**Supplemental Material - Navigating the governance challenges of disruptive technologies: Insights from regulation of autonomous systems in Singapore**

**Supplemental material A: Keywords used for search in Stage 1 and Stage 2**

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|  | **Search theme** | **Keywords** |
| STAGE 1 | Autonomous systems | autonomous systems, unmanned systems, autonomy, artificial intelligence system, AI-enabled systems, self-governing systems, intelligent autonomous systems |
|  | Types of autonomous systems | varieties, autonomous systems, robots, autonomous cars, unmanned cars, driverless vehicles, self-driving car(s), autonomous vehicle technology, driverless, autonomous drone(s), autonomous vessel(s), unmanned vessel(s), autonomous aircraft(s), unmanned aircraft(s), autonomous weapon system(s), autonomous manufacturing system(s), autonomous production, autonomous manufacturing, architecture (of), robots |
| STAGE 2 | Regulations | regulation(s), policy, standard(s), legislation(s), law(s), order(s), ordinance(s), by-law(s), guideline(s), principle(s), specification(s) |

**Supplemental material B: Background on provisional regulations and standards for autonomous systems in Singapore**

Autonomous systems in Singapore are governed by different ministries and have different provisional standards based on the International Standards Organisation (ISO) and government regulations (details in Table B1). The ISO has technical committees for proposing standards and guidelines. The ISO/TC 184 is responsible for standardization in the fields of automation systems including information system, automation, control systems, and integration technologies (‘ISO/TC 184 - Automation Systems and Integration’ n.d.). Singapore follows the standards by ISO for industrial robots, personal care robots, and collaborative robots. The Standards or Technical references are proposed for relevant devices and are reviewed regularly, and any required amendments are made. These are not mandatory unless imposed by an authority, but can be used in contracts as a business necessity (SS ISO 10218-1 2016; TR 68: Part 1 2021). There are clear provisional standards for the following autonomous systems in Singapore (details about standards and definition of autonomous systems in Table B1): AVs, unmanned aerial vehicles, industrial robots (including collaborative robots) and personal care robots.

The Manufacturing Standards committee appointed the Technical Committee on Automation, Robotics and Precision Engineering and approved the standards for personal care robots and collaborative robots. The provisional standards for AVs are available in the technical reference document (TR-68) proposed by Singapore Standards Council’s (SSCs). Manufacturing Standards Committee in consultation with ‘Technical Committee on Automotive’ appointed by SSC comprising of four working groups (on AV basic behaviour, AV safety, Cybersecurity Principles and Assessment, and Vehicular Data Types and Formats for the relevant TRs) formed of representatives from the AV industry, research institutions, institutes of higher learning and government agencies. (TR 68: Part 1 2021; TR 68: Part 2 2021; TR 68: Part 3 2021; TR 68: Part 4 2021). The TR-68 was introduced in 2019 and serves as a step eventually towards setting standards for AVs after 3 years. A revised version of the TR on AVs was introduced in September 2021, after 2019 with the additions of guidelines on AV behaviour with persons, new elements for safety, improved cybersecurity standards with risk assessment frameworks, and new data formats for AVs (LTA, 2021). The TR-68 defines AVs as a vehicle with a level 4 or level 5 automated driving system[[1]](#footnote-1) with a given operational design domain to conduct a dynamic driving task (DDT) without a human operator. The section on driving policy document outlines the driving rules for the physical movement of the vehicle and interaction with the environment, and resolution of conflicting directive by proposing the primary and secondary instructions for the AVs. Since driving rules are region-specific, the TR borrows from The Basic Theory of Driving (10th edition) and Final Theory of Driving (9th edition). The DDT comprises of all the functions in real time required to operate the AV and not any functions related to calculated behaviours like destination or scheduling a trip. The TR specifies standards for the conditions of deploying AVs on roads with AV and non-AV users and traffic. The Road Traffic Act (2017) was amended in 2017 to acknowledge the existence of autonomous vehicles and providing legislations for the Minister of Transport to set standards and rules on AV trials and designs, and acquiring data from the trials (Taeihagh and Lim 2019).

The Civil Aviation Authority of Singapore (CAAS) is responsible for and updates information on rules related to unmanned aircraft (UA). At present, the regulations proposed for unmanned aircraft in Singapore are not for fully autonomous aerial vehicles. They are for aircraft without any human operator onboard, but remote-controlled and automated. Following the classification of unmanned aerial vehicles, the regulations by CAAS are for drones in the form of rotorcrafts that can hover (Floreano and Wood 2015).

