Guest Editorial

I. INTRODUCTION

RECENT advances in sensing technology have produced exciting new ideas in the growing field of biomechatronic devices. The successful integration of such devices requires thorough understanding of not only mechanical and electrical components, but also related physiology, biology, and neuroscience. To date, however, performances of sensing technologies for living systems falls short in comparison to the ones for nonliving systems, primarily due to the complexity and uncertainty in living systems. There are still major challenges that need to be addressed.

This "Focused Section on Sensing Technologies for Biomechatronics" of the IEEE/ASME TRANSACTIONS ON MECHATRONICS (T-Mech.) highlights the new advances in modeling, design, fabrication, analysis, implementation, and validation of such sensors and related technologies for biomedical applications. Of the 44 papers submitted, 12 have been accepted and are published in the Focused Section.

II. RELATED ARTICLES PUBLISHED IN THE IEEE/ASME TRANSACTIONS ON MECHATRONICS

A. Novel Sensing Principles and Theories

A wireless network of multiple sensors allows for more comprehensive studies compared to a single sensor. Networks are especially useful in modeling large systems as they can span a large volume. Pan and Yang introduced a novel wireless system for real-time monitoring of livestock odors in farms [1]. The system is a network of electronic nose (e-nose) which is capable of collecting odor data from various locations and combines them to predict odor dispersion. A new model of odor dispersion was also made in the same study.

Another active and popular field in biomechatronics is tactile sensing. Compliance and multidirectional sensing are desired properties for a tactile sensor yet usually these two are not achieved at the same time. Beccai *et al.* achieved both flexibility and multidirectional performance by introducing a proper integration of a microsensor to a soft layer [2]. Their soft compliant tactile microsensor is sensitive to slip event detection and complies with the model of skin represented by neurophysiology of grasping.

MRI-compatible component development promotes new approaches in sensing due to the extraordinary environment in MRI rooms. Cine-MRI is the method of utilizing MRI scans to monitor deformed state of active parts of the body such as heart or lungs. However, passive organic tissues require an external actuation synchronized to cine-MRI. Rajendra *et al.* used electrostatic film motor synchronized to MRI machine to achieve high range deformation [3]. This newly proposed method for applying cine-MRI to passive tissues allowed them to visualize deformations without using an external displacement sensor.

Sensors are involved in monitoring physiological motion of biological tissue as well. Bebek and Cavusoglu [4] proposed a whisker-like, elastic position sensor which involves multiple strain gauges and is able to measure dynamic motion at a bandwidth of 10 Hz.

B. Novel Materials and Components

Piezoelectric elements are able to generate an electrical voltage in response to the compressive force applied to its surface, or alternately will deform in the presence of an electric field. These effects make piezoceramics useful as actuators [5], [6], sensors [7], [8], and power generators [9], [10].

Electroactive polymers (EAPs) (or similarly magnetoactive polymers) are another family of promising novel materials employed in mechatronic applications. EAPs are materials that exhibit a change in shape and size when subjected to an electric field. There exist two main categories of EAP actuators: ionic and electronic, which are distinguished according to their activation mechanism. An example of ionic polymers is ionic polymer–metal composites (IPMCs). In 2008, John *et al.* used polypyrrole, a highly conducting polymer, to manufacture a polypyrrole trilayer bender actuator [11]. IPMCs need to maintain wetness and have difficulties to sustain a constant displacement under activation of a dc voltage; however, their low activation voltage, limited power consumption, silent operation, and high flexibility make them suitable for underwater propulsion [12].

Electrorheological (ER) fluids are usually made of extremely fine suspensions of polymer particles in an electrically insulating fluid. These fluids exhibit a rapid change in viscosity under application of an electric field. Thanks to this property, these fluids have been used as ER brakes to alter the resistance or block the output especially in MR-compatible devices. For example, Chapuis *et al.* used an ER fluid-based "clutch" in combination with an ultrasound motor where the clutch was used to control the output force of the system [13]. The downside of ER fluids is that only resistive forces can be produced, and these are achieved through electric fields as high as 4000 V/mm .

