Guest Editorial
Introduction to the Focused Section on Anthropomorphism in Mechatronic Systems

I. Introduction

ANTHROPOMORPHISM has served as a useful guiding principle for design and control of robotic systems in man's pursuit of "making a machine in his own image." The renewed interest in recent years arises from the need to develop human-like robotic and mechatronic systems (and subsystems) to operate in, interact with, and cohabit human-built environments.

From a morphological perspective, numerous novel designs have been proposed ranging from prosthetic/robotic hands, for performing dexterous grasping and manipulatory tasks, to lower limb exoskeletons and walking robots, for enabling ambulation in our homes and the outdoors. The new generations of anthropomorphic mechatronic systems (and subsystems) capitalize on advances in miniaturization of sensing/actuation and the ongoing revolutions in embedded computation and wireless communication.

This "Focused Section on Anthropomorphism in Mechatronic Systems" of the IEEE/ASME Transactions on Mechatronics (TMECH) is dedicated to new advances in modeling, design, analysis, control, implementation, and validation of such anthropomorphic mechatronic systems as we pursue the dream of reaching the level of mobility, manipulation, fluidity, and expressivity of humans. This collection of nine multidisciplinary papers examines the role of anthropomorphism in inspiring and informing the design and control of mechatronic systems. In keeping with the traditions of the Transactions, these papers not only highlight the amalgamation of the life sciences with the science/engineering of mechatronic systems, but also the merger of theoretical rigor with experimental validation. We hope that this Focused Section will serve as a compilation of the recent developments in these topics and will be an important source of information for researchers.

II. Related Articles Published in the Last Five Years in IEEE/ASME Transactions on Mechatronics

At the outset, we would like to note the role played by innovation and advances in the principles and packaging of sensing and actuation. The Transactions archives numerous efforts on developing, validating, and deploying the new generation of novel miniaturized integrated sensor and actuator subsystems, at the forefront of the mechatronic systems revolution. Past Focused Sections including Mechatronic Systems for MRI Applications [1], Medical Mechatronics [2], Microelectromechanical Systems (MEMS)/Nanoelectromechanical Systems [3], and Biomimetics [4], provide a good high-level overview of the more recent efforts that are pertinent to the development of anthropomorphic systems. Recent actuation-related efforts, for human-scale power generation while allowing for safe interactions with humans, are critical for realization of anthropomorphic systems. This includes *individual actuation technologies*, such as shape memory alloys (SMAs) [5]–[7], eddy-current/magnetorheological brakes [8], [9], and elastomers [10], as well as *novel actuator subsystem design realizations*, such as the antagonistically driven linear actuator (ANTLA) [11] or series-elastic actuation [12], and many others, too numerous to list in greater detail.

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A. Bipedal Locomotion and Humanoids

Anthropomorphism is showcased very prominently in the design and control of bipedal locomotion implementations, whether as free-standing and walking humanoids, or wearable exoskeletons coupled intimately with a human user. The desire to match the flexibility and robustness of human walking leads to creation of systems with highly articulated kinematic structure. However, the ensuing complexity of their multi-DOF structure and the significant kinematic and actuation redundancy creates challenges in maintaining postural stability, as well as whole-body operation of humanoid robots.

Agrawal and Fattah [13] propose mechanical design enhancements for a biped that results in simplified dynamic equations of motion. In particular, the constant-inertia matrix, absence of coriolis and centrifugal terms, and simplified gravitational terms simplify the development of robust real-time controllers for stabilization and trajectory following.

While offering high power-to-mass ratio, the slow response of SMAs can potentially destabilize biped robot deployments. Esfahani and Elahinia [14] examine enhancements to an SMA-actuated biped, by modeling articulated walking dynamics and implementing a delay-compensation walking-pattern filter to reshape trajectories and ensure compatibility with SMA-actuated biped robots.

Neo *et al.* [15] developed a method to generate whole-body motion using cascaded inverse-kinematics motion generation schemes, to satisfy the desired movements of the selected intermediary manipulation points. The paper discusses operation of a 30-DOF humanoid robot (HRP-1S) by an operator using two 3-DOF joysticks that can switch between the multiple intermediary operational points.

Harada *et al.* [16] examine implementation of a task-space arm impedance-control behavior in humanoid robots to facilitate pushing manipulation of objects. They implement and experimentally validate a real-time foot placement adaptation behavior to allow the humanoid robot to stably push varying mass objects.

