objectively assessed and levels of compliance determined. *Ontological Standard for Ethically Driven Robotics and Automation Systems*, P7007 [8], provides a set of ontologies with different abstraction levels that contain concepts, definitions, and axioms that are necessary to establish ethically driven methodologies for the design of robots and automation systems. Furthermore, *Standard for Ethically Driven Nudging for Robotic, Intelligent and Autonomous Systems*, P7008 [9], aims to establish a delineation of typical nudges (currently in use or that could be created) that contains concepts, functions, and benefits necessary to establish and ensure ethically driven methodologies for the design of the robotic, intelligent, and autonomous systems that incorporate them. Nudges as exhibited by robotic, intelligent, or autonomous systems are defined as overt or hidden suggestions or manipulations designed to influence the behavior or emotions of a user.

These groups are all open to volunteer experts who are committed to the long-term, sustainable, and humanitarian development of technologies. In the meantime, other SDOs are taking different approaches, keeping their focus on basic safety and essential performance standards. Most importantly, the International Organization for Standardization deals with robotics standards within Technical Committee 299, and its current activities are presented in the following article, "The Flourishing Landscape of Robot Standardization," adapted from the IEEE Standards Education e-magazine December 2017 issue (reprinted with permission) [10].

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The Flourishing Landscape of Robot Standardization

By Theo Jacobs, Jan Veneman, Gurvinder S. Virk, and Tamás Haidegger

International standardization in robotics paves the way to the market for new robotic products, assists to overcome technical barriers in international commerce, and fosters market growth. While safety standards form the primary basis to establish specific types of robotic products in helping create new markets through reducing safety risks for users as well as reducing liability risks for manufacturers, other standards can help to dismantle trade barriers, such as standards on terminology, coordinate systems, performance benchmarking and interoperability-based modular design. With the rapid rise of new robotic domains, standardization also had to shift gears. As the market for (shared space) robots constantly grows, the demand for standards in this area also constantly rises. Due to the large variety of robot designs and application domains, existing and newly developed standards usually do not cover all robots in general but are limited to certain environments and robot types. An important distinction for standards refers to industrial applications versus medical applications versus other (nonindustrial, nonmedical, nonmilitary) applications. This article introduces the main robotics-related standardization activities at the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC).

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Overview of the Robotic Standards Process

Since the early 1990s, standards development organizations (SDOs) have been releasing robotics standards. Yet, given the unprecedented pace of advancement in this field, SDOs are in a very challenging position to regulate rising domains that evolve much faster than the traditional creation cycle of a technical standard. The first IEEE robotic standard came out late (P1872, 2015), born into a rapidly evolving robot standardization environment, mostly outlined by the work of the ISO and IEC. It is important to recognize the work that has been done by these SDOs and review the current hot areas to better understand the landscape of robot standards.

Different SDOs adopt different approaches to fill the existing gaps. While ISO has one central standardization committee, Technical Committee (TC) 299 for robotics, IEC relies on a distributed structure, where robotic standards are mainly developed by TCs and subcommittees (SCs) of various application domains, such as lawnmowers and household appliances. However, IEC has created an Advisory Committee on Applications of Robotics Technology to coordinate robot standardization activities within ISO and IEC. International (safety) standards are based on reaching consensus among the participating countries. Working groups (WGs) are open to all interested stakeholders from industry, academia, and general society, including manufacturers, integrators, and professional end users.

The largest number of robot-related standards has so far been developed by the ISO TC 299 Robotics, which groups together all ISO standardization activities related to robotics, including diverse liaisons with IEC on medical robotics. The current structure of this TC, its (joint) WGs, chairs, and main activities are summarized in Figure 1. Further information on TC 299 is available on the ISO website (https://www.iso.org/committee/5915511.html). The current activities of the TC and the WGs within are detailed in the following sections.

Progress in WG 1: Vocabulary and Characteristics

WG 1 is maintaining robot-related definitions and terminology that are used in the different WGs in TC 299. Fundamental definitions are the terms *robot*, *robotics*, *robotic technology*, and *autonomy*, which are used in the title and scope of the robotics standardization committee. As the market for service robots is still emerging, these definitions are not considered to be final but are expected to be adjusted from time to time as necessary. With the recently initiated review process of ISO 8373, WG 1 will coordinate a systematic review of the definitions with the goal of ensuring that the terminology is fit for future standards and WGs. This will also include a categorization of robots based on their mechanical structure, task, and application domain, which will allow the exact shaping of scopes for standards and WGs.