C. Novel Fabrication Techniques

Innovative sensors have been often supported by microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) technologies. Readers interested in these technologies are kindly invited to visit the "Focused Section on Mechatronics for MEMS and NEMS," T-Mech., vol. 14, no. 4, 2009. Other key technologies for biomedical sensing are Optics ("Focused Section on Optomechtronics," T-Mech. vol. 15, no. 4, 2010) and Magnetics ("Focused section on Mechtronic

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Systems for MRI Applications," T-Mech., vol. 15, no. 4, 2010). Furthermore, a couple of papers concerning biomedical sensing have been recently published in [14]–[16].

Recent years have seen rapid development in novel materials and components, which open a large field of new opportunities in biomechatronic applications. Thermoplastics and photopolymers are amongst the materials that are being employed in new applications thanks to 3-D printing. 3-D printing is an additive rapid prototyping technique where the material is deposited in layers to manufacture objects from computer-aided design models. This technique represents a relatively inexpensive and highly flexible manufacturing process. It enables us to easily try various designs and customize sensors for a range of applications where high-precision measurements are not a primary design consideration, as shown in the paper by Kesner and Howe of this issue. A further advantage is the easy production planning opportunity and the possibility to share the design with a large research community, e.g., in an open source fashion.

D. System Integration and Application

A popular direction for biomechatronic applications is to develop human-like grasp control with the help of advanced tactile sensors. Wettels *et al.* [17] utilized a tactile sensor array combined with a force-minimizing algorithm to prevent a grasped object from slippage. Melchiorri [18] combined a tactile matrix sensor with a force/torque sensor in order to control the slippage. Besides linear Coulomb friction, Melchiorri examined rotational slip. Tactile sensors are also used in wearable applications for enhanced tactile skills. Tanaka *et al.* [19] implemented a polyvinylidene fluoride film as the transducer of a tactile sensor and attached it on a fingertip in order to sense Braille. A postprocessing method of combining the information on the signal and dictionary is proposed and shown effective. Vanello *et al.* [20] developed an MRI-compatible sensing glove that has a distributed sensor network. The posture of the hand is received through arrays of piezoresistive conductive elastomers that are integrated on an elastic fabric. Bouzit *et al.* [21] presented an active glove for dexterous virtual interactions and rehabilitation. They integrated Hall effect sensors and infrared sensors to the actuation cylinders so as to reduce the necessity of a separate sensing glove.

Gait monitoring via multiple pressure sensors has gained attention in recent years. Kong and Tomizuka [22] created a human motion phase detection algorithm by monitoring the human motion via pressure sensors embedded in shoes. Each sensing unit consists of an air bladder and a pressure sensor. Lee *et al.* [23] used a similar system to provoke other feedback systems in order to improve balance performance of amputees. Pressure sensors are connected to a microcomputer that activates subsensory electrical stimulation and auditory/visual feedback systems to alert the patient. They concluded that subsensory electrical stimulation and visual/auditory feedback improved static balance and dynamic gait, respectively. Pressure sensors are also used for human–machine interaction. In order to have computer aware of actions of the user, Tan *et al.* [24] captured static posture of a person sitting on a chair via pressure sensor arrays mounted over the seat. They made posture classifications based on their study.

MRI-compatible component development has also become a popular topic aiming to extend MRI's role on surgeries and neuroscience studies. Gassert *et al.* [25] presented many fiber-optic force/torque sensors and proposed a 1-degree-of-freedom torque sensor. In another study [26], they developed a teleoperated robot that has an MRI-compatible encoder, force/torque sensor, and a drive mechanism.

III. HIGHLIGHTS OF THE FOCUSED SECTION

The paper "The Use of Piezoceramics As Electrical Energy Harvesters Within Instrumented Knee Implant During Walking" from Almouahed *et al.* exploits the properties of piezoelectricity to build a sensor able to approximately assess the amount of electric power that can be produced within a diagnostic knee implant during normal walking without the need to be powered from an external source of energy. While piezoceramic materials are commonly used as sensors, in this study they have been configured so that these elements can simultaneously be used to sense the force distribution and generate the electric power needed to supply the acquisition, processing, and transmission system located in the stem of the implant.

A two-finger haptic device is developed by Ferre *et al.* shown in "Haptic Device for Capturing and Simulating Hand Manipulation Rehabilitation." The haptic device is capable of capturing and simulating musculoskeletal assessment and triaxial manipulation of hand. This haptic device is shown to be suitable for education and medicine.

