ANNEXES A-5

FUTURE-READY SYSTEMS

CONTENTS

1 INTRODUCTION & OVERVIEW

A New Era of Human and Machines: Embracing Future-Ready Systems

With the emergence of Future-Ready Systems across multiple industries across the globe, it is not surprising that the guiding narrative in many articles falls on the uncertainty of how these technologies could disrupt processes and displace workforces across different economic sectors globally.

According to a 2018 study by Forbes, 51% of respondents do not currently use Artificial Intelligence (AI) or robotics in their workplace and 38% of respondents' state that their organisation does not have a plan to cultivate the human skills required to use AI or robotics. Organisations are often divided on the recognition and acceptance of AI and robotics.

However, it is obsolete to view things through a dualistic lens of human versus machines. The last two decades herald a new era of human and machine, spawning the birth of a 'hybrid workplace'. As with all revolutions, the Machine Revolution is also disruptive in nature. More importantly, we need to be prepared for new ways of working and thinking. We need to work together to guide AI and robotics responsibly throughout all industries and recognise the interchangeable potential between human and machines. At the heart of this paper is the idea of the intertwined collaborative nature of human and machine with regards to three key systems: Intelligent-Machine (IM), Machine-Machine (MM) and Human-Machine (HM).

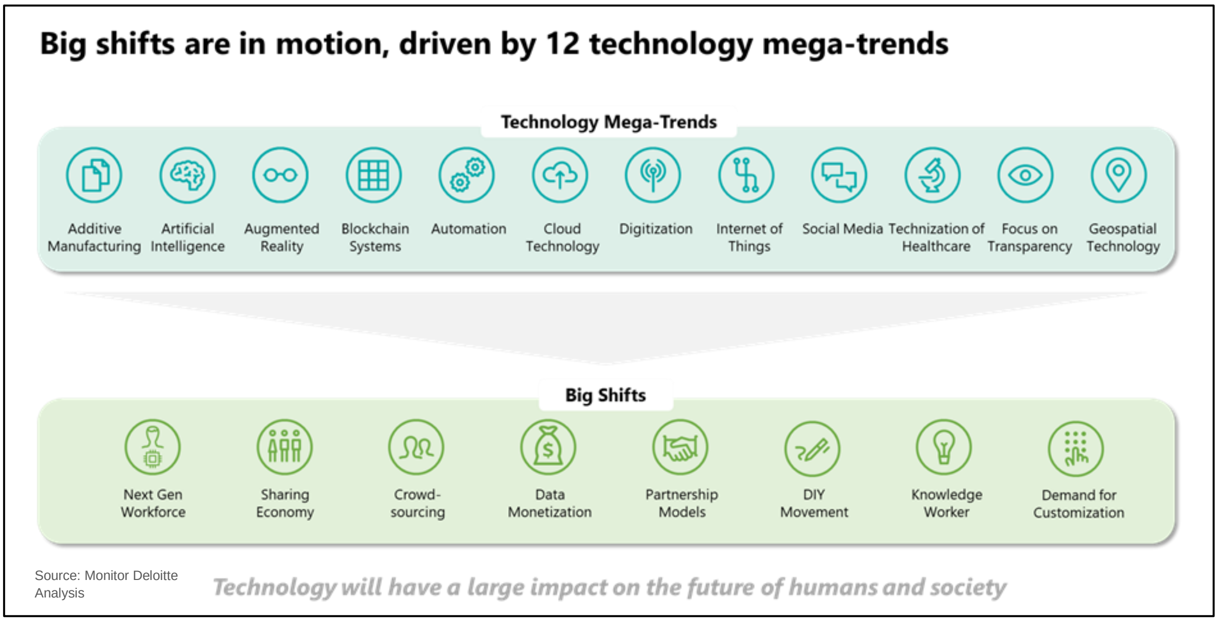


Exhibit 1: 12 Technology Mega-Trends

Deloitte's Centre for Long View has determined that there are 12 technology mega-trends which will drive 8 shifts in the way in which the service industry functions, as discussed in Exhibit 1. These shifts highlight the importance of technology in our future.

1.1 Significance of Emerging Technologies

The emergence of Internet-of-Things (IoT) technologies and AI will pave the way for wide-scale digitalisation, creating new services and opportunities in various sectors. Gartner estimates that by 2021, there will be over 25 billion IoT endpoints, which will connect and transmit large amounts of information from the physical world to the digital world [1]. The advancement of AI, for example, machine learning techniques will help people to better understand the large volume data sets, derive insights, and improve the effectiveness and efficiency of existing business operations. New system technologies could be developed in the future to provide more innovative digital services, bringing benefits to people and organisations in various aspects such as asset optimisation, competitive differentiation, and improved user experience in nearly all industries.

Since the dawn of the industrial age, numerous production facilities and logistics warehouses have benefitted significantly by machine automation. Tasks that are considerably laborious and repetitive are most suited to be operated by robotic systems. Additionally, the quality of products may be further enhanced with greater precision and produced at a larger throughput, ensuring safety and convenience, while at the same time reducing human errors.

With the support of AI and big data analytics, machines gain a higher level of intelligence and capabilities thus enabling them to complete tasks which they previously could not. This further promotes the application of a larger number of machines in various sectors. Depending on the manner in which machines function, three important systems, i.e., digital autonomous system (intelligent-machine), intelligent connected system (machine-machine), psychological collaborative system (human-machine) will have prominent impact on our future.

1.2 Evolution of Future-Ready Systems: Three Important Systems

Digital Autonomous Systems (Intelligent-Machine) refer to systems which are autonomous in operation, able to perform tasks with a high degree of automation and enhance the capabilities of humans. Furthermore, Digital Autonomous Systems can detect deficiencies in environments and humans, and perform tasks autonomously in complex environments indoor and/or outdoor with location awareness, knowledge sharing, etc. These systems enhance human capabilities by adding intelligence, guidance and sensory awareness ability thus enabling humans to operate beyond their limits. Digital Autonomous Systems leverage various technologies such as environmental sensors, deep learning, high performance computing, augmented reality, etc. to extend the capabilities of machines into that of a highly automated system. For example, delivery bots equipped with advanced environment sensing and real-time data processing can navigate and operate autonomously in a complex environment with less human intervention. These systems can be widely used in the future in logistics, transportation, disaster rescue, data collection in hazardous environments, etc., further reducing the constraints on manpower resources and potential risks exposed to humans.

Intelligent Connected Systems (Machine-Machine) refer to systems in which multiple bots interact with other bots in a distributed, intelligent and collaborative manner. Individual bots can obtain data or knowledge about neighbouring bots and the environment. These bots can display collaborative behaviour with their limited local data, without centralised control or human intervention. With the advancement of communication, AI and computing technologies, these bots are able to be self-organised and adapt their organisation structure to carry out diverse tasks in complex environments.

Various communication technologies including mobile 5G and dedicated short-range communications (DSRC) are key components of these systems. With the development of communication technologies, individual bots can quickly obtain massive data sets at a fraction of the cost and securely transfer data without risking malicious interference.

Another key feature of intelligent connected systems is the massive data sets collected, allowing individual bots to perform big data analytics to gain insights for decision making as well as to discard redundant information. This would require individual bots to have certain computational capabilities for big data analytics. Computing technologies such as in-memory computing, edge computing, exascale computing are important components for intelligent connected systems. With these computing technologies, individual bots are capable of making real-time decisions and spontaneously respond to changes.