Apart from basic terminology, WG 1 is dealing with other vocabulary for certain domains, such as navigation or perception, and published ISO 19649 at the beginning of 2017. The standard defines terminology for mobile robots, such as the definitions of wheel types and undercarriage structures. During the last meeting in Suzhou, China, WG 1 started the revision of ISO 8373.

The chair of WG 1 is Soon-Geul Lee (Kyung Hee University, South Korea).

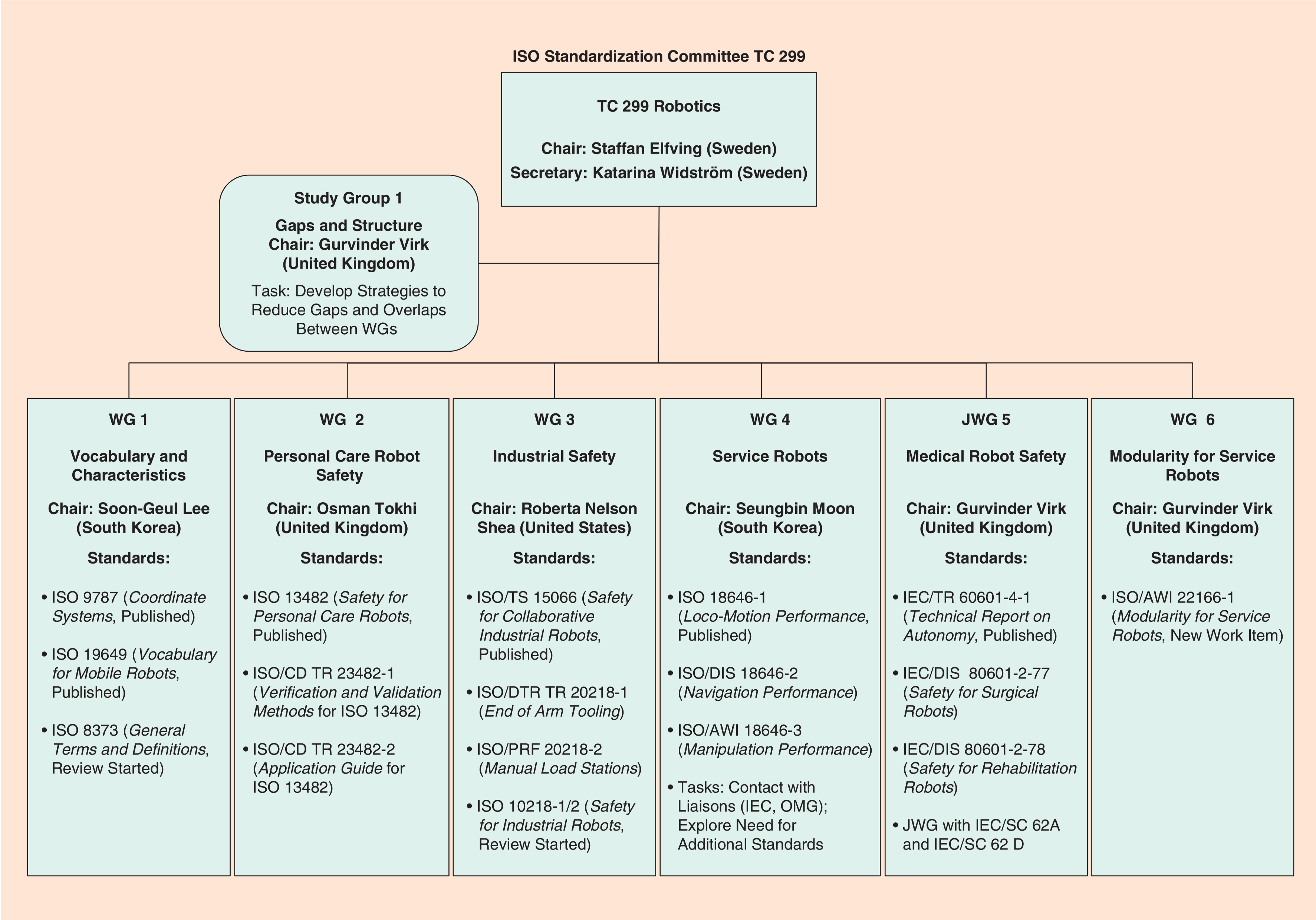

Figure 1. ISO Standardization Committee TC 299.