The industrial robots in international standards include robots and robot systems with actuators, controllers, and manipulators and the standards specify the means to address hazards that can happen due to the nature of the robot, nature of automation, and complexity of installation (SS ISO 10218-1 2016). The standard for industrial robots in Singapore, ISO 10210 defines industrial robots as comprising of the manipulator, actuators, controller, including tech pendant (a hand-held unit linked to the control system for programming or moving a robot), and communication hardware/software (SS ISO 10218-1 2016). These robots can be hand-guided robots, manipulating parts of mobile robots, and robots that collaborate with robots. The standard for industrial robots and robot systems provides guidelines for safeguarding workers during robot integration, installation, testing, programming, maintenance, and repair. Autonomous mobile robots have already been deployed for deliveries in industrial places like warehouses, hospitals, and commercial buildings (in controlled environments) (Autonomous delivery workgroup 2021).

 Standards for personal care robots have been proposed for applications of robotic devices in non-industrial and non-medical environments for providing services rather than manufacturing in industrial environments (SS ISO 13482 2017). The standards include mobile servant robot, physical assistant robots, and person carrier robots and provide guidelines for safety requirements, protective measures, safety-related control system requirements, and information to be provided on and about the robot. A recent TR on safe deployment of robot systems in healthcare sector (TR 108: 2022) covers safety considerations for infection control, risk assessments, and safe deployment across different stakeholders—healthcare facility management, systems integrator/ operators, and end users.

Table B 1:Details on definitions of autonomous systems, relevant ministry, and relevant legislations/regulations

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|  | **Autonomous system** | **Relevant Ministry** | **Relevant legislation(s)/ regulation(s)** | **Definition** |
| 1. | Autonomous vehicles | Land Transport Authority, Ministry of Transport | Road Traffic Act (2019), Singapore Technical Reference for Autonomous Vehicles (Part 1: Basic Behaviour; Part 2: Safety; Part 3: Cybersecurity principles and assessment framework; Part 4: Vehicular data types and formats) | The Singapore Road Traffic (Amendment) Act 2017 defines an autonomous motor vehicle as a motor vehicle equipped substantially or wholly with an autonomous system that is operated without a human operator.  The TR-68 defines AVs as a vehicle with a level 4 or level 5 automated driving system[[2]](#footnote-2) with a given operational design domain to conduct a dynamic driving task (DDT) without a human operator (TR 68: Part 1 2021, 68). |
| 2. | Unmanned aerial vehicles | Civil Aviation Authority of Singapore, Ministry of transport | Air Navigation Act, 2019 | An unmanned aircraft is defined as ‘*an aircraft that can be flown or used without a person onboard to operate it*’ (MPA Singapore 2021). Unmanned aerial vehicles can comprise of radio-controlled aircraft, drones, and remote-controlled kites. |
| 3. | Industrial Robots and collaborative robots |  | ISO10218: Robots and robotic devices—Safety requirements for industrial robots (Part 1: Robots and Part 2: Robot systems and integrations)TR ISO/TS 15066: 2016 Technical Reference -Robotic and robotic devices—Collaborative robots | According to ISO10218, industrial robots are defined as a robots with manipulators including actuators, controllers, a teaching pendant ( a hand-held unit linked to the control system for programming or moving a robot) and a communication interface (SS ISO 10218-1 2016). These can be hand-guided robots, manipulating segments of mobile robots, and collaborating robots that work with humans. Collaborative industrial robots work in close proximity with operators where physical contact between operator and the robot system is maintained in a collaborative workspace. |
| 4. | Personal care robots |  | SSISO 13482: 2017: Robots and robotic devices- Safety requirements for personal care robotsTR108:2022: Robot systems in healthcare sector | Personal care robots operate with the intention to improve the quality of life, specifically personal care applications, of the users regardless of their age or capability, and this excludes medical applications. The international standards cover three types of personal care robots: mobile servant robot, physical assistant robots, and person carrier robots (SS ISO 13482 2017). A personal care robot refers to one that can travel to perform serving tasks such as holding objects or providing information in its interaction with humans. A physical assistant robot is meant to help a user to perform tasks. They can be restraint type that is attached to a human being, for example exoskeleton, or restraint-free that are not attached to human beings, for example powered devices or powered walking aids. A person carrier robot functions with the objective of transporting the user to a specific destination.  |