The high level intelligence of individual bots enables them to collaborate with other bots in a distributed manner. Without a global view of the systems and environments, individual bots can make decisions with local information, display a collaborative behaviour (i.e., capability of organisation, delegation and argumentation) and behave efficiently without any human intervention or centralised control.

Psychological Collaborative Systems (Human-Machine): Traditionally, the design factors surrounding bot systems have always been in achieving maximum precision and throughput in specific tasks. Such machines are devoid of any emotions or "feelings", leaving them unable to effectively communicate with or cooperate with humans who are far more adaptable and intelligent to handle multiple ad-hoc tasks. In contrast to "human versus machine", the notion of "human with machine" depicts a more forthcoming reality, where these machines are referred to as Psychological-Collaborative Systems that are endowed with capacities to recognise, interpret and express emotions.

Emotions prove to be an essential element for people to function as rational decision-making human beings [2]. Either an abundance of or a lack of emotion could impair reasoning capabilities [3]. Research findings on patients with frontal-lobe disorders suggest that poor decision-making was directly correlated to an impaired ability to feel [2]. This is substantiated by neurological evidence which indicates emotions are an essential component contributing to decision-making processes made by people in an optimal manner, and not superfluous [3].

For these reasons, emotional AI [4] technologies have been increasingly ingested by contemporary AI systems. Computer vision algorithms (e.g., convolutional neural networks (CNN)) are utilised to detect and analyse visual emotional cues (e.g., facial expression recognition and head attitude determination) [5] [6] [7] [8] [9]. Of equal importance, audio analysis using emotion speech recognition algorithms (e.g., recurrent neural networks (RNN)) of a person's voice patterns may be utilised to extract vocal cues of emotion.

2 MARKET STUDY

2.1 Future-Ready Systems & Their Enabling Technologies

This market study seeks to understand the landscape of Future-Ready Systems and their enabling technologies. The study suggests that there are three distinct categories for future-ready systems: Intelligent-Machine, Machine-Machine Systems and Human Machine Systems. The development and implementation of the three aforementioned systems give rise to paradigm shift in the service industry as shown in Exhibit 2 below. It is important to understand how to develop and cultivate these systems in order to harness their benefits in the future.

To understand the impact of technology development on human and machine interactions, it is imperative to trace the evolution of human and machine interactions [10].

2.2 The Trajectory of Human-Machine Interactions, Powered by Technology

The technology evolution signals a new era in human and machine interactions. Technological developments are changing the world and the way we work. 20 years ago, it would have been deemed impossible for someone to speak to their watches in order to send a message yet now it is an everyday reality due to the exponential rate of change in technology. This exponential change was first predicted by Gordon Moore, the co-founder of Fairchild Semiconductor and Intel [11]. Self-driving vehicles, 3D printers, and AI are providing new business opportunities, urging businesses to alter their approach to technology implementation across their business functions [12].

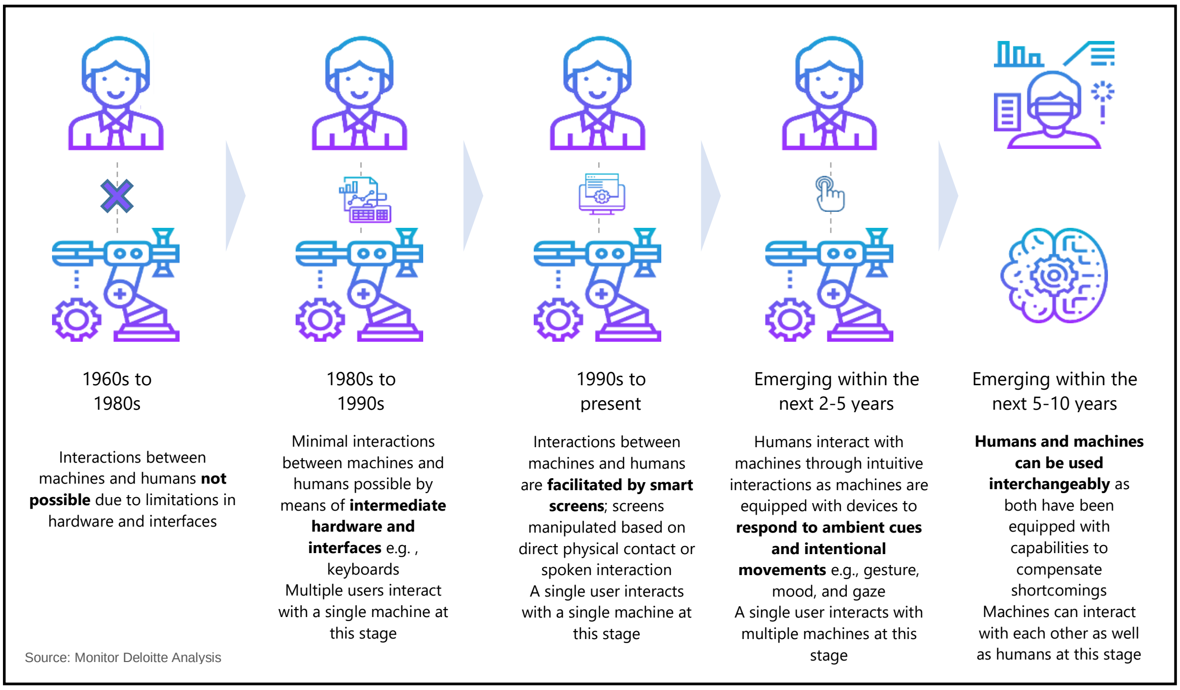


Exhibit 2: Development of human-machine interactions

As technology develops, the extent to which humans and machines interact increases in tandem with the complexity of the interactions is depicted in Exhibit 2 [13]. In stage 1, interactions between man and machine were not possible due to the lack of technology to facilitate such interactions; at this stage, machines would accomplish individual tasks which a user would oversee. The user would help the machine by feeding in materials and this was the extent of the interaction between the user and the machine due to a physical separation in the workspace. The development of basic hardware and interfaces, such as keyboards and graphic user interfaces, facilitated stage 2 where users can interact with the machine and control certain aspects of the machine in order to better fulfil the task at hand. Stage 3 is a culmination of further development of adaptive multi-modal interface technologies (e.g., smart screens, voice, gesture etc.) allowing users to manipulate and interact with machines to a greater degree, using the most appropriate interface depending on the environment and situation (e.g., in a noisy environment, gesture may be more appropriate over voice.). Furthermore, the user can collaborate with the machine while it is in motion. At stage 4, users are able to accomplish tasks efficiently as machines are able to respond to ambient cues and intentional movements due to advancements in sensor technology. At this stage, machines and users form synergies to better accomplish the tasks at hand. At stage 5, humans and machines can be used interchangeably as humans are equipped with technology to enhance their capabilities while machines are endowed with human-like cognition and emotions due to developments in AI. In sum, collaboration between humans and machine is fostered through shared workspaces and technology development [14] [15] [16].