The standards WG 1 is working on include the following:

- ISO 9787, *Robots and Robotic Devices—Coordinate Systems and Motion Nomenclatures* (published in 2013)
- ISO 19649, *Robots and Robotic Devices—Vocabulary for Mobile Robots* (published in 2016)
- ISO 8373, *Robots and Robotic Devices—Vocabulary* (published in 2012, scheduled for periodic review).

Progress in WG 2: Personal Care Robot Safety

WG 2 has the task to develop safety standards for personal care robots—earthbound robots in direct interaction with the human and contributing directly to his/her well-being. Three robot types representing the personal care robot, i.e., mobile servant robots, person carrier robots, and physical assistant robots, were identified and serve as examples in the standard ISO 13482. With respect to the special situation that personal care robots act in direct vicinity of the user and that the autonomy of these robots is generally high, some clauses were added that are unique in machinery safety, such as instructions dealing with incorrect autonomous actions and decisions.

During the last meeting in Suzhou, China, the WG continued developing two guidance documents that will help manufacturers to apply the standard and to verify compliance of their products. In the technical report ISO TR 23482-1 that is currently under preparation, measures for verification and validation are described that can be used by robot manufacturers for safety testing. Tests include stability tests for different travel patterns (e.g., on ramps or while accelerating or stopping) but also impact tests with crash test dummies. A second technical report, ISO TR 23482-2, provides guidance on how to perform risk assessment and risk reduction for personal care robots.

When these two technical reports are published, WG 2 will start the systematic review of ISO 13482. Most likely this will include splitting up the standard into several parts, so that each robot type can be maintained in a separate document and new robot types can easily be added.

The chair of WG 2 is Osman Tokhi (London South Bank University, United Kingdom). The standards WG 2 is responsible for include the following:

- ISO 13482, *Robots and Robotic Devices—Safety Requirements for*

Personal Care Robots (published in 2014)

- ISO/CD TR 23482-1, *Technical Report: Validation Criteria for Personal Care Robots* (committee draft)
- ISO/CD TR 23482-2, *Application Guide for ISO 13482*, to be published as a technical report (committee draft).

Progress in WG 3: Industrial Safety

WG 3 is dealing with the safety of industrial robots. After the technical specification ISO TS 15066, which provides extended requirements for human–robot collaboration and specifies limits for impact forces and pressures, WG 3 developed two new work items. One is a technical report on the safety of manual load stations, i.e., stations where a worker hands over a part directly to a robot end effector (e.g., a gripper). In addition, a guidance document is developed on the safety of industrial robot end effectors. WG 3 is also in the process of doing a systematic review of ISO 10218-1 and -2, which are now five years old. During the update process, it is intended to integrate content from ISO TS 15066 into these standards.

The chair of WG 3 is Roberta Nelson Shea (Universal Robots Inc.,). WG 3 standards include

- ISO 10218-1, *Robots and Robotic Devices—Safety Requirements—Part 1: Robots* (published in 2011, periodic review started)
- ISO 10218-2, *Robots and Robotic Devices—Safety Requirements—Part 2: Robot Systems and Integration* (published in 2011, periodic review started)
- ISO TS 15066, *Robots and Robotic Devices—Safety Requirements for Industrial Robots—Collaborative Operation* (published in 2015)
- ISO/DTR TR 20218-1, *Robots and Robotic Devices—Safety Requirements for Industrial Robots—Part 1: Industrial Robot System End of Arm Tooling (End-Effector)* (new work item)
- ISO/PRF 20218-2, *Robots and Robotic Devices—Safety Requirements for Industrial Robots—Part 2: Industrial Robot System Manual Load Stations* (committee draft).

Progress in WG 4: Service Robots

WG 4 is engaged in developing standards on robot performance. To compare the performance of functions like path finding, object recognition, or the ability to move on difficult terrain, standardized test methods are necessary. The first standard, ISO 18646-1 for measuring locomotion performance, was published in 2016. The second part, ISO 18646-2 on navigation performance, is also close to publication and includes, e.g., test setups for measuring path repeatability of the turning width of a mobile robot. A third part dealing with manipulation performance has recently been started. In addition, WG 4 has for many years had the special task to monitor the development on the service robot market to identify the need for additional standards for service robots. In recent years, several liaisons have been established with IEC, because the development of standards for autonomous vacuum cleaners and lawnmowers was initiated there.

