Guest Editorial
Introduction to the Focused Section on Wireless Mechatronics

***Abstract*—Wireless mechatronic devices, services, and systems are experiencing fast growth in a variety of application fields, such as manufacturing, transportation, and healthcare. For instance, it is envisaged that service and personal care wireless mechatronic systems will become more and more prevalent at home in the near future and will be very useful in assistive healthcare particularly for the elderly and disabled. Another concrete example is radio-frequency identification-based devices and systems that are showing significant potentials in applications from manufacturing, security, logistics, airline baggage management to postal tracking. In an effort to disseminate current advances on wireless mechatronics, this Focused Section reports some of the latest theoretical developments and applications in this fast-growing area.**

***Index Terms*—Mechatronics, radio-frequency identification (RFID), wireless devices.**

I. Introduction

In RECENT years, a rapid growth has been witnessed in the use of wireless techniques across the full range of Mechatronic systems. In terms of areas of usage, manufacturing, transportation, and healthcare are but indicative examples [1]. In particular, radio-frequency identification (RFID)-based systems are showing significant potential in applications ranging from security, logistics, and sensors to airline baggage handling and postal tracking, even stretching to human implantation. It is envisaged that, because of the advantages offered, the trend toward wireless implementation will not only continue but is likely to increase over the years to come. Yet such employment unveils a variety of opportunities and problems.

The steady increase in mechatronic systems that are designed based on a requirement for a wireless communications protocol is necessarily shifting the more traditional centralized network architecture toward a distributed system topology. Such a move decentralizes, the decision-making procedures thereby potentially compromizing the usually encountered hierarchical regimes that have formed the basis of the field till now. A direct consequence of this is that new analytical methods are needed in order to assess the possibilities that have opened up as well to ensure that fail-safe procedures operate and that unforeseen eventualities are restricted and possibly even removed.

This "Focused Section on Wireless Mechatronics" of the IEEE/ASME Transactions on Mechatronics aims at bringing together some of the most promising state-of-the-art exemplars in the field of Wireless Mechatronics at a time when new application areas can benefit from lessons already learned. The 13 papers contained in this section, selected out of the total 56 submitted, cover the bases in terms of theoretical rigor along with practical implementation. The application areas discussed involve some of the more traditional along with some of those newly emerging. Overall, however, the emphasis has been here on selecting papers for this section that contain exciting, innovative, and insightful solutions to the problems witnessed.

II. Recent Work on Wireless Mechatronics

Wireless mechatronic systems are currently used in many application fields. For instance, wireless mechatronic devices, services, and systems consisting of spatially distributed autonomous sensors are used to monitor globally or locally physical or environmental conditions, such as temperature, vibration, pressure, motion, or pollutants. The global increasing adaptation of renewable and alternative energy sources also introduces new challenges on wireless mechatronic technologies.

In robotic applications, a large volume of research has been conducted to advance the state-of-the-art in wireless self-localization and mapping (SLAM), navigation, and stabilization. Menegatti *et al*. [2] addressed the SLAM problem of a mobile robot using the received signal strength indicator (RSSI) transmitted from nearby nodes of a wireless sensor network, along with the robot's odometric information. An extended Kalman filter was adopted to filter the excess of noise characterizing the radio signals due to the typical RF inference and reverberations. An average localization error of less than 1 m was obtained when no *a priori* knowledge is assumed on the wireless node positions.

Wong *et al*. [3] proposed a real-time SLAM algorithm with a relatively lower computational complexity than the optimal Bayesian filter. The algorithm is based on Joint Probabilistic Data Association (JPDA) to locate and track the radiated sources in dynamic and ad hoc robotic wireless sensor networks. In this technique, the observations and their radiated sources are correlated through a semitemporal three-scan JPDA. It was shown that the resultant algorithm could outperform some of its alike primitives.

Miah and Gueaieb [4] developed a mobile robot navigation technique using a customized multiantenna RFID reader mounted on the robot. It avoided adopting the usual noisy and erroneous RSSI-based distance estimation algorithms to measure the distance between the RFID tags fixed in the robot's working environment and the reader. Instead, the proposed technique is based on comparing the relative signal strengths

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received from each tag to continuously tune the robot's direction. Numerical tests showed satisfactory tracking errors under various RF's signal-to-noise ratios.

In another application, the synergistic integration of e-health and wireless mechatronics has opened fruitful research avenues to many researchers recently. Burdea *et al.* [5] presented the Rutgers Arm II, which is a rehabilitation system that helps training patients on strengthening their arms and shoulders, on controlling their arm motion, and on enhancing their endurance and grasp capabilities. The system takes advantage of custom virtual reality games to motivate the patients. Data communication between the sensors mounted on the patient's arm and shoulder and the virtual game is secured through a wireless channel.

