual decomposition control approach. This makes a stability-guaranteed (based on the L_2 and L_∞ stability) nonlinear-model-based control (NMBC) of hydraulic robotic manipulators possible for the first time in both free-space motions and constrained motions. Experiments with a heavy-duty hydraulic manipulator rigorously support the mathematical theorems on the stability-guaranteed (Theorem 3 in the paper) target impedance behavior (Theorem 1 in the paper).

The third paper is authored by Hutter *et al.* and treats the topic of force control for active chassis balancing of a walking excavator. Automated balancing is implemented as a contact force optimization problem including constraints on contact forces and joint torques. The approach was tested in a Gazebo simulation and validated in different experiments using a prototype walking excavator machine. The authors demonstrate how the approach allows the operator to directly set simple high-level commands like cabin pose.

The second group contains two papers in the field of legged robot design. The first paper is authored by Hyon *et al.* and describes the design and experimental evaluation of a fast torque-controlled hydraulic humanoid robot. The presented robot is called TaeMu and has 15 hydraulically actuated joints. Its six-DOF legs have a similar mass distribution to that of human legs. The authors present details of the hardware design, as well as the passivity-based controller design for joint torque and whole-body motion control. Experimental results demonstrate the robot's joint speed, basic torque control, full-body compliant balancing with attitude regulation/tracking, and balanced squat motions.

The second paper is authored by Semini *et al.* and presents the design of the hydraulically actuated, torque-controlled quadruped robot HyQ2Max. The new 80 kg robot has 12 torque-controlled DOF and is an evolution of IIT's agile and versatile robot HyQ. The paper describes various aspects of the improved, ruggedized design with a special focus on the actuators. The selection and optimization of the hydraulic actuators and four-bar linkage parameters are based on the simulation of seven characteristic motions that include trotting on rough terrain and stair climbing. The robot demonstrated trotting and self-righting.

The focus of the paper of Yang *et al.* is an investigation in performance of variable-speed-displacement pump controlled motor system (VSDPM), which is a commonly used driving method in heavy-duty hydraulic manipulators. These types of hydrostatic systems in open-circuit or closed-circuit configuration are used especially in base rotation joint in heavy-duty excavators and cranes in which inefficient valve controls are replaced by them. For enhanced energy efficiency, variable-displacement pump controlled motor system (VDPM) is compared with a variable-speed-displacement pump controlled motor system (VSDPM) utilizing an experimental test rig. Through comparative analysis, the paper reports that VSDPM can achieve a better efficiency performance at low speed and low torque, whereas VDPM performs better at high speed.

The paper written by Aguirre *et al.* presents a proposal and preliminary feasibility study of a novel toroidal magnetorheological piston. The paper is an extension of previously published work by the authors on a new magnetorheological piston head design inspired by toroidal electromagnets. The paper describes the mechanical, electromagnetic, and hydraulic models of the damper that led to the equation for the damping force. Several experiments were conducted to assess the damping force performance of the prototype in comparison with a conventional annular head damper. Force control experiments round off the paper.

The last paper authored by Mattila *et al.* presents a survey on control of hydraulic robotic manipulators with projection to future trends. The survey introduces the recent advancements in the control of multiple-DOF hydraulic robotic manipulators, covering both free-space and constrained motions. The main focus of the survey was on papers that promote good scientific practices of: 1) theoretically sound stability-guaranteed control design; and 2) replicable and measurable robotic research. To evaluate and benchmark different free-space control methods, a normalizing performance indicator ρ (the ratio of the maximum position tracking error with respect to the maximum velocity) is used. The indicator reveals that stability-guaranteed NMBC designs have resulted in the most advanced control performance. The literature survey also reveals that, unfortunately, from the reviewed papers only a few papers promoted the aforementioned good scientific practices. The survey includes 50 papers on control of multiple-DOF hydraulic robotic manipulators and, in total, 131 papers are cited. In addition to stable closed-loop control, lack of energy efficiency is another significant challenge in hydraulic robotic systems. After the literature survey, the paper pays attention to the tradeoff between energy efficiency and control performance, and potential solutions are presented. Finally, for hydraulic robotic systems, open problems are defined and future trends are projected.

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