The chair of WG 4 is Seungbin Moon (Sejong University, South Korea). The standards under this WG include the following:

- ISO 18646-1, *Robots and Robotic Devices—Performance Criteria and Related Test Methods for Service Robot—Part 1: Locomotion for Wheeled Robot* (publication by the end of 2016)
- ISO/DIS 18646-2, *Robots and Robotic Devices—Performance Criteria and Related Test Methods for Service Robot—Part 2: Navigation* (committee draft)
- ISO/AWI 18646-3, *Robots and Robotic Devices—Performance Criteria and Related Test Methods for Service Robot—Part 3: Manipulation* (new work item)
- Additional task: determining need for additional standards for service robots.

Progress in Joint WG 5: Medical Robot Safety

Other than industrial robots and (nonmedical) service robots, robots used for health-care purposes have to fulfill safety requirements for medical devices instead of or in addition to requirements for machinery safety. With this possible conflict in mind, a joint WG (JWG) between ISO TC 299 (responsible for robot safety) and IEC SC 62 A (responsible for medical electrical equipment safety) was founded in 2010. The JWG spent quite some time on evaluating the boundaries and requirements for the new standards. As a first result, a technical report providing guidance on medical equipment with autonomous functions, ISO 60601-4-1, was published in 2017. The committee outlined the various subdomains of medical robots being affected by the new standards (Figure 2).

In 2015, two subgroups were founded inside JWG 5 with IEC SC 62 D. The first subgroup (JWG 35) is developing a standard for basic safety and essential performance of robots for surgery, IEC 80601-2-77. The second subgroup (JWG 36) is dealing with medical robots used for rehabilitation and has started the development of IEC 80601-2-78. In 2017, both documents reached the status of draft international standards, now being circulated for final voting among member states.

The ISO convener for JWG 5 is Gurvinder Virk (CLAWAR Association, United Kingdom). The IEC convener is Michel Brossoit (CSA Group, Canada). The project leaders are JWG 35 (IEC numbering), medical robots for surgery: Kiyoyuki Chinzei (AIST, Japan), and JWG 36 (IEC numbering), medical robots for rehabilitation: Burkhard Zimmerman (Hocoma AG, Switzerland). The JWG 5 standards include

- IEC/TR 60601-4-1, *Medical Electrical Equipment—Part 4.1: Guidance and Interpretation—Medical Electrical Equipment and Medical Electrical Systems Employing a Degree of Autonomy* (published)
- IEC/DIS 80601-2-77, *Medical Electrical Equipment—Part 2-77: Particular Requirements for the Basic*