B. Wearable Mechatronic Systems and Exoskeletons

The TRANSACTIONS also has many examples of wearable mechatronic systems, such as gloves or shoes, with advances driven by improvements in components, better ergonomics, or new functional settings (e.g., within an MRI machine).

For example, Vanello *et al.* [17] discuss a fabric-based sensing glove, made of a distributed sensor network of piezoresistive conductive elastomers integrated into an elastic fabric that can be used to monitor hand posture and gesture in functional MRI studies. Chiara *et al.* [18] develop a wearable shoe-based system to detect pressure variations on the shoe insole and distinguish four different voluntary foot movements of the user. Biomechanical analysis, using foot anatomy and kinematics, facilitated development of the wearable mechatronic interface that was used to control hand prosthesis.

There is also considerable interest in using data acquired from such sensors and sensor suites for compensatory neural or muscular electrical stimulation, such as for rehabilitation applications. Ming-Yih *et al.* [19] present a computerized foot-pressure-activated sensory-compensation system that uses subcutaneous electrical stimulation combined with visual-auditory biofeedback to enhance standing balance and gait performance in five unilateral transtibial amputees with prosthetic legs.

Nevertheless, while offering reasonable sensing solutions for capturing human-user intent, *the ability to afford bilateral motion and force interactions requires various forms of wearable powered exoskeletons.* Exoskeletons are powered or passive articulated mechanical robotic systems that are designed to be worn by the human user so as to enhance their functional motor performance. Their capabilities and functionality depend both on the *morphological compatibility* of their articulated designs with the human body and *shared volitional control* with the human user wearing them.

To *et al.* [20] discuss a variable-constraint hip mechanism to provide postural stability and coordinate/control the sagittal hip rotation throughout the gait of individuals with paraplegia. Their paper describes the design and testing of the hydraulic system to reciprocally couple the hips or provide passive resistive torques to individually lock and/or free a hip to rotate in one or both sagittal directions.

Zoss *et al.* [21] present the design and analysis of the anthropomorphic Berkeley lower extremity exoskeleton, developed as a pair of active wearable robotic legs for force amplification and enhanced strength/endurance, while supporting significant payloads. The paper discusses aspects of realization of this functionality by an integrated mechatronic paradigm, merging articulated architecture design, hardware implementation, and control realization.

Similar compatibility considerations guide the efforts of Perry *et al.* [22] in their design of a cable-actuated 7-DOF dexterous exoskeleton for neurorehabilitation (CADEN)-7. An anthropometric database, compiled from 19 arm activities of daily living, facilitated the design while accounting for anatomical/physiological workspaces and upper limb joint ranges of motion. Careful mechanical design with base-mounted motors and cable-pulley reductions and routing was employed to realize a low-inertia, high-stiffness, backdrivable, low-backlash design while including the full glenohumeral, elbow, and wrist joint functionality.

Gupta and O'Malley [23] discuss the requirements and constraints involved in the design of a 5-DOF haptic arm exoskeleton for robot-assisted training and rehabilitation in virtual environments. Their work seeks to enhance performance by optimizing the space and weight limitations, workspace requirements, and the kinematic and dynamic constraints placed by the need to work in close contact with the human arm. The resulting stiff, singularity-free, and low-inertia device design is intended to provide high-fidelity kinesthetic feedback for use in robot-assisted rehabilitation and training.

The weight of the wearable exoskeleton often proves to limit deployment, especially in elderly and weakened patients. Kong and Doyoung [24] designed and validated a tendon-driven exoskeletal power-assistive device, called EXPOS, wherein heavy motors, drivers, controllers, and batteries are moved to a castered walker allowing the weight and volume of the wearable exoskeleton to be minimized.

C. Multifingered Hands and Grasping

Several papers have also focused on innovative systems design realizations and control strategies for highly articulated multifingered hands in an effort to recreate some of the flexibility of the human hand. This is an arena where anthropomorphism serves as a guiding light to realize designs and implementations that match the human hand in physical morphology or functional behavior and performance (or both).

From a systems design perspective, Zollo *et al.* [25] examine the design of an anthropomorphic artificial hand that is able to mimic the natural motion of the human fingers for prosthetics and humanoid applications. The mechanical design examines realization of human-like kinematics/dynamics—with three revolute joints in each of the three fingers (thumb, index, and middle) and the abduction/adduction of the opposable thumb. The hand takes advantage of passive distal-finger-joint compliance and a special underactuated transmission to facilitate self-adaptive grasps, driven by only four motors. Subsequently, a hand control scheme uses collected finger-motion data to derive reference control inputs to achieve a human-like motor behavior.

