Digital Technologies and Automation: The Human and Eco-Centered Foundations for the Factory of the Future

By George Q. Huang, Birgit Vogel-Heuser, Mengchu Zhou, and Paolo Dario

Digital manufacturing processes (Figure 1) have been extensively transformed by ubiquitous connectivity and collaborative robots so much that the industry of the future is pursuing high productivity, efficiency, and customization by becoming increasingly collaborative, connected, and cognitive (IC^3). In fact, these new technologies have fostered a remarkable increase in production efficiency and an exceptional economic growth worldwide. Furthermore, the need to improve the work environment and the reliability of work procedures in complex and integrated systems has been sustaining a fast and increasing adoption of anthropocentric approaches in robotics and automation solutions for industrial processes. We are currently witnessing a real "revolution" aimed at recycling waste materials obtained from production processes. The circular economy paradigm represents a new way of managing value. It also opens up new opportunities for robotics and automation to deliver new manufacturing processes for resource efficiency and smart assembly/disassembly/recycling, in line with the approaches for a sustainable industry.

Figure 1. Digital manufacturing is the application of computer systems to manufacturing services, supply chains, products, and processes. Digital manufacturing technologies link systems and processes across all areas of production to create an integrated approach to manufacturing, from design to production and on to the servicing of the final products.

History

Back in 2018, these arguments strongly motivated the establishment of a dedicated IEEE Robotics and Automation Society (RAS) technical committee (TC) able to bridge and guide academic and entrepreneurial/industrial communities toward the procurement and integration of disruptive technologies (such as collaborative robots, digital manufacturing, 3D printing, industrial Internet of Things (IoT)/cyberphysical systems, and cloud computing) safely and smoothly integrated with humans and within manufacturing/demanufacturing processes. The proposed TC was also conceived to address global, crucial challenges, such as ethical issues on the future role of humans and automation as well as the effect of the introduction of these disruptive robotic and robot-like technologies on workers' conditions in the workplace, well-being at work, valorization of human skills, and the reshaping of production processes.

The workshop titled "IC^3—Industry of the Future: Collaborative, Connected, Cognitive. Novel Approaches Stemming From Factory of the Future and Industry 4.0 Initiatives," held on 2 June 2017, at the International Conference on Robotics and Automation (ICRA) 2017 in Singapore, set the stage for the establishment of the RAS TC on Digital Manufacturing and Human-Centered Automation. It also originated analyses in the field, leading to a TC proposal to RAS in late 2017 by a group of four founding cochairs from three different areas (the Americas, Europe, and Asia): Prof. Paolo Dario, Scuola Superiore

Digital Object Identifier 10.1109/MRA.2021.3095732
Date of current version: 10 September 2021

Sant'Anna, Italy; Prof. George Q. Huang, University of Hong Kong, China; Prof. Peter Luh, University of Connecticut, United States; and Prof. Mengchu Zhou, New Jersey Institute of Technology, United States.

The TC was officially approved during the RAS Technical Activities Board (TAB) meeting at ICRA 2018 (20–25 May 2018, Brisbane, Australia), with the aim of serving as a reference forum to promote research, development, and innovation under two constitutive subfields:

1) *Digital manufacturing*: This embraces and represents the principles of total connection in the factory, integrating automation of production, stock management, product orders, and labor force management.
2) *Bioautomation*: This includes human-centered and environmentally friendly automation, sustainable production, collaborative robotics, circular economy, design for disassembly and waste management, and eco–green social responsibility (Figure 2).

On the one hand, the aim of the TC is to trace the current trends in digital manufacturing with particular attention to social aspects and sustainable welfare. In fact, the adoption of these new technologies tends to reallocate tasks from humans to machines: humans devote themselves to cognitive tasks and coordination/problem-solving activities, whereas machines take care of the routinized ones while simultaneously learning from human expertise. The emerging generation of collaborative robots and robot-like systems is expected to produce humans' work teams instead of competitive replacements and to play a key role in increasing the quantity and enhancing the quality of jobs.

On the other hand, the TC aims at addressing challenges to increase the efficiency and competitiveness of industrial processes by generating interconnected and collaborative robots and robot-like systems that are well integrated into manufacturing industries. They should cooperate with/assist human workers in a bioinspired way, promoting safety at work and improving the ecosustainability of industrial processes. Indeed, humans possess a huge knowledge, and by combining machine learning, data analytics, and human knowledge, a human–machine team can make more reliable and high-quality decisions during runtime.