2.3 A New Era of Human-Centric Future-Ready Systems

Human-centric technology interactions are increasingly becoming a commonplace across a variety of industries. A recent study investigating interactions between humans and machines across 1,500 companies suggests that firms achieve the most significant performance improvements when humans and machines work together [17]. Through such collaborative intelligence, humans and machines actively enhance each other's complementary strengths: the leadership, teamwork, creativity, and social skills of the former; the speed, scalability, and quantitative capabilities of the latter. For example, interactions which come naturally to humans (making a joke, for example) can be challenging for machines, whereas analytical activities which are straightforward for machines (analysing gigabytes of data) remain virtually impossible for humans. Modern businesses require both kinds of capabilities in the new era of human-machine interactions.

Three trends will impact Future-Ready Systems:

Firstly, it will be driven by high performance computing power. The hyperscale computing market is projected to grow from US$32.11 billion in 2017 to US$44.98 billion by 2022, at a CAGR of 7% [18]. Experts suggested that the SME segment in the hyperscale computing market is expected to grow at a higher CAGR than large enterprises as SMEs increasingly adopt cloud-based hyperscale computing solutions in order to flexibly scale a company's IT infrastructure [18]. Furthermore, in order to meet the ever increasing amount of data produced and processed by enterprises, technology companies are investing in the development of computational power [19]. Experts predict that computational power will exceed that of the human brain by 2025 due to the exponential technological change. This exponential rate of change was predicted by futurist Ray Kurzweil in 2001, stating that in the 21st century we will experiencing 20,000 years of progress (at today's rate). The evolution of computational power supports Kurzweil's prediction has been proven true.

In the future, machines and humans will be able to operate interchangeably. These technological changes have profound implications across a variety of industries; some scientists have predicted that these developments will result in a 50% chance that unaided machines can accomplish every task better and cheaper than human workers within the next 45 years [20].

The advent of advanced computer systems will complement the ever-increasing amounts of data being stored and processed thus broadening the scope of computational analysis. This is evident from the increase in data centre traffic expected to reach 19.5 zettabytes (ZB) per year by 2021, up from a mere 6.0ZB per year in 2016 [21]. This is predominantly a result of more applications and services moving into the cloud which require larger-scale data centres; much of the growth in the cloud-IT market is ensues because many businesses deciding to give up owning their own data [22]. Cloud data centre traffic will represent 95% of total data centre traffic by 2021, compared to 88% in 2016.

The growth of cloud-IT adoption is fuelling the growth of hyperscale data centres. The requirement to store and process ever-increasing amounts of data has given rise to the concept of 'hyperscale data centres', which are large-scale public cloud data centres [22]. By 2020, 47% of all servers sold are expected to go to hyperscale customers [22]. By 2021, hyperscale data centres will hold 53% of all data centre servers (compared to 27% in 2016), accounting for 69% of all data centre processing power (compared to 41% in 2016), 65% of all data stored in data centres (51% in 2016) and 55% of all data centre traffic (compared to 39% in 2016) [22].

The data stored in data centres and hyperscale data centres alike will be highly valued, providing useful insights for population level analytics. By 2025, over 20% of the data created in the global datasphere will be beneficial for analytics if tagged, yet only 15% of this data will actually be tagged and analysed. Hyperscale computing systems are well positioned to process and glean useful insights from the data stored in data centres and hyper scale data centres [23]. Current hyperscale computing systems operate in the petascale region, this is significant because these systems can compute one quadrillion floating point operations per second [24] [25].

However, as we look into the future, the importance of the next-generation of hyperscale computing systems, exascale computers, cannot be overlooked. Exascale computing refers to computing systems capable of at least one exaFLOPS. The Oak Ridge National Laboratory is the only known entity which has successfully performed a 1.8×10^{18} flop calculation. This was done on the Summit OLCF-4 Supercomputer whilst analysing genomic information in June 2018 - a momentous occasion in that it was faster than any previously reported science application. Exascale computing is well suited for the analysis of large data sets such as genomic information as it is expected to carry out more than a quintillion calculations per second. To illustrate this point, one hour on the Summit OLCF-4 Supercomputer, will solve a problem that would take 30 years on a desktop computer [26].

Many countries have invested in the development of exascale computers; the development of this next generation of high-performance computer is no surprise as it follows the trend of continually evolving hyperscale computing systems. After 2010 the world has seen rapid turnover in the leader hyperscale computing league tables as a result of expedited developments in semiconductor chip technology and our understanding of technology as a whole.

Based on the trends of the last 50 years, experts have posited that we will begin to see successfully exascale systems by 2023 [27]. Experts predict that exascale architecture will feature fully integrated hardware acceleration with GPU variants, whilst others suggest that there are possibilities for an ultra-heterogeneous chip with integrated FPGA combined with GPU and other workload-specific acceleration. Other experts suggest that the PEZY processor out of Japan, may also prove to be the key component in exascale computers as this processor is currently proving its mettle on top-ranked systems with its unique 2048-core design; additionally, NEC and others with vector based architectures may also contribute to the development of exascale computers [28].

The development of exascale computing has a number of implications for diverse industries due it its implications for modelling purposes. For example, while petascale computers can model many molecular systems, there are many very large complex systems that academia strives to solve but are currently unable to do so due to the lack of computational power. One such problem is understanding

Source: Communications of the ACM

the molecular processes that control the response of plants to stress, especially to drought. The lack of this type of understanding prevents scientists from designing plants for the production of biomass that can be grown on lands that are unsuitable for the production of food. Similarly, our current understanding of molecular processes that control the production of biofuels from biomass is limited. In this case, the lack of understanding of the molecular aspects of these catalytic processes prevents the development of more energy-efficient processes for the conversion of biomass products into biofuels [29].

In the energy sector, the increasing pace of power grid modernisation drives the urgency of solving such an expansion problem cost-effectively and securely within the next decade. Renewable energy sources like wind and solar farms are providing carbon-free energy and increasing flexibility for utility customers who increasingly demand energy savings, better reliability and efficiency. However, the intermittent productivity of renewable energy and the unpredictable nature of electricity uses are introducing new challenges to an aging electric grid. Exascale computers provide the opportunity to create models that can analyse data electric grids to generate models for expansion planning and enable the cheapest, most reliable mix of energy generation and uses [30].

Secondly, development in the field of robotics will play an active role towards the evolution of human-machine systems; robots can perform tasks and deliver quality outputs efficiently without causing physical damage to humans. The global sales of industrial robots which have reached a new record of 387,000 units in 2017 is testament to this growth. China saw the largest growth in demand, from last year, for industrial robots, an increase of 58% whilst sales in the U. increased by 6% and Germany by 8% compared to the previous year. This upward trend in the implementation of robots across all sectors is projected to grow further over the next five years [31]. In 2025, the robotics market is estimated to be worth almost US$500 billion globally. Industry 4.0 will link the real-life factory with virtual reality and play an increasingly important role in global manufacturing. Robots will acquire or adapt new skills through learning processes and smarter robots will benefit from big data and collective learning via cloud-based intelligence. It is estimated that global robot installations will increase by at least 15% on average per year (CAGR) from 2018 to 2020. The mobile robots market is expected to grow and reach US$10.6 billion by 2020 with a CAGR of 16.31% between 2015 and 2020 [32] [33] [34]. The agricultural robots market is expected to garner US$15.34 million by 2025, growing at a CAGR of 20.95% during the forecast period, 2018 to 2025. However, the lack of awareness of agricultural robots among farmers and their inability to meet the human dexterity causes the market to slow down [35].