The paper "FES-Induced Torque Prediction With Evoked EMG Sensing for Muscle Fatigue Tracking" from Zhang *et al.* presents a joint torque estimation method by using stimulus-evoked electromyography. An adaptive myoelectrical mechanical parameter model effectively predicts torque in fatiguing muscles. The method can be applied to a function electrical stimulation rehabilitation system.

In another work, Gopalai and Senanayake introduced a small-sized, comfortable, light-weight biofeedback system in "A Wearable Real-Time Intelligent Posture Corrective System Using Vibrotactile Feedback." The system includes Internal Measurement Units for calculation of posture and vibration actuators for forewarning the user in case of poor posture. Experiments indicate that the system improves postural control.

The paper, from Li *et al.* is on "Estimating System State During Human Walking With a Powered Ankle-Foot Orthosis." The effective control of ankle-foot orthoses (AFOs), used to correct gait impairments, critically depends on detecting gait events. However, many state-of-the-art AFOs detect gait events simply by checking if each sensor measurement at a particular time exceeds a given threshold. In contrast, this paper develops a state estimator to detect gait events and tests it on healthy subjects and patients with spinal cord injury.

The paper "Photoprocessible Hydrogel Microsensor for Local Environment Measurement on a Microfluidic Chip," from Maruyama *et al.*, introduces a novel hydrogel microsensor to investigate ambient conditions of cells on a microfluidic chip.

pH distribution is detected with a color indicator and oxygen consumption of brown fat cell using a fluorescent oxygen indicator. This can be used to measure the physiological properties in a single cell and can be used for analysis of cell-to-cell communication.

Viscoelastic sensing elements are superior in accuracy compared to metal elements since they have smaller inertia. However, the force–displacement relation in viscoelastic materials is not explicit; therefore, time history of force–displacement measurement has to be tracked. Parietti *et al.* addressed that problem and proposed an observer-based solution in "Series Viscoelastic Actuators Can Match Human Force Perception." This sensor and actuator integrated design allows for high accuracy with less computation.

The paper "A 1-D Capacitive Micromachined Ultrasonic Transducer Imaging Array Fabricated With a Silicon-Nitride-Based Fusion Process" from Logan *et al.* reports a 64-element array capacitive micromachined ultrasonic transducer. The membrane is user-deposited low-stress silicon nitride and the insulation layer is a stacked layer of low-stress and stoichiometric nitride.

The paper "Design Principles for Rapid Prototyping Forces Sensors using 3-D Printing" from Kesner and Howe presents a flexible way of developing sensors using 3-D printing. This allows the fast development of sensors dedicated to the application, but requires specific design principles that are described and exemplified in this paper.

The paper "Wireless and Portable EOG-Based Interface for Assisting Disabled People" from Úbeda *et al.* describes the hardware of an electrooculography-based device that detects the movement of the eyes. The device enables hands-free control of a robot manipulator.

About the decision-making algorithm of network systems, Modi *et al.* proposed an alternative method in "A Socially Inspired Framework for Human State Inference Using Expert Opinion Integration." The proposed method employs several decision-making algorithms and then fuses their results based on the expertise level assigned to them. In this study, the fatigue state of human being is determined using several cues received from a set of sensors.

"A Wearable Sensor Network for Gait Analysis: A Six-day Experiment of Running Through the Desert" from Chelius *et al.* presents a wearable wireless sensor network. The system consists of motion sensors for orientation detection, force sensors in shoe insoles for gait monitoring, and master nodes for monitoring the environment and the network. The sensor network gathers data from all over the body and synchronizes them. It endures long hours of operation.

IV. FUTURE TRENDS

Breakthroughs in biomechatronics are often brought by the advancement of sensing technology. For example, optical coherence tomography (OCT) [27] has been developed for noninvasive cross-sectional imaging in biological systems. OCT uses low-coherence interferometry to produce a 2-D image of optical scattering from internal tissue microstructures in a way that is analogous to ultrasonic pulse–echo imaging. Tomographic imaging is demonstrated *in vitro* in the peripapillary area of the retina and in the coronary artery, two clinically relevant examples that are representative of transparent and turbid media, respectively. OCT has been greatly contributed to medical diagnosis, especially for internal eye surface where it is really hard to be visualized without the assistance of OCT.