After the establishment of the TC, the relevance of the synergistic interaction between the two constitutive foci (namely, the extreme optimization of processes targeted by digital manufacturing and the sustainability issues addressed by bioautomation) has grown significantly in scientific communities worldwide. In fact, at the European level, the Directorate–General for Research and Innovation (European Commission) released the document titled "Industry 5.0. Towards a Sustainable, Human-Centric, and Resilient European Industry" on 4 January 2021 (https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/). This document frames the novel concept of Industry 5.0 as a complement to the existing Industry 4.0 (I4.0) paradigm (https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/) by highlighting research and innovation as drivers for a transition to a sustainable, human-centric, and resilient European industry (see Figures 3–5). The following excerpt from the abstract states that: "Industry 5.0 attempts to capture the value of new technologies, providing prosperity beyond jobs and growth, while respecting planetary boundaries, and placing the well-being of the industry worker at the center of the production process."

This document paves the way toward different research opportunities and challenges on sustainability, green and blue economies, and other issues related to megatrends that are shaping the world at a global level (for example, robotics and automation; artificial intelligence (AI); climate change; digital, ecological, and energy transitions; and urbanization), and the 17 United Nations global Sustainable Development Goals for achieving a comprehensive, sustainable, and people-centered development.

Along these lines, many initiatives worldwide [the Paris Agreement for climate change, the European Green Deal for a sustainable future, the U.S.–China joint agreement on climate change, the recent European Union report "Industry 5.0. Towards a Sustainable, Human-Centric, and Resilient European Industry," and the United Arab Emirates (UAE) Energy Strategy 2050, among others] were launched to secure a new paradigm for a sustainable world to combat climate change, pursue a

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Figure 2. Bioautomation includes human-centered and environmentally friendly automation, sustainable production, and collaborative robotics.

human-centric economy, and support digital, ecological, and energy transitions. These themes are very close to the heart of the younger generations, especially Millennials and Generation Z, as demonstrated by the Fridays for Future international movement.

In this regard, the role of robot companions is also particularly important. In fact, the themes of Industry 5.0 and robot companions are closely related and face common challenges in different sectors (the automotive industry, agriculture, medicine, and process digitization) as well as in everyday life (for example, logistics, mobility, high-quality services, affordable health care, and safety) in complex and integrated ecosystems. The concept of robot companions was first introduced in 2011 in the Future and Emerging Technologies

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Figure 3. Document, released by the Directorate–General for Research and Innovation (European Commission), which frames the novel concept of Industry 5.0 as a complement to the existing I4.0 paradigm by highlighting research and innovation as drivers for a transition to a sustainable, human-centric, and resilient European industry. (Source: stock.adobe.com.)

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Figure 5. Infographic representing the concept of Industry 5.0 according to the document titled "Industry 5.0. Towards a Sustainable, Human-Centric, and Resilient European Industry," released by the European Commission. (Source: https://op.europa.eu/en/publication-detail/-/publication/aed3280d-70fe-11eb-9ac9-01aa75ed71a1.)