Whilst industrials robots will continue to grow, it is the collaborative robots that will push the boundaries of human-machine collaboration. Collaborative robots or cobots are complex machines which work hand in hand with human beings; this increasingly growing segment of the overall industrial robot market is set to revolutionise the way in which robots interact and work alongside human workers [36]. Unlike their hard industrial counterparts, cobots are able to execute much more complex tasks across a variety of industries as they go beyond the regular protocols of robotics process automation (RPA) which only automate simple tasks. Initially, robots based on RPA programming were limited to automating administrative tasks however, with the growth of additional technologies such as neuromorphic computing, advanced communication technologies and advanced AI systems, cobots can accomplish a number of tasks across a variety of settings, from sorting packages for e-commerce distribution warehouses to automating food production at restaurants. We need to distinguish cobots from conventional bots that use RPA technologies for process automation to reduce paper work.

The cobot market was valued at US$176.7 million in 2016 and is expected to reach US$4.28 billion by 2023, at a CAGR of 56.94% between 2017 and 2023 [37]. These lighter weight, lower cost robots can be outfitted with sensors that allow them to perform tasks like gripping small objects, seeing, and even learning [38]. With the increased functionalities the robots have compared to standard industrial robots, they are increasingly revolutionising a number of industries including the service industry. They are being widely adopted for warehouse automation and logistics, food & beverage, household maintenance, healthcare and education. For example, cobots can perform e-commerce sorting and can automate management of multiple 3D printers. In the agriculture industry, they can harvest fruits thus reducing a farmer's dependency on transient labour. In the food and beverage industry, to cope with the extra order volume from digital platforms robots are used for food preparation. For example, a burger restaurant employs 20 computers, 350 sensors, and 50 actuator mechanisms to prepare a US$6 burger in 5 minutes which is then delivered by humans to the recipient. These intelligent yet small-sized robots may also be more financially viable compared to traditional industrial robots; select cobots have ROIs of around 195 days [38].

Thirdly, advancements in artificial intelligence technologies such as machine learning (ML), will also spur increased human-machine interactions. There is a distinct upward trend in the revenue generated by AI across the globe; this upward trend is projected to continue over the next five years as AI tools are projected to create nearly US$3 trillion in business value by 2021 [12] [39].

The rise of AI tools also gives rise to the demand for digitalisation and enabling systems, such as Digital Twins, which provide an integral offering of new sets of services with digital models, real-time data feeds, simulate the interaction of discrete elements, and respond to changes for users. Digital Twins will create new opportunities for organisations to leverage on AI-based analysis, modelling and simulation, 3D inspection, augmented reality, etc. to transform existing business workflows and optimise physical assets. By 2022, the IoT powered by digital twins will save consumers and businesses US$1 trillion a year in asset maintenance. Well-designed digital twins based on business priorities have the potential to significantly improve enterprise decision making and cooperate with the changes. It was estimated that moving into predictive maintenance can save 10% to 20% over preventive maintenance. By 2020, digital twins for industrial equipment will drive a 25% reallocation of end-user spending from "procure and maintain" to "service" models. Augmented reality, virtual reality and mixed reality immersive solutions will be evaluated and adopted in 20% of large enterprises as part of their digital transformation strategy. By 2023, 50% of major enterprises will use digital twins, in combination with digital business platforms, to optimise process efficiency, effectiveness and customer outcomes.

Similarly, the number of patents for machine learning technologies have been steadily increasing since the early 2000s. The International Data Corporation (IDC) forecasts that spending on AI and ML will grow from US$12 billion in 2017 to US$57.6 billion by 2021. Machine learning enables decision making capabilities in machines such as robots. Machine learning provides computers with the ability to learn from labelled examples and observations of data-and to adapt when exposed to new data-instead of having to be explicitly programmed for each task.

Developments in machine learning will in turn foster developments in cognitive computing; a cognitive computing [40] system can adapt and make sense of information – even for input that is unstructured, such as images or natural speech, thus making it well suited to recognise and interpret patterns, giving them meaning [41]. Cognitive computing technologies are predicted to have a projected market value of US$1.2 trillion by 2020, assuming an annual growth rate of 3% to 5% [42]. Cognitive computing is already augmenting and accelerating human capabilities by mimicking how humans learn, think and adapt. When perfected, these technologies will replicate the human capabilities of sensory perception, deduction, learning, thinking and decision-making [43].

Machine-Machine systems are also reliant on advancements in data transmission such as 5G, dedicated short-range communications (DSRC). Global mobile data traffic growth is projected to increase at a CAGR of 57% till 2019 [44].

The increase in mobile data traffic growth is being facilitated by investments in 5G technology [45]. 5G Network Infrastructure Market to Grow at a CAGR of 70%, accounting for US$28 billion in annual spending by 2025 [46].

Finally, it is important to understand the importance of convergence. Robots on their own will not generate the impact but, coupled with the application of technologies such as AI and hyperscale computing systems, greater advancements can be made.

Within the Asia Pacific region, there is a flurry of activity within the space of Future-Ready Systems

Spending on cognitive and AI systems within the Asia Pacific (APAC) [a] region is forecasted to reach US$4.6 billion in 2021 with a CAGR of 72.9% over the 2016-2021 forecast period. Aggregate spending on cognitive and AI systems within APAC totalled US$458 million in 2017, which is an increase of 53.3% over 2016 [47]. The banking and healthcare industries are forecast to have the highest spending on cognitive and AI systems in 2017 with investments of US$65.5 million and US$47.3 million, respectively. Other industries such as insurance, central government and education will have the highest growth rate for 2016-21, with a CAGR greater than 83%. The supportive government policies and digitalisation activities in the region are driving the market growth. China leads the investments in technology and accounts for 17% of the global external investments in AI. Increasing investment by Chinese players is also one of the major factors driving the growth in the region. Some of the major vendors that are serving the AI are Nuance Communication, Microsoft, AWS, IBM, Google, Cognii, Pearson, Jenzabar, Volley.com, Content Technologies, Pixatel Systems, PleIQ, Knewton, Blippar, Blackboard, Century Tech, Quantum Adaptive Learning, and Liulishuo [48].

