Guest Editorial
Special Section on Recent Trends and Developments in Industry 4.0 Motivated Robotic Solutions

I. Introduction

THE fourth industrial revolution, which becomes matter of fact in the recent and next years, is expected to deeply change the future manufacturing and production processes, and lead to smart factories that will benefit from the main design principles of Industry 4.0: interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity. Robotics will have a key role in this development since innovative technologies and solutions, traditionally associated with the service robotics sector, are going to migrate to industrial smarter robots, exploiting the maturing of navigation, localization, sensing, and motion control technologies. These smarter robots will draw on a much broader range of technology, allowing higher levels of dexterity and flexibility, the ability to learn tasks without formal programming, and to autonomously collaborate with other autonomous devices and human operators, thus reaching nonmanufacturing industries and fields. A deeper attention will have to be paid on safety in dynamic and shared environments with the human-beings and to energy consumption. The development of robotic solutions for the smart factories of Industry 4.0 is already going on, also taking advantage from industry–academia collaboration. Some studies [1], [2] confirm the importance of various enabling factors from a technological readiness perspective when implementation of Industry 4.0 is considered. Research findings conclude that process related objectives/performance measures (flexibility in production/service and stability of the process) are key to technological readiness as part of Industry 4.0 implementation. Application of Industry 4.0 in manufacturing industries is able to minimize the communication boundary in the whole top-down manufacturing supply chain from service providers, retailers, manufacturers, and supplies in the physical world [3]. Even key safety challenges posed by Industry 4.0 have been explored and identified the characteristics that its safety assurance should exhibit. In [4], a set of safety assurance responsibilities, e.g., system integrators, cloud service providers, and things suppliers are presented and discussed. Industry 4.0 architectures and services have enough modularity of such a safety assurance approach as a basis for cooperative, on-demand, and continuous reasoning. Finally, for a historical perspective on industrial robotics, from the beginning to Industry 4.0, see [5].

The aim of this Special Section is the illustration of trends and advanced robotic solutions that can significantly contribute to the smart factories of Industry 4.0.

For this Special Section of the IEEE Transactions on Industrial Informatics, we received 34 article submissions. After a detailed and rigorous peer-review process, we have included 12 original and unpublished articles in the domain of Industry 4.0 with an industrial robotics perspective from different points of view for integrating this new revolution in real applications. We have organized these 12 articles into the following four categories:

1) innovative solutions for robots;
2) smart factories;
3) autonomous mobile agents; and
4) new technologies and applications.

II. Innovative Solutions for Robots

Flexibility, usability, safety, learning capability, and high performance are key issues for the robots working in a smart factory. The three selected papers in this section deals with these topics, proposing solutions for quickly deployable robots, an iterative learning procedure for high-accuracy force tracking, and time-optimal trajectory planning for redundant manipulators through higher order inverse kinematics method.

In “Integration of robotic technologies for rapidly deployable robots,” by Dean *et al.*, the authors present a system that integrates novel technologies to achieve an easy deployment of robots to different production lines, allowing nonrobotics expert users to teach robots different tasks, while they safely interact with them without the need of fences. The proposed innovative technologies, through which the goal is achieved, are an autocalibrated multimodal robot skin, a general robot control framework able to fuse multiple sensor signals, and an intuitive and fast teaching by demonstration method based on semantic reasoning.

In “Iterative learning procedure with reinforcement for high-accuracy force tracking in robotized tasks,” by Roveda *et al.*, the authors investigate a control approach involving multiple learning levels for training the manipulator to execute a repetitive yet partially changeable task, while controlling the interaction

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forces. The proposed approach is based on compliance control and the learning algorithms rely on the iterative learning and reinforcement learning procedures to automatize the controllers' parameters tuning. The authors demonstrate the proposed procedure on a standard industrial UR 10 Universal Robot, equipped by a compliant pneumatic gripper and a force/torque sensor at the robot end-effector.

In "On higher-order inverse kinematics methods in time-optimal trajectory planning for kinematically redundant manipulators," by Reiter *et al.*, the authors address the time optimal path following along a predefined end-effector path for kinematically redundant robots, while nonredundant robots are included as a special case. The authors resolve the kinematic redundancy within the trajectory planning by using the joint space decomposition and a novel pseudoinverse-based solution of the higher order inverse kinematics. They demonstrate the proposed approaches on two examples of kinematically redundant manipulators, while performing the time-optimal motions along the prescribed end-effector paths in compliance with technological constraints.

III. Smart Factories

Smart factories are intended to be characterized by a proper integration of different levels of automation, to achieve a satisfying tradeoff between flexibility, performance, and resources, by a strong networking between real hardware and virtual testbeds, and robust real-time verification procedures to guarantee safety. The three papers in this section give innovative contributions to such issues, through the lessons learned during the Amazon Robotics Challenge 2016, the development of experimentable digital twins (EDTs), and an original data-centered, real-time verification approach for robot systems.