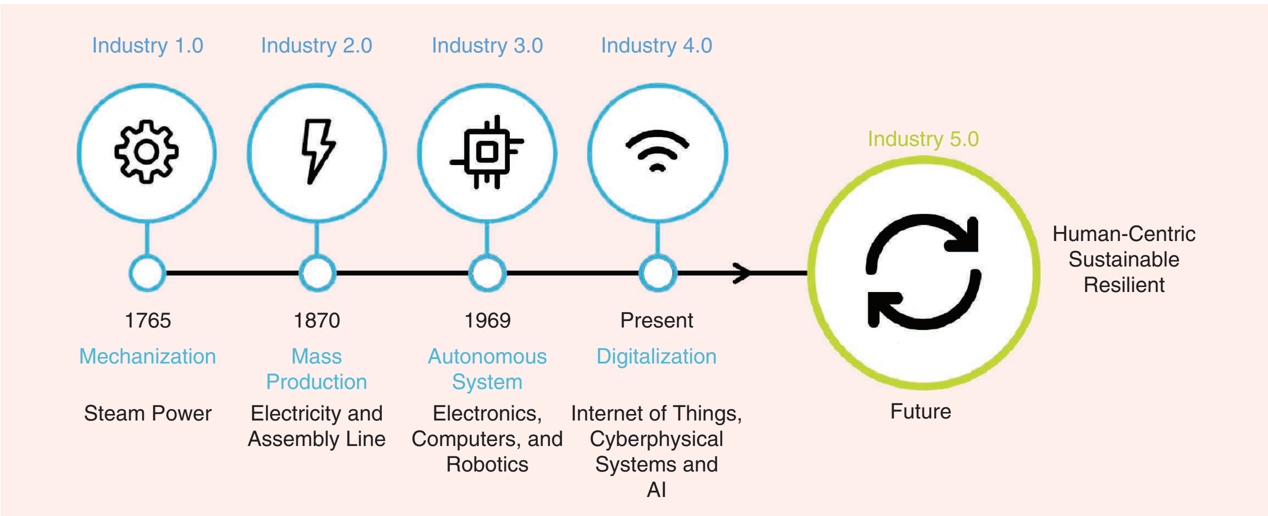


Figure 4. The five industrial revolutions. Like the First Industrial Revolution's steam-powered factories, the Second Industrial Revolution's mass production, and the Third Industrial Revolution's beginning of digitization, the Fourth Industrial Revolution's technologies, such as AI, augmented reality, automation, robotics, and 3D printing should be humanly and ecologically deployed, rising a Fifth Industrial Revolution, changing the way humans create, exchange, and distribute value. Industry 5.0 recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the well-being of the human worker at the center of the production process. AI: artificial intelligence.

(FET) coordination action CA-RoboCom, developed in the 2012 FET Flagship RoboCom proposal, and further elaborated in the FlagEra RoboCom++ Project (https://robocomplusplus.eu/). Robot companions are now receiving increasing attention worldwide, especially in Japan's Society 5.0 [a human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space (https://www8.cao.go.jp/cstp/english/society5_0/index.html)].

Among the roles of robot companions in Society 5.0 (Figure 6) are sustainability, that is, a sustainable (circular) economy, and regeneration, in other words, intervening to remediate the damage already done to the environment. Low energy consumption and recyclable robot companions can play an active role in this paradigm in different ways, including human-centered automation.

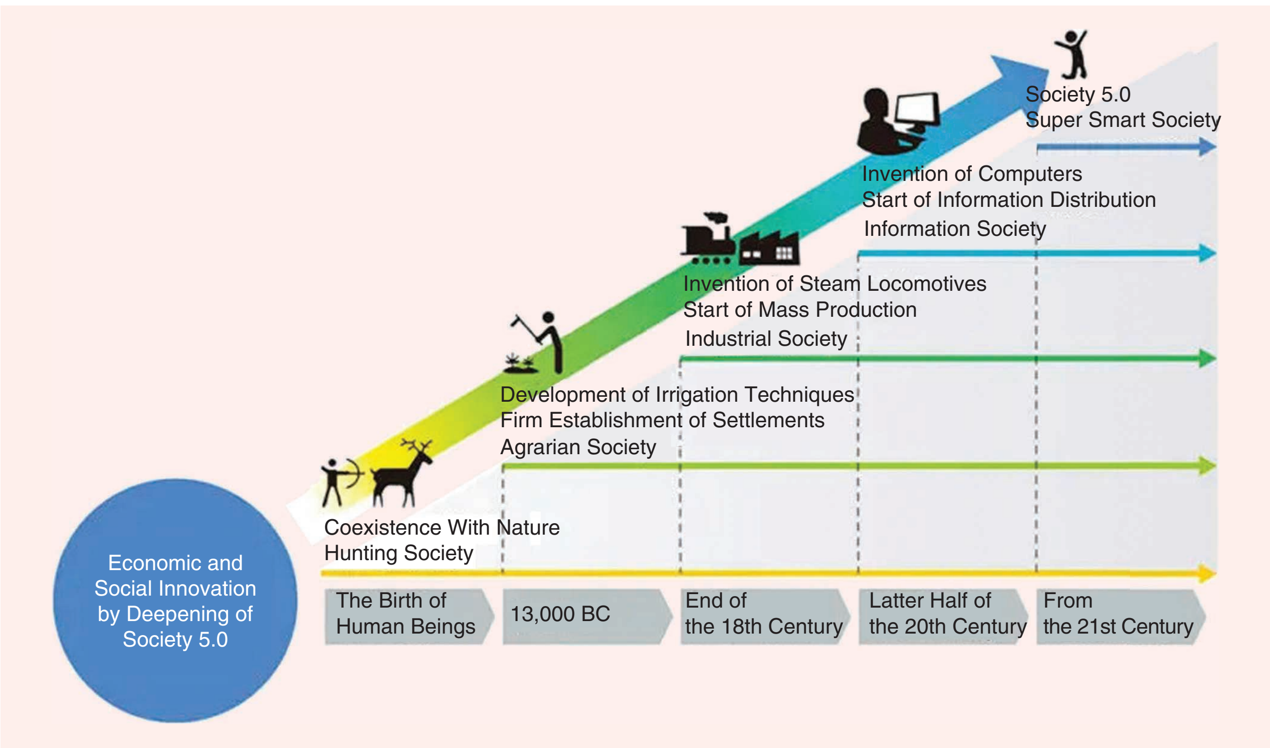
The TC has been sustaining many activities to bridge the gap between digitalization in all phases of the lifecycle of manufacturing systems and humans—the engineers, operators, and maintenance staff of these systems. In the light of the emergence of the Industry 5.0 paradigm and Society 5.0, the TC plans to continue supporting industrial professionals as well as academics, providing an organizational platform on which to discuss, share knowledge, and open issues with experts in the field and also share the use cases and tools that are under development or already available. Recently, the TC has also addressed the sector of automation and robotics for logistics, which is emerging as crucial for economy, technology, society, and the environment after the COVID-19 pandemic.