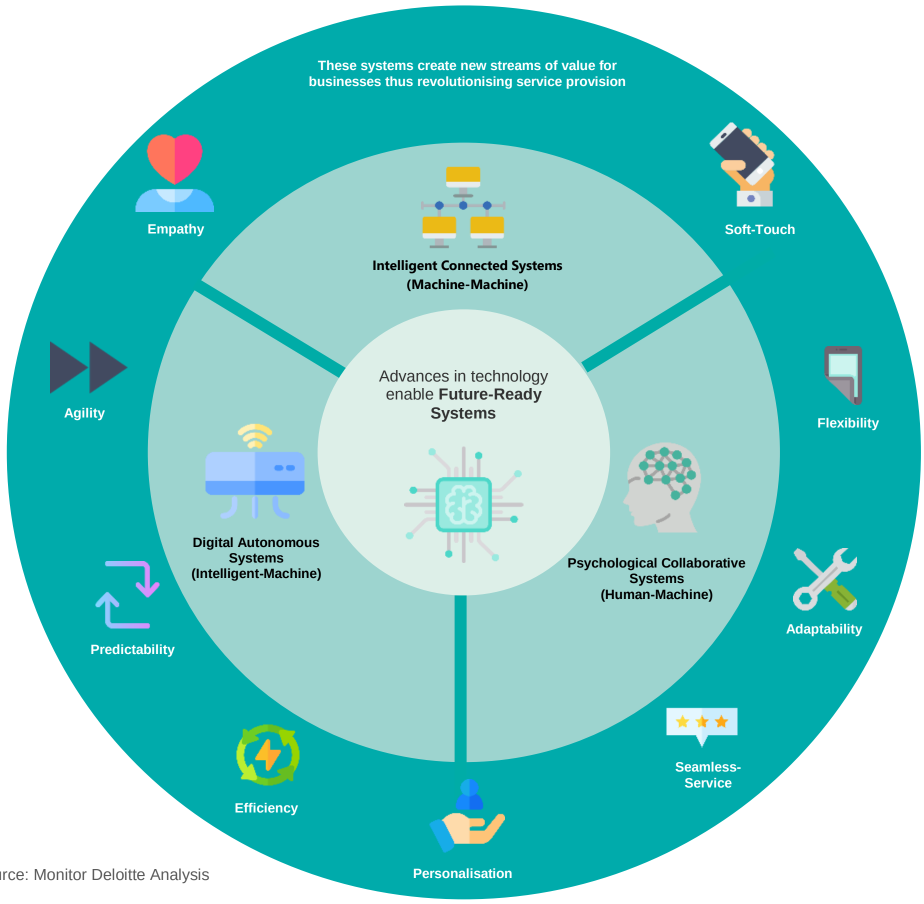
Spending on robotics (including drones) and related services within APAC was US$66 billion in 2017, over a five-year forecast period of 2017-2021, experts predict the market size to reach a value of US$162 billion by 2021 with a CAGR of 25.2%, with spending on robotic systems expected to grow to US$92 billion. This represents over 70% of the world's total robotics market in 2021. China dominates the Asia Pacific robotics market, with spending on robotics and related services expected to reach US$74 billion in 2021, which represents 45.7% of Asia Pacific's total spending in the next five years [49]. Within the market for robotics, there is significant demand for wearable robots such as exoskeletons in the Asia Pacific region; the global exoskeleton market is projected to be valued at US$3.4 billion by 2024 and the Asia Pacific region is estimated to contribute US$780 million over the forecast timeframe. The growth can be attributed to increasing spending on healthcare and awareness about industrial

[a] Excluding Japan

robotics in manufacturing sector; nations such as China and South Korea are investing heavily in development of wearable robots for defence and security purposes [50]. Some of manufacturers in the exoskeleton market include Bionik Laboratories Corp., 20 Knots Plus, Activelink Co., Ltd., Hocoma, Ekso Bionics, CYBERDYNE, Inc., MedEXO Robotics, Mitsubishi Heavy Industries, Noonee, Fourier Intelligence, Lockheed Martin Corporation, ReWalk Robotics, Parker Hannifin Corporation and Revision Military. The nature of the industry is consolidated with few companies permitted to commercialise the product. Stringent regulations from the US Food and Drug Administration (FDA) create high entry barriers for robotic technology manufacturers [50].

The global hyperscale computing market is projected to reach US$36.62 billion by 2020, at a CAGR of 5.45%, with higher computational power driving the hyperscale computing market growth. The Asia Pacific region is expected to witness the highest growth and hyperscale computing servers to gain maximum market share during the forecast period [51]. The rapid expansion of various industrial verticals and robust urbanisation in counties such as China, India and Indonesia is partly driving the adoption of various cutting-edge technologies including hyperscale in region's industrial verticals [52]. Alongside this growth, the hyperscale data centre market size is expected to grow driven by increasing awareness and adoption of effective and scalable solutions in this region [53].

2.3.1 Emerging Technologies Provide Novel Applications of Technology



Source: Monitor Deloitte Analysis

Exhibit 3: Exhibit showing how technology will revolutionise service provision

The development of technology gives rise to three different classes of systems which may be used to describe human-machine interactions as discussed in Exhibit 3.

2.3.2 The Three Systems and their Relevant Enabling Technologies

1. Digital Autonomous Systems (Intelligent-Machine):
   These systems can complement human capabilities thus allowing users to function at a level which exceeds their normal physical limits. There are multiple examples of such systems:

   - ***Digital twin*: **Emerson has provided a virtual platform that allows companies to test any proposed adjustments to operations risk-free and in real time, before they are applied to the actual plant. Using the industry's first integrated control and simulation platform, Emerson is able to create an exact digital replica of the live plant. This high-fidelity simulator, known as a "digital twin," runs in parallel with the real control system, making advanced testing possible to ensure that any changes will not affect the supply of electricity [54].
   - ***Robotics:*** Amazon has 100,000 robots in operation currently, thus shortening training for holiday workers to less than two days. These robots reduce the amount of manual labour required at Amazon's warehouse facilities [55].
   - ***Smart Manufacturing:*** The ability of some asset or piece of equipment to make decisions based on what's going on in the factory floor without the need of human intervention; these decisions that are not necessarily pre-programmed in some factory control system. The aim of Smart Manufacturing is to utilise a more programmatic data-led approach to develop new and higher quality goods faster. Technologies e.g., Edge Computing, can enable this autonomy where machines in the factory floor extract insight and formulate actions at near real-time. Running AI/machine learning algorithms in their own electronics, almost as if they had their own brains. Alibaba's logistics arm, Cainiao Network, unveiled a "smart" system to manage warehouse complexes at scale. "Cainiao Future Park," the logistics platform aims to digitise the park experience with IoT applications, big data, edge computing and AI.

2. Intelligent Connected Systems (Machine-Machine):
   - ***Connected vehicles:*** refer to vehicles with communication devices can connect with other vehicles and infrastructures, to share their mobility data, etc. and have the ability to make decisions on traffic issues [56].
   - ***Swarm Bots:*** refer to a number of robots collaborate to complete tasks in a distributed manner through the interaction of neighbouring robots and their interaction with the environment.
     - An example of such as system is seen in swarm robots used in the agricultural industry. SwarmFarm has developed the world's first 'swarming' robots which work in groups to spray crops and carry out other tasks. Rather than relying on large farm machinery, it hopes farmers will instead be able to use the small, lightweight robots to carry out tasks more accurately and effectively. As well as applying fertiliser and irrigating crops, the swarm bots can carry out planting, weed and insect control and harvesting. SwarmFarm aims to utilise this technology to improve farm productivity further by using the platform to deliver new, simplified solutions around weeds, labour, sustainability and application timing [57].
     - Swarm bots can also hypothetically be applicable in a number of industries ranging from manufacturing to logistics. In the manufacturing industry, swarm bots could be used for the maintenance of machinery while in logistics they can be used to transport or inspect containers in ship terminals. Similarly, in sea transport, swarm bots can be used to conducted searches which alleviates the burden of such dangerous tasks from humans. In the healthcare industry, swarm bots can

revolutionise how surgeries and monitoring procedures are conducted as they may conduct currently invasive procedures, non-invasively.