In "Integrating different levels of automation: Lessons from winning the Amazon Robotics Challenge 2016," by Hernandez *et al.*, automating pick and place operations in semistructured environments are presented, demonstrating that current robot technology can already address most of the challenges in product handling: object recognition, grasping, motion, or task planning, under broad yet bounded conditions. The system combines an industrial robot arm, three-dimensional cameras and a custom gripper, based on the robot operating system to implement solutions based on deep learning and other state-of-the-art artificial intelligence techniques.

In "Experimentable digital twins streamlining simulation-based systems engineering for Industry 4.0," by Schluse *et al.*, the authors present the so-called digital twins as nodes within the Internet of things (IoT), which enable networking and automation of the complex value-added chains. The authors demonstrate digital twins becoming EDTs. The networking of EDTs with the real assets leads to hybrid application scenarios in which EDTs are used in combination with real hardware, while realizing complex control algorithms, innovative user interfaces, or mental models for the intelligent systems.

In "From off-line towards real-time verification for robot systems," by Wang *et al.*, the authors propose a real-time verification approach, named *RobotRV*, able to detect potential failures and improve the safety of the robot system. The proposed approach includes a domain specific language (*RoboticSpec*) and an engine to automatically translate the *RoboticSpec* model into a real-time verifier.

IV. Autonomous Mobile Agents

Manufacturing industry is going to benefit from an increasing presence of autonomous mobile robots and automated guided vehicles (AGVs) to enhance the flexibility of the production lines. The three papers collected in this section propose new solutions for mobile robots navigation in an industrial scenario, for shopfloor material handling using AGVs, and for motion planning and scheduling of this type of vehicles.

In "Supervisory control-based navigation architecture: A new framework for autonomous robots in Industry 4.0 environments," by Basilio *et al.*, the authors propose a modular supervisor for the navigation of autonomous robots, actually constituted by two supervisors: The first one enforces the robot to follow the path defined by a planner (running in an external agent), whereas the second one guarantees the satisfaction of specifications relative to collision avoidance and task and movement management.

In "CPS-based smart control model for shopfloor material handling," by Zhang *et al.*, the authors design a cyber-physical system-based smart control model for shopfloor material handling. In the shown approach, the AGVs and base stations at intersections can communicate and interact with each other, therefore, sharing the real-time information online, in contrast to the traditional vehicle control methods. The designed smart control model is demonstrated by a set of simulations and an experiment, while consisting of car-following model, overtaking model, and collision warning and avoidance model.

In "Decentralized motion planning and scheduling of AGVs in an FMS," by Demesure *et al.*, a decentralized motion planning and scheduling of AGVs in a flexible manufacturing system is proposed. The proposed strategy, based on two steps, consists of planning the presumed trajectory so as to avoid collision conflicts detected previously by a central supervisor, and using the presumed trajectories of the neighbors so as to compute a collision-free trajectory with respect to a priority policy. The authors demonstrate the numerical results and an experimental proof of the concept.

V. New Technologies and Applications

The most recent and innovative robotic applications rely on a continuous renewing technological process, which allows the adoption of robotic solutions in various contests, e.g., for inspection purposes and for manufacturing personalized medical stent grafts, like in the papers presented in this section.

In "Dynamic wireless charging for inspection robots based on decentralized energy pickup structure," by Liu *et al.*, the problems of charging for inspection robots in substations are dealt with, proposing a dynamic wireless charging system. Centralized energy pickup and decentralized energy pickup (DEP) are investigated and, on the basis of the comparison of their working performances, the DEP structure is selected. The positioning scheme is realized based on imitative relaying coil structure including the DEP device and the additional sensor coil, and a switching control strategy of the segmented transmitting coils is proposed for the implementation of the developed solution.

In "Deep endoscope: Intelligent duct inspection for the avionic industry," by Martelli *et al.*, the authors present the first autonomous endoscope for the visual inspection of very small ducts and cavities that has been designed and tested in an avionic industrial scenario. As inspected objects, the metallic gearboxes have different residuals, such as sand, machining swarfs, and metallic dust, inside the oil ducts. The designed automatic system uses a robotic arm moving the endoscope with a microcamera. The authors provide different tests with different types of residuals and duct structures while reporting a high detection rate of nearly 98%.

In "A multirobot cooperation framework for sewing personalized stent grafts," by Huang *et al.*, the authors propose a system, adopted as modular design, that includes a personalized mandrel module, a bimanual sewing module, and a vision module. The system implements a learning-by-demonstration approach to transfer human hand-sewing skills to the robots. The demonstrations by human are first observed and then encoded using statistical model. During the autonomous robot sewing, the vision module coordinates the multirobot collaboration. The shown experimental results demonstrate the robots can adapt to the generalized stent designs.

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