The TC Organizational Structure and Membership

The main organizational structure of the TC consists of four cochairs. At the end of 2020, one founding cochair, Prof. Peter Luh, retired, and a new female cochair, Prof. Birgit Vogel-Heuser, from the Technical University of Munich, Germany, was recommended to the RAS president and TAB vice president to take over Prof. Luh's role and promote gender diversity of the cochairs. As of 1 March 2021, Prof. Vogel-Heuser is officially the new TC cochair. The TC Scientific Secretariat is coordinated by Dr. Rossella Raso, from Scuola Superiore Sant'Anna, Italy.

A TC website (https://www.ieee-ras.org/digital-manufacturing-and-human-centered-automation) was created at the TC establishment, and it has been updated regularly with relevant information on the TC and news on the activities that it organizes. A dedicated section of the website allows interested persons to join the TC as members. A subscription form (https://app.smartsheet.com/b/form/e099b621f68f45f4a877dcb4888ec490) is available, thanks to the "Smartsheet app" web service, which allows easy management of the members list.

Since the TC establishment, the number of members has increased from a starting core of four founding members to 14 members in 2019, 67 in 2020, and 105 as of 30 June 2021. About 5% of the TC members are affiliated with industry, resulting from subscriptions coming from the Japanese Workroid Users Association (particularly related to the concept of Society 5.0), the Italian Competence Centers,



PREPARED BASED ON MATERIALS FROM THE JAPAN BUSINESS FEDERATION (KEIDANREN).

Figure 6. Society 5.0 is a human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space. (Source: https://www.innovationpost.it/tag/society-5-0/.)

and other European Digital Innovation Hubs, whereas the rest are affiliated with academia.

The geographic coverage, that is the worldwide distribution of the TC members, is good, although there is still a need to engage people from uncovered regions, such as France, Germany, and Singapore, and to attract more members from industry. The official YouTube channel of the TC is available at the following link: https://www.youtube.com/channel/UCIKaqiuOhm-myWN47CZgETQ.

Activities Organized by or Related to the TC

The TC has been quite active over the last couple of years, accomplishing many different tasks. In particular, it has participated in RAS TAB meetings and IEEE major conferences, helped organize several conference workshops, endorsed many activities organized by other RAS TCs, helped with the proposal of special issues and the submission of articles to relevant IEEE journals, and promoted TC fields and related research.