3. Psychological Collaborative Systems (Human-Machine):
Machines in Psychological Collaborative Systems are endowed with capacities to recognise, interpret and respond to human commands and emotions. Examples of such systems include:

- ***AI Personal Assistant:*** Mark Zuckerberg has successfully built a home assistant AI system and has plans for developing an Android app to commercialise this product. This system leverages three AI systems, speech recognition, facial recognition and language processing to allow the user to interact with a number of home appliances e.g., lighting, food appliances etc. Users may interact with the central server by means of their door camera, iOS Voice App or Facebook's Messenger App [58].
- ***Collaborative Robots:*** Manufacturers such as Airbus and Nissan are finding ways to use collaborative robots, or cobots, which work side by side with workers in factories [12].
- ***Soft Robots:*** Soft robots can be used to serve and interact with human. Soft robots can also be used in medical appliances due to their malleable nature and ability to act as biomimetic. One such example is a heart sleeve which can be used to force the heart to pump blood in patients with heart failure. Multiple research laboratories are also developing soft robots which can be used in surgeries to better assist surgeons [59].
- ***Exoskeletons:*** German artificial limb manufacturer Ottobock plans to start selling a mechanical exoskeleton that makes manual labour for factory workers easier; the firm is seeking to tap new growth opportunities ahead of a possible stock market listing. This is an example of a man-enhancing system, which can provide capabilities to users so that they may better accomplish a given task [60].
- ***Soft Exosuits:*** They are wearable robots which can either augment the capabilities of health individuals or compensate for the impaired ability of individuals with physical or neurological disorders. Compared to a traditional exoskeleton, these systems have several advantages in that the wearer's joints are unconstrained by external rigid structures, and the worn part of the suit is extremely light. These properties minimise the suit's unintentional interference with the body's natural biomechanics and allow for more synergetic interaction with the wearer [59].

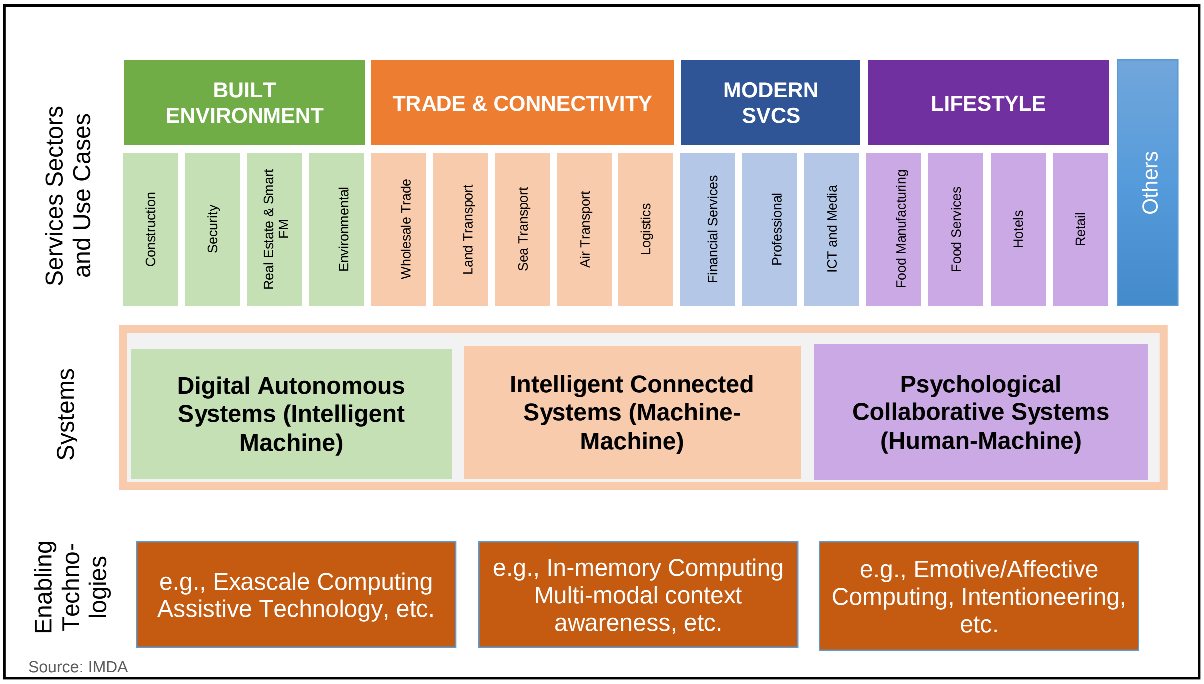


Exhibit 4: Alignment of the sectors use cases with the three systems

Exhibit 4 gives a comprehensive overview of the services sectors and use cases associated with each of the three systems. There are four services sectors delineated here: Built Environment (construction, security, real estate and environmental services), Trade and Connectivity (wholesale trade, land transport, sea transport, air transport and logistics), Modern Services (financial services, professional services, ICT and mobile) and Lifestyle (food manufacturing, food services, hotels and retail). The impact of these three systems across all sectors will not only change the way we work but the way we live.

With the advancement of Digital Autonomous Systems technologies, Digital Automation Platforms (e.g., Digital Twins) and Autonomous Systems (e.g., mobile robots) will become more feasible and accessible in the future. Digital Autonomous Systems will be developed to meet requirements according to various scenarios and applied widely across multiple domains or sectors.

2.4 Implications of Future-Ready Systems on Singapore's Economy

While we have discussed the global and regional trends thus far in the market study, it is prudent to take stock of Singaporean ecosystem with respect to Future-Ready Systems to assess Singapore's strengths and weaknesses. Singapore has long been a leader in the ICT space; in the 2017 UN ICT Development Index, Singapore was ranked 18th globally and 6th regionally in terms of access to ICT, use of ICT across industries and skill-development pertaining to ICT systems [61].

Singapore has made many advances in the area of robotics; the ABB Automation Readiness Index [62] ranks Singapore 3rd globally as a result of a strong innovation environment, future-oriented education policies and forward-looking labour market policies. The International Federation of Robotics (IFR) [63] reports that between 2010 and 2015, the number of industrial robots in Singapore grew at a CAGR of 20%, outstripping the global CAGR of 16%. Singapore is well-placed to drive growth in the adoption and development of robotics and automation solutions as a result of government initiatives such as the National Robotics Programme [64] which brings together public agencies and companies to develop a vibrant robotics and automation ecosystem. For example, the state Agency for Science, Technology and Research's (A*Star) Industrial Robotics Programme works with the robotics research community from the National University of Singapore, Nanyang Technological University, Singapore University of

Technology and Design, and A*Star research institutes to advance robotics solutions for industry partners, such as Sembcorp Marine and Spiral Marine. Furthermore, Singapore has a significantly higher density of industrial robots compared to the global average of 74 industrial robots installed per 10,000; Singapore has 488 robots per 10,000 employees in 2016 and 90% of these robots are installed in the electronics industry in Singapore, which has increased its number of robot installations significantly in recent years [63].

Singapore has made a number of decisive partnerships and programmes in order to become a forerunner in the development of human-machine interactive technologies. For example, the Singaporean government has partnered with Microsoft to develop intelligent chat-bots that can deliver a set of tech-based human-like customer services; these bots will eventually respond to personalised queries in a conversational manner, taking away the need for customers to scroll through numerous pages on government websites [65]. Hanwha Robotics, part of the South Korean industrial giant Hanwha Group, is partnering with engineering company PBA Group to open a collaborative robot production facility in Singapore in order to boost Singapore’s local production capacity of cobots and increase the accessibility of cobots for local companies [66]. Singaporean Traditional Chinese medicine (TCM) clinics have adopted cobots to relieve the load on physicians and physiotherapists; Emma (Expert Manipulative Massage Automation), the cobot used by NovaHealth TCM Clinic, is able to carry out highly articulated movements in delivering customised massages for each patient, mimicking the human touch [67]. This cobot allows the physician to focus on the consultation and treatment planning, lightening the physical effort required of the therapist, and reducing waiting times for patients.