It is not exaggerated to say that mechatronic design is on the verge of a revolution, due to novel materials readily available such as described earlier, e.g., materials used in 3-D printing, EAP, and magnetorheological fluids. However, even more innovation can be expected from combining different old and new materials, even existing components readily available, into new mechatronic systems. While not long ago, design was limited to a few materials such as aluminum, brass, and iron, a large range of different materials and components is currently available. For example, to design MRI-compatible systems for well-controlled experiments, we have at disposal plastic components and actuators from LEGO parts, 3-D printing together with hydraulic and pneumatic transmissions, aluminum, and brass [25], [26].

Use of biomolecules is the next trend in chemical odor sensing. Organic cells are highly sensitive to certain molecules; therefore, they are useful in odor detection and differentiating similar odors. Misawa *et al.* designed a microfluidic device that measures the electrophysiological activity of frog eggs (Xenapus laevis oocyte) [28]. Their device can differentiate bombykol and bombykal molecules which have similar odors.

Alternative sensing methods are being applied on most recent robots. Sato *et al.* developed a new type of finger-shaped haptic sensor for a humanoid robot [29]. They made use of the tactile sensor (GelForce) proposed by Kamiyama *et al.* [30]. This sensor consists of a transparent elastic body and red and dark marker matrices to be observed by a charge-coupled device camera aligned to the body. Surface traction fields can be visualized by this method. Tactile sensors also started being utilized in surgery robots in order to enable minimally invasive surgeries. To be used in cardiac surgeries, Ahmadi *et al.* introduced a catheter-based technique that measures the hardness of the tissue in contact [31]. Their design involves a fiber-optic sensor which detects tip deflection and a piezoresistive film that measures the force.

Polygerinos *et al.* [32] presented a triaxial force sensor for MR-guided cardiac catheterization. A fiber-optic extrinsic sensor is utilized to have full MRI compatibility. Zbyszewski *et al.* [33] proposed a novel MRI-compatible tactile sensor for detection of tissue abnormalities. Displacement of a spherical wheel relying on a cushion of air is sensed via transmitted light over an optical fiber. Moreover, new theories on efficiency of MRI guidance in detection of deformation are evolving. Zamani *et al.* proposed a new theory (Compressive Sensing Theory) which states the minimum number of image samples required to construct the observed tissue [34]. By reducing the sampling rate, it is aimed to elevate image acquisition speed.

Various sensors are being used for health monitoring besides motion and gait sensation. Postolache *et al.* [35] embedded ballistocardiographic sensors and three-axis accelerometers to a wheelchair and established a Wi-Fi connection between the sensors and a computer. Besides posture of the patient, they are able to monitor a patient's cardiac and respiratory performance. Meyer *et al.* [36] developed capacitive pressure sensor arrays and integrated them into clothing in order to measure the muscle activity of a local point on the body. They completed several experiments on upper arm and observed muscle activity based on pressure distribution on the system. Another potential application area of pressure sensor arrays is biometrics. Qian *et al.* [37] analyzed the pressure distribution on the floor caused by footsteps and proposed a robust identification method based on gait. Pressure profile and 2-D trajectory of motion could be observed using a network of pressure sensing mat modules.

The most challenging issue in biomechatronics sensing is perhaps to sense the TRUE brain signal. Since the brain signals are extremely small compared with existing noises, it is really hard to say that these are TRUE but not noise. If we can successfully develop a novel sensing system for brain signal, it will greatly contribute to monitoring brain disease or brain–machine interface and so forth.

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Dr. Kaneko served as the Editor-in-Chief of the *Journal of Robotics and Mechatronics*, an Associate Editor of the IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, and an Editorial Member of the *IEEE Robotics and Automation Magazine*. He served as a Part Editor of the *International Handbook of Robotics* and also coauthored a chapter on robot hands. He was the Director of the Hyper Human Research Project Center and the Project Leader of the 21st Century COE on "Hyper Human Technology toward the 21st Century Industrial Revolution." He was a Vice President of the IEEE Robotics and Automation Society during 2004–2005. He has received 21 awards including the Humboldt Research Award, IEEE Best Conference Paper Awards (ICIA, ICRA, ISATP) and IEEE RAS Best Transactions Paper Award. He is currently serving as an Officer of the International Federation of Robotics Research. He was the General Chair for both the IEEE RAS Technical Exhibition of Robotics and Automation (2004) and the 13th International Symposium of Robotics Research (2007).

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Dr. Mihailidis is currently the President-Elect of the Rehabilitation Engineering and Assistive Technology Society of North America.