In truth, while keeping focus on its original scope on I4.0, many of the most recent TC activities also have addressed the technological challenges posed by the Industry 5.0 paradigm, which are becoming increasingly popular. The first major event promoted and organized by the TC in cooperation with the FET Flagship European Research Area Network Joint Transnational Call 2016 RoboCom++ Project was the IEEE RAS ICRA 2018 Workshop (https://robocomplusplus.eu/2018/06/11/robocom-workshop-at-icra-2018/) titled "Grand Scientific Challenges for the Robot Companion of the Future," held on 21 2018 May, in Brisbane, Australia.

Several workshops related to major IEEE RAS Conferences were also organized, including the IEEE International Conference on Automation Science and Engineering (CASE) 2020 Workshop (https://www.imse.hku.hk/case2020/ThET5.html), titled "New Frontiers in Smart Factories: Smart Automation and Human–Robot Interaction," held (virtually) on 20 August 2020; the IEEE/Robotics Society of Japan (RSJ) International Conference on Intelligent Robots and Systems (IROS) 2020 Workshop (https://www.santannapisa.it/it/istituto/biorobotica/news/iros-2020-international-workshop-robots-building-robots-digital), titled "Robots Building Robots: Digital Manufacturing and Human-Centered Automation for Building Consumer Robots," held on 26 October 2020, virtually; and the IEEE RAS ICRA 2021 Workshop (https://www.santannapisa.it/it/istituto/biorobotica/news/dinosaurs-vs-unicorns-time-covid-19-pandemic), titled "Dinosaurs vs. Unicorns at the Time of the COVID-19 Pandemic. How Robots May Save Business Dinosaurs From Extinction by Turning Them Into Start-Ups Again," held on 4 June 2021, virtually.

In addition to organizing workshops, the TC also endorsed others, including the European Robotics Forum 2021 Workshop, titled "The Role of Robot Companions in the New Paradigm of Industry 5.0," held on 13 April 2021, virtually; two IEEE RAS ICRA 2021 workshops, titled "Unlocking the Potential of Human–Robot Collaboration for Industrial Applications" and "Multidisciplinary Approaches to Advance Physical Human–Robot Interaction: Physical Assistance for Occupational Applications"; and the 29th Mediterranean Conference on Control and Automation Workshop, titled "Toward Industry 5.0: Sustainable and Regenerative Economy With Focus on Smart Small Towns," held on 22 June 2021, virtually.

The TC also endorsed the Frontiers of Logistics 5.0, organized by Dubai Future Labs, UAE, in partnership with Scuola Superiore Sant'Anna, Italy, a series of events beginning on 28 June 2021 and aimed at exploring the socio-economic, legal, and environmental impact of technological transformation across logistics and the global supply chain in light of the COVID-19 pandemic; and the IEEE RSJ IROS 2021 Workshop titled "Global Research Infrastructures in Robotics: Challenges and Opportunities," to be held on 27 September 2021.

To sustain the development of the two constitutive subfields, a special section on "New Frontiers in Smart Factories: Smart Automation and Human–Robot Interaction" has been proposed to the editor-in-chief and the editorial board of *IEEE Transactions on Automation Science and Engineering* (*TASE*). The special section received 25 manuscripts for possible consideration, and the reviews are currently ongoing at the time of writing. This special section is expected to be published in the October 2021 issue of *TASE*.

The TC cochairs have also been very active in other editorial activities in both IEEE and non-IEEE journals, contributing to the following: (IEEE) "Special Issue on Emerging Social Internet of Things: Recent Advances and Applications," *IEEE Internet of Things Journal*, 2017; "Special Issue on Advancing Intelligent Automation in Sharing Economy," *TASE*, 2018; and the "Special Section on Cyber-Physical Systems," *IEEE Access*, 2019; (non IEEE) "Special Issue on Emerging Edge-of-Things Computing: Opportunities and Challenges," *Future Generation Computer Systems*, 2018; and the "Special Issue on Pushing Artificial Intelligence to Edge: Emerging Trends, Issues, and Challenges," *Engineering Applications of Artificial Intelligence*, 2020. The cochairs have also given keynote/plenary speeches, such as "Internet of Things and Smart Systems—the Next Industrial Revolution," at the 2018 International Conference on Robotics and Automation Sciences in Wuhan, China, and "Smart Manufacturing Ecosystem with Industry 4.0 Technologies," at CASE 2019, Vancouver, Canada.