Singapore’s expertise in robotics and AI suggests that it can have an important role to play in the development of augmented robots and other human-machine interactive systems. Singapore can use its size and strategic location to become a test bed for human-augmentation solutions; organisations can trial and refine their solutions in Singapore thus providing an effective means for knowledge exchange as well. Human-augmentation solutions can be applied across a number of sectors, specifically in the services industry e.g., robot-nurses to relieve the burden of mundane medical tasks on nurses etc. This will help Singapore become a leader in the Services 4.0 space.

In order to successfully develop and implement Future-Ready Systems in Singapore, it is imperative that Singapore develops its foundational computational and technological architecture. Singapore has successfully developed a strong foundation for the implementation of cloud technologies, in fact Singapore is ranked as the best country in the APAC region for the implementation of advanced cloud technologies as a result of high-quality broadband, governmental support, emphasis on cybersecurity and strong IP protection laws [68]. Cloud platforms can enable “as-a-service” business models thus enabling the next generation of service provision in Singapore.

Conversely, Singapore is still trialling advanced communications [69], such as 5G, and remains far behind the front runners China, South Korea, Japan and the US [70]. This would suggest that in order to make significant advancements in intelligent connected systems, Singapore needs to develop is advanced communications capabilities at a greater pace so as to not be outpaced by other countries.

Lastly, while Singapore has a burgeoning number of hyperscale data centres [71] [72], Singapore currently only possesses two petascale computers and therefore lacks the ability to analyse this data. As we move towards a data-driven future where technologies such as AI and machine learning are heavily dependent on data, it is imperative that Singapore develop its computational abilities so as to not be outpaced by other countries such as China which has 206 hyperscale computers.

Given the burgeoning number of hyperscale data centres in Singapore, developments in hyperscale computing and communications technology can form a solid foundation of emerging advanced data analytics and other uses. As data communications and advanced computational power can also help in the development of other Future-Ready Systems, it is of key importance that knowledge transfer be enabled in order to facilitate Singapore’s development in these areas.

Current projections suggest that Singapore can attain the status of a 1 exaFLOPS computing performance country if the nation is able to ramp up the adoption of hyperscale computing applications. In order to do so, Singapore needs to take measures on both the demand and supply side to catalyse growth of hyperscale computing. On the demand side, Singapore must identify the high compute applications in targeted sectors and take measures to drive adoption of these applications. On the supply side, Singapore must ensure the development of optimal computational architecture and supportive infrastructure such communications technology, data centres and computing hardware, in order to foster the development of the aforementioned applications [10].

Lastly, an overview of the Singaporean talent market with respect to Future-Ready Systems suggests that that there is a shortage of local talent. For example, Singapore does not feature on the top 10 global lists for AI enterprises or talent [73] [74] and reportedly outsources [75] much of the development of these tools to countries such as China and India. As the services industry becomes increasingly reliant on technologies such as AI, it is imperative that Singapore develop a sustainable talent pool to support Services 4.0 as increased local talent will improve access to AI solutions for local firms.

As evidenced in the discussion above, Human-Machine systems based on emerging technologies has the ability to push the boundaries of the economy and society. The potential to revolutionise our lives can be likened with revolution achieved with the advent of electricity. Below are three broad opportunities to shed light on the impact:

2.4.1 Massive Productivity Improvements

Emerging technologies in the Human-Machine Interaction space, have the potential to massively improve labour productivity on an unprecedented scale;

- Cobots, a relatively low-cost solution, has resulted in productivity improvements of up to 6,500% and created new jobs, resulting in increased headcount [54].
- AI technologies are projected to increase labour productivity by up to 40% and enable people to make more efficient use of their time [76]. AI could double annual economic growth rates in 2035 by changing the nature of work [77].
- Robotics has been observed to result in a staggering 250% increase in productivity and a significant 80% drop in defects [78]. Exoskeletons can make workers up to 27 times more efficient by increasing the amount of weight a human can lift [79].
- Agricultural technologies such as swarm bots and driverless tractors enable farmers to control and operate any field operation with the use of remote hand-held tablets offering small farmers greater operational efficiencies for tasks such as planting, spraying, and harvesting. The technology also helps achieve higher productivity and save on costs [35].
- Hyperscale computing architecture utilises cloud for scalability, employs infrastructure reliability and faster deployment of applications that can increase productivity [80].

2.4.2 Rise of New Services Ecosystem

Technology gives rise to new ways of providing services that do not exist today. In a span of less than two decades, human-machine systems have changed the way services are delivered, providing highly individualised products. For instance, in General Motors' plants, half-a-dozen cobots work alongside humans to deliver greater variety of derivatives, making highly personalised cars and derive premium (*Auto plants of future may have a human touch*"). In a B2C business environment, collaborative systems have also emerged. For instance, automatic burger restaurants such as Creator, make burgers that are robot-supported but delivered to customers by human workers. The intertwined and collaborative nature of humans and machines will continue to bring productivity and customised solutions to greater heights.

2.4.3 Emergence of New Skillset Development Today

In the near future, technology-economic paradigm is bound to shift. In the US alone, technology-related jobs are expected to grow by 22% up to 2020, creating 758,800 new jobs [81]; some estimates suggest that 65% of these jobs have not been created yet and are a direct result of implementing emerging technologies [82]. By 2020, 40% of outsourced services will leverage smart machine technologies, rendering the offshore model obsolete for competitive advantage, indicating the paradigm shift resulting from the implementation of emerging technologies [83]. These technologies will enable the provision of a greater number of services as technology fuels industry growth and innovation [84].

Technology is generating exponential waves of disruption. The key is to channel the technology evolution towards making humans and businesses remain relevant, unique, purposeful, and indispensable. Human-machine systems will therefore be a critical field of study that will force the technology providers to think about how their efforts can help humans live better.

3 TECHNOLOGY STUDY

The technology adoption readiness map intends to inform the stakeholders on which technologies are expected to become mainstream in the coming years globally. A consistent time frame has been used in the narrative – now to 2 years (short-term), 3 to 5 years (mid-term) and beyond 5 years (long-term). Broadly,

- Technologies included in the now to 2 years timeframe are already or expected to be viable for adoption by the majority of industry players in now to 2 years (short-term);

- Technologies included in the 3 to 5 years timeframe have shown evidence of promising use cases, are being provided and afforded by a handful of companies but still not viable for mass adoption. These are expected to be viable in the next 3 to 5 years (mid-term);

- Technologies included in the beyond 5 years timeframe are mostly in the R&D stage and remain inaccessible to industry players. These are expected to become viable beyond 5 years (long-term).

In this chapter, we will describe the technology roadmap of the three systems i.e., Digital Autonomous System (Intelligent-Machine), Intelligent Connected System (Machine-Machine), and Psychological Collaborative System (Human-Machine). The Technology Adoption Readiness Map for each system shows what technologies will be adopted in different phases over time and the Technology Capability Map outlines the capabilities of each system that evolve over time. Relevant use cases will also be presented in this chapter.