A more advanced mobile instrument for motion instruction and correction is reported in [6]. This system enables a physical therapist to map his movements to a patient in a hands-free fashion through expert (trainer) and trainee modules embedded in the system. The captured trainer body motion information is transmitted wirelessly to the trainee. Based on the computed difference between the trainer and trainee motions, directional instructions are generated through vibrotactile stimulus to the skin. This instructs the trainee to follow the direction of the vibrations until they fade away.

The authors in [7] suggested an intelligent monitoring system that can help relatives, home assistants, and healthcare centers, for instance, to monitor people with special needs without interrupting their everyday lives. Since patients, in general, do not like to carry special equipment whenever they go, a home sensor network along with a multisensor analysis and fusion system are developed to monitor the patient's activities and evaluate his health status.

Wireless communication technologies in healthcare applications raise at least two main challenges: 1) the electromagnetic interference (EMI), caused by the RF transmissions, may disturb the functioning of biomedical devices, which may lead to critical consequences and 2) different types of e-health systems may require different quality of service. As an attempt to alleviate these issues, Phunchongharn *et al.* [8] introduced a novel EMI-aware prioritized wireless access scheme. An extensive survey on wireless access schemes and their applications for telemedicine and e-health services can be found in [9]. As for specific applications, for instance, wireless capsule endoscopes have great potentials to overcome problems faced by conventional endoscopy because they are unable to reach small intestines in addition to pain and discomfort to patients. Kim *et al.* [22] developed a locomotive mechanism for wireless capsule endoscopes by using microbrushless dc motors, an ionic polymer metal composite actuator and shape memory alloy wires. Different from Kim *et al.* [22], Simi *et al.* [23] developed a hybrid locomotion mechanism, for which an internal actuating legged mechanism modifies the profile of the capsule while small magnets outside the human body drag the capsule to move to the desired direction. With these active locomotive mechanisms, it aims that an actuating endoscope capsule will be able to move within human intestines and locate the areas of bleeding or tumors.

As for data transmission through wireless links, Paraskevopoulos *et al.* [24] presents an optical wireless communication system with a data rate of Gb/s for industrial applications, such as mechatronic automation systems.

In order to help people with severe motor disorders, Ubeda *et al.* [25] used five electrodes placed the area around the eyes of the user to measure electrooculography (EOG) signals. With this interfacing device, a patient was able to control a robotic arm in the experiments. Chelius *et al.* [26] developed a wireless network consisting of various wireless embedded sensor nodes for analyzing walking and running gaits.

There are many other on-going projects and applications using wireless mechatronic technologies. We just list the aforementioned few examples to shed a light into this promising area.

III. Highlights of This Focused Section

In the paper "*Embedded System Integrated Into a Wireless Sensor Network for Online Dynamic Torque and Efficiency Monitoring in Induction Motors*" by Lima-Filho *et al.*, an embedded system is presented and they had integrated into a wireless sensor network, in doing so providing self-organizing and local processing capabilities. The system was employed directly for on-line dynamic torque and efficiency monitoring in induction motors. The authors reported on a range of experimental tests with which they were able to analyze torque values and compare them favorably with those obtained by means of a workbench dynamic model. They went on to demonstrate the relationship between spectral occupancy and packet error rate for the network.

In "*A Magnetically Sprung Generator for Energy Harvesting Applications*," an electromagnetic energy harvester is introduced and it can harness mechanical vibrations using a resonant generator with a nonlinear magnetic suspension for improved efficiency, reliability, and safety, with smooth integration of energy sources, through automatic control and wireless communication technologies. A toolbox is presented to develop energy harvester, comprising accurate models of the magnetic suspension force and electromagnetic coupling coefficient, which links the mechanical and electrical domains.

The paper "*A Wireless Sensory Feedback Device for Real-Time Gait Feedback and Training*" reported on a real-time feedback system for gait rehabilitation. It is based on transmitting data between force sensors and an Android smartphone after being treated by a dedicated microprocessor. It was shown that the proposed system can improve the gait of the person carrying it without the direct supervision of a rehabilitation specialist. Hence, it is presented as a novel, inexpensive, and effective rehabilitation system for those suffering from gait abnormalities.