**Supplemental material C: Hazard identification for autonomous systems and quality assurance for AVs**

A hazard identification strategy considers the following factors: 1) uncertainty of autonomous decisions, 2) differentiating levels of knowledge, experience, and conditions of users and other people, 3) unexpected/unintended movement of the robots, 4) uncertainty of safety objects, and 5) conformity to human anatomy for physical assistant robots and personal carrier robots. Major foreseeable hazards have been listed in the Standards’ Annex for personal care robots including battery charging hazards, energy storage and supply hazards, hazards during start-up and due to robot shape, due to noise, lack of awareness of the robot, contact of the user with hazardous substances or fluids, harmful environmental conditions, extreme temperatures, radiation, stress caused due to specific posture or usage of the robot, harm caused due to movement of the robot (like getting crushed, trapped, or loads being dropped), colliding with safety-related obstructions, harmful contact during human-robot interaction, harm caused due to lack of durability, and navigation-related hazards. The creation of restricted and safeguarded spaces has been specified in the standards along with safety-related control system performance, design and installation, power sources and stopping functions. Similarly, a hazard identification and risk assessment (HARA) process for industrial collaborative robots considering risks from robot characteristics (structure, power, momentum, load, force, and torque), robot system, and application- related risks (process-related like temperature, limitations of protective gear, and improper design) has been outlined (TR ISO/TS 15066 2017). The HARA is done through elimination of hazards or preventing accidents for operators by encountering harmful components.

Full quality assurance for AVs consists of the following: 1) basic design and functions of components (sensors, cameras, interfaces and potential interactions, and approvals for safety), 2) documenting the software architecture level (inventory of units for the AVs, explanation of control systems, performance process of AV and the monitoring, fixed AV software features at the production level, 3) presenting the methods by providing details of defining key driving scenarios like during traffic, circuit breaker, road traffic testing, fail-safe concepts and contingent solutions, and functional safety audits, 3) requirements for deploying AVs: allocating roles, responsibilities, and accountability for stakeholders (AV developers/operators, manufacturers, suppliers for life cycle of the AV), and 4) test results for traceability in the legal requirements for AVs.

**REFERENCES**

Autonomous delivery workgroup. 2021. ‘IMDA Guidelines for the Use of Autonomous Mobile Robots for Delivery within Commercial Buildings’.

Floreano, Dario, and Robert J. Wood. 2015. ‘Science, Technology and the Future of Small Autonomous Drones’. *Nature* 521 (7553): 460–66. https://doi.org/10.1038/nature14542.

‘ISO/TC 184 - Automation Systems and Integration’. n.d. ISO. Accessed 19 October 2021. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/committee/05/41/54110.html.

LTA. 2021. ‘LTA | Joint Factsheet by the Land Transport Authority (LTA) & SSC - Enhanced National Standards for the Safe Deployment of Autonomous Vehicles in Singapore’. 3 September 2021. https://www.lta.gov.sg/content/ltagov/en/newsroom/2021/9/news-releases/enhanced-national-standards-for-the-safe-deployment-of-autonomou.html.

MPA Singapore. 2021. ‘Flying of Unmanned Aircraft over Singapore Waters’. Maritime and Port Authority of Singapore.

SS ISO 10218-1. 2016. ‘Robots and Robotics Devices-- Safety Requirements for Industrial Robots Part 1: Robots’. Singapore Standards Council, Enterprise Singapore.

SS ISO 13482. 2017. ‘Robots and Robotics Devices-- Safety Requirements for Personal Care Robots’. Singapore Standard. Singapore Standards Council, Enterprise Singapore.

Taeihagh, Araz, and Hazel Si Min Lim. 2019. ‘Governing Autonomous Vehicles: Emerging Responses for Safety, Liability, Privacy, Cybersecurity, and Industry Risks’. *Transport Reviews* 39 (1): 103–28. https://doi.org/10.1080/01441647.2018.1494640.

TR 68: Part 1. 2021. ‘Autonomous Vehicles-- Part 1: Basic Behaviour’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

TR 68: Part 2. 2021. ‘Autonomous Vehicles-- Part 2: Safety’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

TR 68: Part 3. 2021. ‘Autonomous Vehicles-- Part 3: Cybersecurity Principles and Assessment Framework’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

TR 68: Part 4. 2021. ‘Autonomous Vehicles-- Part 4: Vehicular Data Types and Formats’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

TR 108: 2022. ‘Safe Deployment of Robots on Healthcare Sector’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

TR ISO/TS 15066. 2017. ‘Robotics and Robotic Devices-- Collaborative Robots’. Technical Reference. Singapore Standards Council, Enterprise Singapore.

1. This is aligned with the five levels of automation proposed by the Society of Automotive engineers (SAE) for AVs: Level 0: No automation, Level:1 Driver assistance, Level 2: Partial automation, Level 3: Conditional automation, Level 4: High automation, Level 5: Full automation [↑](#footnote-ref-1)
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