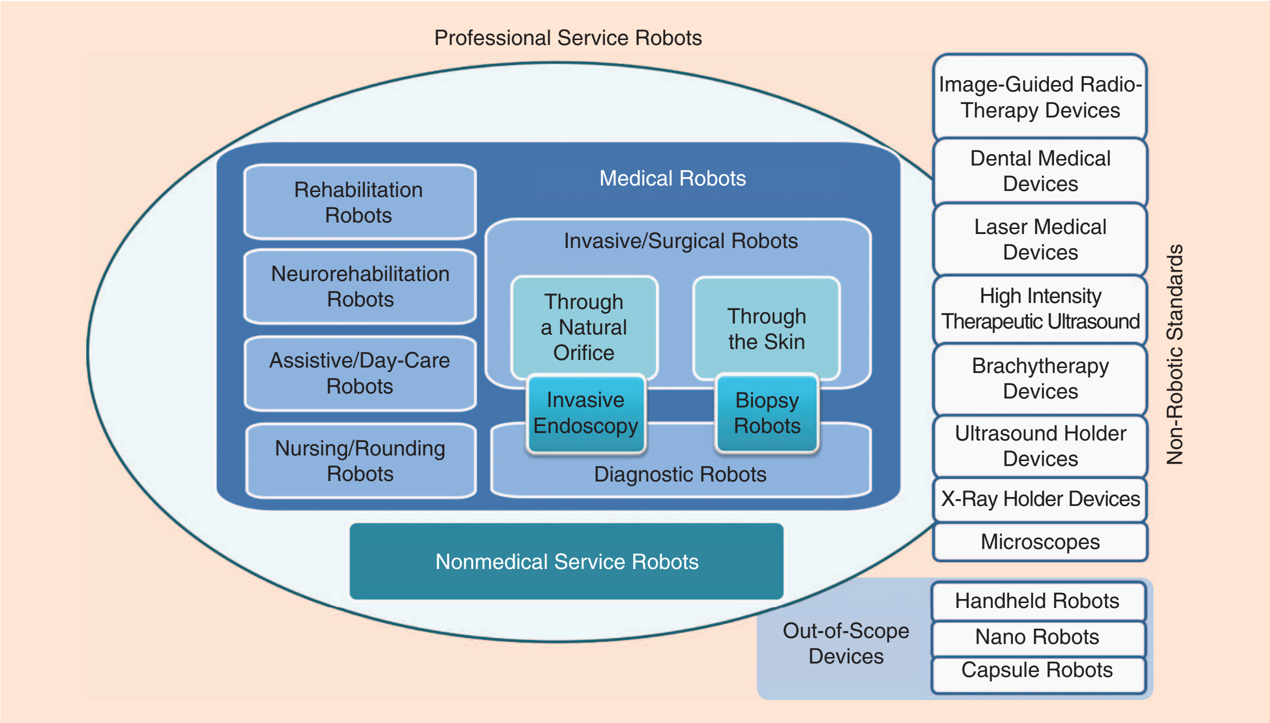

Figure 2. The current domains of medical robots, as derived from the IEC 60601:2015 medical electrical equipment and the ISO 8373:2015 robot vocabulary standards.

Safety and Essential Performance of Medical Robots for Surgery (committee draft)

- IEC/DIS 80601-2-78, Medical Electrical Equipment—Part 2-78: *Particular Requirements for the Basic Safety and Essential Performance of Medical Robots for Rehabilitation, Compensation or Alleviation of Disease, Injury or Disability* (committee draft).

Progress in WG 6: Modularity for Service Robots

During the last meeting in Suzhou, China, WG 6 finished a series of changes originating from the new work item balloting and prepared a document for the committee draft ballot. WG 6 has the task to prepare the development of a new standard for interoperability and reusability of robotic components on mechanical, electrical, and software levels. WG 6 is currently working on its first work item to create safety requirements and guidance for service robot modularity. The goal of the standard is to provide guidance to manufacturers who want to develop their own modular architecture. Key sections being developed include

- definitions
- generic modularity issues (including connectivity, interoperability, and safety at the module level)
- safety and security issues of modular systems
- frameworks for hardware and software
- key robotic components.

The chair of WG 6 is Gurvinder Virk (CLAWAR Association, United Kingdom). The cochairs are Shuping Yang (RIAMB, China) and Hongseong Park (Kangwon National University, South Korea). The standard WG 6 is working on is ISO WD 22166-1, *Robotics—Part 1: Modularity for Service Robots—Part 1: General Requirements*.

Apart from the standards already mentioned, ISO is continuously looking into the revision and amendment of its existing robot standards and looking into cooperations to align with similar domains (e.g., standards for self-driving cars, currently guided by vehicle standards within ISO). One prime example for that is the establishment of Study Group 1 (SG 1), which is solely focusing on the gaps and inconsistencies between the output of the existing WGs so their future work can be better focused and streamlined.

Conclusion and Outlook

It is clear that robotics is evolving from its industrial manufacturing roots at an increasing rate, and new robot use cases are emerging. The new robot application sectors are posing new challenges for standardization, and ISO and IEC have reacted rapidly over the past ten years or so to create new WGs to develop the needed standards, especially those related to safety. The foremost aim of international standardization is to facilitate the exchange of goods and services through the elimination of technical barriers to trade. The process of standardization, and especially the organization of the WG meetings, is a voluntary effort of the international experts devoted to robotics, where international peers from academia, industry, and government can work together toward clear targets. With the increasing usage of robots, the needs for standardized solutions has intensified. The focus of ISO TC 299 is to identify and address these needs related to all robotics disciplines, preferably in a collaboration with other SDOs and professional organizations, like IEEE. The new robot domains are giving rise to boundary and overlap issues and where one type of robot ends and another starts, e.g., when does a physical assistant exoskeleton robot governed by WG 2 become an industrial robot governed by WG 3? SG 1 has recently been set up to address such issues, to help provide recommendations on how to organize future robot standardization projects, and to identify gaps in robot standardization projects.

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