A wireless hands-free surgical pointer (WHaSP) to serve minimally invasive surgeries was described in "*The WHaSP: A Wireless Hands-Free Surgical Pointer for Minimally Invasive Surgery.*" The device aims at optimizing the pointer's movements while guaranteeing a satisfactory level of accuracy. Experimental evaluations showed an improved performance over a similar commercial hands-free pointing system.

The problem of the centralized control of multiple nonlinear systems through a wireless communication medium is addressed in the paper "*Shared Nonlinear Control in Wireless-Based Remote Stabilization: A Theoretical Approach*." The paper first derives a sufficient condition for stabilizing a single nonlinear system with time-varying delay using a wireless-based remote controller. Then, it generalizes the concept to the control of plural nonlinear systems with a single centralized control scheme.

In the paper "*A Smartphone-in-the-Loop Active State-of-Charge Manager for Electric Vehicles,*" the authors proposed a novel, spatially distributed and hierarchical control architecture that is capable of regulating the battery state-of-charge by imposing a desired discharge rate, to correct handling of the energy behavior on board. To design such a control system, a three-layer architecture is adopted, composed of a smart phone to run the high-level optimization and control, of a gateway to host the low-level motion controllers, and of the vehicle electronic control unit to take care of the electric motor control and the battery management system.

In "*Hand-Motion Crane Control Using Radio-Frequency Real-Time Location Systems*," Peng *et al*. developed a crane position and sway control system was developed. The operator defines the crane's position reference signal by carrying and moving a radio-frequency tag in his hand. The tag's virtual path is tracked in real time by dedicated position sensors before being fed to a feedback loop to control its trajectory. In addition, an input-shaped controller is implemented to control the crane sway to minimize possible delay times.

Nagaya *et al*. present a robot able to climb on a perpendicular brackched piping and move on the ceiling in the piping with radio control in "*Wireless Piping Inspection Vehicle Using Magnetic Adsorption Force*." This inspection robot adsorbs to the piping using the magnetic adsorption force of a magnetic crawler and moves in piping. They analyzed the magnetic adsorption to design the crawler, and shown the design method of the inspection robot. The robot mounts a radio control unit and a compact radio camera so as to inspect inside of piping.

The control and stability problems for wireless haptic applications are tackled in "*Transparent Virtual Coupler Design for Networked Haptic Systems With a Mixed Virtual Wall*." by Huang *et al*. and "*Wireless Haptic Communication Under Varying Delay by Switching-Channel Bilateral Control With Energy Monitor*," by Tian *et. al*. The first paper presents a virtual coupler for a Phantom Omni Haptic System, for which the manipulator and the controller communicate over a wireless network channel. The design is accomplished through transforming the problem into an $H\infty$ optimization problem. The stability of the entire system is guaranteed based on the passivity theory. The latter one introduces a switching-channel bilateral control scheme for teleoperation over wireless channels. They use a so-called energy monitor to detect whether the slave robot is controlled by the human operator or not. Depending on the detection results, the bilateral controller then decides whether the closed-loop through the channel is switched on or off. Therefore, the position tracking between master and slave robots is improved and the fidelity of haptic feedback is enhanced when the remote environment is of hard objects.

In the paper "*Wireless Mobile Sensor Network for the System Identification of a Space Frame Bridge*" by Zhu *et al*., the field evaluation of the performance of flexure-based mobile sensing nodes (FMSNs) for system identification and condition monitoring of civil structures is presented. In their design, each FMSN consists of a tetherless magnetic wall-climbing robot capable of navigating on steel structures, measuring structural vibrations, processing measurement data, and wirelessly communicating information. The flexible body design of the FMSN allows it to navigate with sharp corners on a structure, and attach/detach an accelerometer onto/from structural surfaces.

Wang *et al*. introduce a communication module design and a model of physical-layer links for wireless intelligent transportation systems in "*An Experimental Vehicular Wireless System and Link Performance Analysis*." The hardware consists mainly of a low-cost multi-interface wireless mesh and a control unit, which functions as a node in a vehicular wireless network, providing high quality of services. A physical-level model of radio links between double mobile nodes is developed to characterize the fading effects in the vehicular wireless network. Experiments show that the proposed system describes well the packet-level behaviors compared with other physical models and packet-level estimators.

In the paper "*Wireless Vision-Based Stabilization of Indoor Micro Helicopter,*" Tanaka *et al*. used a parallel tracking and mapping technique, which employed an on board wireless camera, to detect the position and attitude of a helicopter. The overall scheme presented included the elimination of noise in calibrating between the locally measured coordinate system and a world coordinate system. Excellent path tracking and control performance were shown through experimental results which, impressively, included take off and landing.