Similarly, Hong *et al.* [26] highlight the hardware and software architecture of the newly developed German Aerospace Research (DLR)–Harbin Institute of Technology (HIT) hand with four identical articulated fingers and a DOF for the palm. The high level of mechatronic integration, in the form of distributed sensing/control with high-speed serial communication coordinating high-performance sensors/actuators, facilitates the compact, modular, and robust electromechanical realization of the hand.

In contrast, Dollar and Howe [27] present design, fabrication, and evaluation of a compliant robotic grasper using a polymer-based shape deposition manufacturing process to develop joints using elastomeric flexures and embed actuator and sensor components in tough rigid polymers. The increased compliance (and robustness) of robot grasping in unstructured environments arises from both the enhanced hand geometric design, and the polymeric material substrate.

Human hands also rely on contact compliance, due to the skin and tissue padding at fingertips, to enhance the quality of the grasping process. Doulgeri and Fasoulas [28] examine the role of soft deformable fingertips in realizing stable grasping and rolling manipulations in 2-D space. Such modeling and analysis serve to guide design enhancements or inform the development of feedback controllers for enhanced robust stabilization to the equilibrium conditions.

Miniaturizing tactile sensing capabilities is a vital precursor to deployment. Beccai *et al.* [29] develop a soft compliant tactile microsensor by embedding a high shear-sensitive triaxial force microsensor into a soft, compliant, and flexible 2-mm-thick package. Their paper discusses various facets of overall implementation, calibration, robustness, and performance testing of this for real-time experimental slippage measurements for application in robotic hands.

From a control perspective, the kinematic and dynamic redundancy inherent in highly articulated multifingered robotic hands creates novel opportunities for dextrous manipulation. However, this potential can be realized only through careful resolution of this redundancy and development of real-time implementations of motion- and force-planning/control strategies.

In particular, the highly nonlinear kinematic and dynamic equations, ensuing from the redundantly articulated finger structures and the joint-coupling transmissions, create challenges. On one hand, Li *et al.* [30] propose and validate interpolation over a lookup table built using an approximate closed-form solution of the finger's inverse kinematics to achieve real-time performance. On the other hand, Liu and Li [31] explore efficient algorithms for real-time optimal grasping, exploiting advances in treatment of linear matrix inequalities. In addition to a comprehensive review, they also present comparative experimental validation of the various real-time optimal grasping-force controls on their three-fingered hand platform.

III. Highlights of the Focused Section

The need for reconfigurability and flexibility has led to the creation of highly articulated electromechanical platforms which pose significant challenges for design and subsequent real-time interactive control of such systems. From the theoretical perspective, enhanced deployments have become possible aided by our improved understanding of both the mathematical tools (e.g., new formulations) as well as the fundamental underlying science (e.g., biomechanics). From a technological perspective, the resulting platforms in every generation become more compact, energy efficient, and easier to control, capitalizing on the triple convergence of computation, communication, and miniaturization.

A. Design Enhancements for Humanoids/Exoskeletons

A set of three papers examines aspects of how to enhance the design of the underlying articulated mechanical system from the view of enhancing energy efficiency, as well as other dynamic-level performance characteristics. For example, there is considerable interest in recreating some of the energy efficiency seen in natural bipedal walking (both human and bird-like) by taking advantage of the natural dynamics.

Mimicking such natural systems has resulted in the creation of nonlinear underactuated systems that have proven difficult to model and control. Nevertheless, Sangwan and Agrawal present their efforts at deployment of a design methodology that renders planar bipedal robots differentially flat, which allows determination of existence, and subsequently, systematic generation of a parameterized limit cycle for this class of planar nonlinear underactuated bipeds. The paper discusses the use of numerical optimization methods to optimize these limit cycles, while satisfying the motion constraints, as illustrated on a two-link biped.

Interest in humanoid robots has also focused on creating human-scale locomotor platforms that can effectively operate (as surrogate humans) in environments engineered for use by humans. The key to this effort is the availability of reliable biped locomotion capabilities—Lohmeier *et al.* focus on aspects of the mechatronic hardware design and real-time control system of a new biped robot *LOLA* intended to mimic dynamic walking of humans. The paper also discusses the newly developed trajectory planning and control algorithms tested in simulation on *LOLA* and physically on another bipedal robot *JOHNNIE*.