Summary of Top Three Technical Innovations in the Two TC Constitutive Subfields

All of the TC cochairs have been very active in the TC subfields, implementing several related tasks and projects. The top three technical innovations in the TC subfields are hereby summarized as a description of the outcomes and relevant achievements deriving from completed projects, although mainly related to the TC chair. The TC cochairs' recent work and projects, i.e., on the environmental, social, and governance blockchain and IoT, which are still ongoing, will be disclosed on the TC website and/or in the next year's TC report as soon as they are finalized.

A significant milestone is represented by the establishment of the Italian I4.0 Competence Center "ARTES 4.0." Prof. Paolo Dario is the scientific coordinator of ARTES 4.0, which is a network that specializes in the areas of advanced robotics and enabling digital technologies, such as communication networks, big data, data mining, cybersecurity, the cloud, the Industrial Internet, the IoT, additive manufacturing, simulation, and models of business integration. ARTES 4.0 covers the entire Italian territory and provides support to small and medium enterprises (SMEs) in developing and facilitating I4.0 transformational projects in all domains. The network includes 13 universities and research centers, 112 private partners, seven regions, six Italian Digital Innovation Hubs, the municipality of Pontedera town, and chambers of commerce. The services offered by ARTES 4.0 to companies are 1) I4.0 training and awareness, 2) technical advice on I4.0 for SMEs, 3) the launch and acceleration of technological development and innovative projects, and 4) trial support and "on-site" development of new I4.0 technologies.

In the European initiative European Network of Digital Innovation Hubs With Focus on Artificial Intelligence (AI DIH Network), Prof. Paolo Dario participated with the Competence Center ARTES 4.0 and with the DIH Robotics Innovation Facility BioRobotics Institute. The project was related to AI, which is one of the enabling technologies for digital manufacturing. The initiative aimed at developing a blueprint for cross-border collaboration based on a thorough assessment of hub business models, common systems, collaboration, and governance structures. The action also supports the development of a concrete action plan, including a business case, for the collaboration and networking of DIH and helps the chosen DIHs to unlock their collaboration and networking potential through mentoring and coaching activities.

The project Recovery of Fiberglass Yachts, Trains, and Campers (REVYTA) was cofunded by the region of Tuscany, Italy, under POR FESR 2014–2020. REVYTA–robotics and I4.0 constitute a new industrial and ecosustainable model for fiberglass recycling. The project objective was to develop an industrial and ecosustainable model of a fiberglass waste management and recycling system, first in Europe, leveraging on innovative solutions in the fields of robotics and I4.0, through the dismantling, disposal, and recycling of fiberglass used in the naval sector (boats), the automotive sector (campers), and in transports (railway carriages).

Future Challenges

The principal objective in the near future is to increase the technical value of the TC, particularly in the area of I4.0 and in the emerging area of Industry 5.0. This goal will be pursued by establishing collaborations with other RAS TCs, including Automation in Logistics, Sustainable Production Automation, and Agricultural Robotics and Automation, among others, and with other IEEE TCs, such as Systems, Man, and Cybernetics' TC on Intelligent Systems to Human-Aware Sustainability and the Oceanic Engineering Society's TC on Ocean Observation Systems and Environmental Sustainability.

Another important objective is to strengthen activities tailored to increasing the number of TC members, with particular attention to involving members from industry as well as students, to extending geographic coverage, in particular to uncovered areas in Asia, the Middle East, and developing countries in Central and South America and Africa, and to considering diversity (in particular gender issues).

Finally, the TC commits to propose and organize both conferences and independent workshops and other events (in-person and/or virtual seminars) on topics of interest to the TC community. It will also propose a new Distinguished Lecturer Program, structured as a cycle of online live events involving speakers from academia and industry, aimed at becoming a platform for open discussion and interaction on several topics in robotics and automation and involving popular social media.

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well after the conclusion of the workshop. This document also contains some basic information to introduce students to circuits, electricity, and programming. The projects in the handbook are divided into difficulty levels measured from one to five stars. Each project provides a list of parts required, steps to build the circuit, a circuit diagram produced using Fritzing, and the code for the Arduino if necessary.

The kit (Figure 1) provided to the students contained 33 unique components for a total of 117 parts. This kit was designed to give students the opportunity to build their own creative circuits and explore the possibilities of both circuits and the Arduino. The funds to build this kit and organize the workshop were generously provided through the RAS Initiative Grant as well as through our local Fort Worth IEEE Section.