IV. Future Trends of Wireless Mechatronics

Mechatronics is the synergic integration of mechanical engineering, electronics and electrical systems, robotics, computational hardware and software and intelligent control in the design of product, process, and systems. The wireless mechatronics involves the high performance wireless communication technologies, networking, embedded microcontroller, smart sensors, microelectro mechanical systems to take the challenges of the 21st century in technological problems and solution. The rapid adaptation of wireless mechatronics and associated techniques into product designs, making the system simple, cost effective, and highly capable of taking the challenges of the new arising problems is in progress.

The future trend of wireless mechatronics will not be restricted to one area or so, rather toward a high degree of collaboration of multidisciplinary research, adaptability and self-organization [10], [15], [16]. It will outcome a very successful intelligent systems. In the past, "intelligence" in the behavior has so far always been achieved by gathering information from one single machine but in future, the usage and retrieval of information will be characterized by an exchange of information between different machines. The smart car with the Lane Keeping Assist System (LKAS) [20], [21] is a perfect example of wireless mechatronics. The system is a combination of different sensing system, environment monitoring, actuation, and control. A lane-departure system may alert the driver that the vehicle is drifting toward the edge of the lane by playing a rumble-strip noise through the speakers. If the driver fails to respond, the system progresses to generating a vibration in the steering wheel that mimics the feel of passing over road-edge rumble strips. If the driver still does not rouse from blissful slumber, the LKAS will actually take over the steering of the car, at least momentarily, to keep the vehicle in its lane. This will be the general future trend of wireless mechatronics: the smart devices will turn into populations of smart devices, exchanging information for optimizing their global behavior as well as possibly competing for limited resources. To achieve a successful wireless mechatronics system there are many challenges and future system will be characterised by the properties such as: higher level of concurrency consisting of large number of autonomous components, decentralization of the control and the principle of self-coordination. A combination of many engineering branches such as mechanical engineering, electrical and electronics engineering, communication technologies, modeling techniques, software engineering especially new code generation techniques, formal analysis methods, and a few other areas need to work together [16]. Though a lot of works are currently undergoing to achieve the desired objective still there are a lot of unsolved issues in the design of current systems. Though the wireless mechatronic systems incorporate parts constructed by different engineering disciplines and computation hardware and software, the actual cooperation during the construction is less developed. Currently, there is no joint development process, no joint modeling formalism, no joint tool usage, and no joint analysis. Each discipline has its own approach, an integrated framework for the construction of wireless mechatronic system is, thus, missing.

For a successful wireless mechatronic system for the future, the general trend and consequently the requirements to achieve that are common in nature, and adhere to all types of wireless equipment, devices and networks. They are as follows.

Cost Effectiveness: the complete system must be cost effective, both in terms of installation and daily operation. If the cost of wireless mechatronic system is very high it will take a long time to become very popular in future.

User Interface: the future wireless mechatronic system should provide a simple and intuitive interface for easy connection and operation, advanced configuration, control, and management.

Security: every wireless mechatronic system with their advanced technology should support mechanisms for securing information flow and ensure data integrity. Communication in future wireless mechatronic system will cross the border of one agent and, thus, has to be more secured.

ISM Bands: for the purpose of global license free operation, wireless mechatronic system should wherever possible use international ISM (industrial, scientific, and medical)—frequency bands for wireless communication [10]–[14].

International Standard: the wireless mechatronic system should follow an international standard to ensure interoperability between equipment from different vendors.

Software Adaptability: the future mechatronic system consists of several autonomously acting agents capable of monitoring their own physical environment as well exchanging information with their agents. This will give rise to new possibilities of adaptation, beyond the current software control. A significant change in current software engineering practices is to spanning over all involved domains, rather that tailoring toward a particular domain.

Mechanical Robustness: the wireless mechatronic system should be industry-grade with respect to mechanical quality and robustness, following some IP rating.

Operation in Explosive Areas: the future wireless mechatronic system should have national certification from the country it is intended to be used if the system is used in explosive zones [15].

EMI Issues: the future wireless mechatronic system should coexist with other systems operating in the same portions of the frequency spectrum. It should not cause any interference to other systems as well as it should be resilient to interference from other systems.

Energy Harvesting: the future wireless mechatronic system will have energy harvesting technologies to generate power for supplying wireless sensors and actuators with energy. The developed device should reside on the developed mechatronic system that generates an electrical power from an ambient mechanical vibration by use of a suitable construction of electromagnetic generator or any other forms such as solar, wind, etc. [17]–[19].

The aforementioned are the general issues the future wireless mechatronic system should deal with though a set of specific requirements to be maintained for individual system.

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