Sup *et al.* describe efforts at design, control, and testing of a powered knee and ankle prosthesis for transfemoral amputees that is capable of producing human-scale power. The paper reports their experimental results with a unilateral amputee showing that the device can match biomechanical performance of a healthy person at power consumption levels that allow for 9 km walking between battery recharges.

B. Higher Level Control for Humanoids/Exoskeletons

Four of the papers focus on efforts to develop higher level strategies for control of large-DOF humanoids and exoskeletons, which can potentially enhance the overall performance while reducing the computational loads.

Researchers have long speculated that bipeds, and especially humans, have the ability to estimate and keep track of their center of mass (CoM) during dynamic maneuvers. Cotton *et al.* present work on estimating the CoM location for a tree-structured articulated multibody using the notion of statically-equivalent serial chains. The key benefit comes from the ability to estimate the CoM without using either the system or individual body's mass or length properties, but only knowledge of the kinematic architecture of the system. The authors present a good case for use of this CoM estimation technique for assessing performance of postural control, in humans as well as humanoid robots, to enable a range of applications without requiring an external force plate.

Similarly, compliance is a desirable property both from the viewpoint of engendering safety and recreating human-like performance within human-friendly assistive devices. However, implementing compliant motion/force control on legged robots or exoskeletons has proven to be difficult—especially when coupled with performing difficult motor control tasks, such as bipedal balancing or walking.

Hyon presents a full-body compliant motor control strategy with a virtual musculoskeletal system. Here a passivity-based task-space controller controls Cartesian forces, providing the robot with full-body compliance and balancing ability, while the joint stiffness controller locally stabilizes desired posture trajectories. A set of detailed experimental studies with four kinds of full-body motion control experiments on a hydraulic biped anthropomorphic robot is also presented.

The highly nonlinear and unmodeled bilateral dynamical interactions of the human neuromuscular system with the exoskeleton controller make the design of exoskeleton controllers a challenging prospect. In their paper, Kong and Tomizuka model the brain as a control algorithm amplified by a fictitious gain that can be adjusted to compensate for characteristic musculoskeletal dynamics, varying loads, or other uncertainties. The performance and robustness of such an exoskeleton controller that realizes the fictitious gain is discussed prior to validation by experimental testing with two case studies of elbow-joint and lower extremity active exoskeleton-based assists.

Aoyama *et al.* describe the development and experimental verification of a 3-D biped dynamic walking algorithm based on passive dynamic autonomous control (PDAC). The robot dynamics is modeled as an autonomous system of a 3-D inverted pendulum with two conserved PDAC quantities. Velocity and direction of the walking are now governed by controlling the PDAC constants. The performance of developed controllers for the two PDAC constants is tested by numerical simulations, as well as by experimental testing of the Gorilla Robot III (multi-locomotion robot).

C. Design/Control of Anthropomorphic Hands

A highly constraining factor in the development of biomimetic/anthropomorphic robots is to control the significant number of excess DOF (which allows for reconfigurability and robustness) with the limited number of control channels available. The last two papers in this Focused Section examine biomimetic methods for design and control of highly articulated anthropomorphic multifingered hands that retain much of the flexibility, but offer simplified means of control

The efforts of Dalley *et al.*, in creating an anthropomorphic prototype hand prosthesis for use with a limited five-channel myoelectric interface, highlight this fact. Their highly articulated (16 jointed) hand is differentially driven by a set of five independent actuators to achieve a set of canonical hand postures. The paper describes the design realization of the prosthesis prototype, as well as the experimental force and speed characterization studies performed on the device.

Fingertip-level tactile feedback allows for continuous adjustment of the applied forces and reduction of energy consumption, and the chances of damage/instability as a result of excessive or poorly directed grip forces. However, the absence of this capability in the form of a sensor platform solution that can be deployed for human-scale robotic hands had constrained the efficacy of such multifinger hands. Wettels *et al.* discuss their efforts at developing a compliant MEMS-based design of a triaxial force-sensing tactile sensor and Kalman-filter-based algorithms for estimation and control to provide for rapid, reflexive adjustments of grip, and minimization of forces by a multifingered hand.

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