3.1 Digital Autonomous Systems (Intelligent-Machine)

Digital Autonomous Systems can be useful for a variety of applications. For example, a digital twin is a digital representation of the operations of entities in the real world. It can receive real-time or near real-time data feeds from real-world entities, analyse the objects' status and, respond to changes. Another example is mobile robots [85] which encompass a wide range of technologies such as multi-lens cameras, location sensors, and AI to become autonomous. A programmed robot is able to recognise objects using machine learning techniques, process real-life data feeds via embedded intelligence, learn about the environment and performance tasks in even unfamiliar situations. For instance, drone technology which makes use of technologies such as geo-fencing, computer vision, and robot interactive interfaces to perform tasks independently.

- Digital Automation Platforms and Services

Some organisations have already started to build digital automation platforms and services to represent physical objects of products and the relevant processes for production. Digital Twins can be applied to manufacturing, buildings, energy generation and other operational environments and cover various functions from ideation to design and development to production. Commercial companies like Siemens [86] built digital twins to create digital design of machines, simulate complex manufacturing operations, and monitor the status in real-time to improve quality and efficiency. GE Digital developed a suite of applications and peripherals [87] with advanced IoT technologies and AI for "Smart" inspection to help field engineers for part identification, condition tracking, issue resolution, etc.

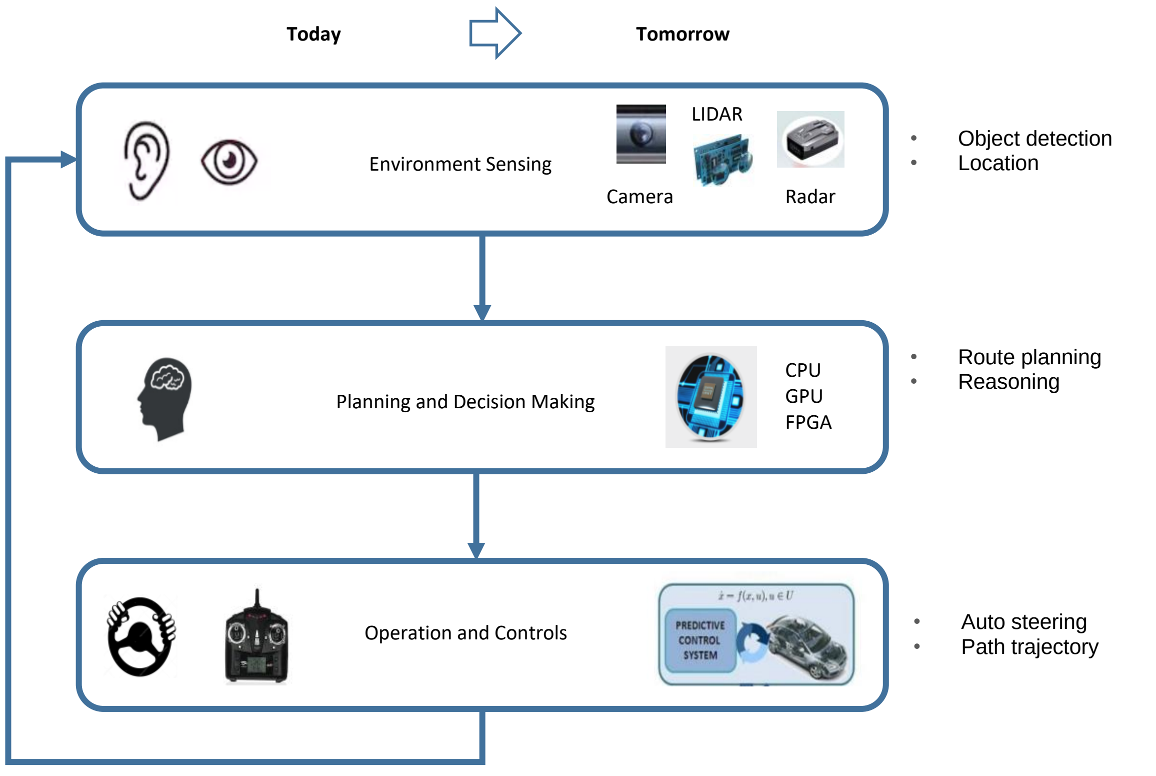
The actual implementation of a digital twin could be a software platform or system which supports users to download data, software, models, and to update the real-world entity, and track the status in real-time or near real-time. It has been extended to a suite of cloud-based software tools and services where models can be stored in the cloud and users can run machine learning or use analytic tools to simulate various scenarios in a remote data centre. This has enabled data from multiple digital twins to be aggregated for a composite view covering multiple designs across a number of real-world entities. Some organisations are experimenting with blockchain and distributed-ledger technologies to complement digital twins by providing a digital representation of asset value, and a mechanism to track asset flow and related processes [88]. Leading players in the global Digital Twins market include GE, Siemens AG, IBM, Microsoft, Oracle, PTC, ANSYS, Dassault Systemes, Bosch, SAP, etc.

A simple digital twin representation could be a dashboard connecting real-time data feeds to monitor the status of real-world objects and associated processes. Users can use the dashboard to understand real-life situations or simulate various scenarios for preventive maintenance. Future digital twins can be equipped with other tools such as conversational interfaces, 3D inspection, and advanced user experience channels to interface with both real-world objects and their virtual counterparts. A variety of apps and services can be built on top of the digital twin platform with open APIs or interfaces to integrate with other technologies such as machine learning, modelling and simulation, cognitive analysis, supercomputing, etc. Meanwhile, it will be essential to integrate security protocols during the design phase itself to provide a secure runtime [88].

Autonomous Systems

An autonomous system is a system which can operate independently and complete tasks with little human invention. It can be as simple as an automatic vacuum cleaner for house cleaning or complex devices such as personal assistant robots (PAR) and robots for high performance operations or high accuracy inspections. Autonomous systems add intelligence to machines by programming a robot with the ability to acquire knowledge using machine learning techniques. They augment human capabilities by combining advanced sensing techniques and data analysis, for example, night vision enhancement and motion path correction. Some autonomous systems can connect with cloud and learn new tasks or enhance existing capabilities. Next-generation mobile robots will transform warehouse operations and perform complex tasks such as unloading trucks and deliver palettes of goods with high efficiency and accuracy.

Autonomous systems have abilities such as environment sensing, division making, and operation and control, as shown in Exhibit 5. Robotic middleware integrates various software components, interfaces to drive multiple robot functions (e.g., camera, microphone, and actuators), intelligent computing modules (e.g., image processing, feature recognition, localisation) and control systems (e.g., auto steering, navigation) into one autonomous system. Some also include operation simulators and system development tools to simulate various scenarios in advance and optimise the performance with predictive controls. Major robot middleware projects and related vendors are robot technology middleware (RTM), Yet Another Robot Platform (YARP), Orocos, ROS, NAOqi, H-ROS and Rock [89].



Source: IMDA

Exhibit 5: Autonomous systems and key features for future application services

Two ways for an autonomous robot to conduct the analysis:

- Embedded analysis in a robot's hardware system, and
- Cloud "brain" which is connected with analytic services requiring high computation power and complex analysis.

Sometimes a robot can use two approaches concurrently. The computing resources in a robot can be based on CPU, GPU or FPGA devices which are programmable for highly customised data processing and analytical tasks. The MIT researchers at the RoboEarth project allow robots to share knowledge about specific tasks over the Internet. However, the challenge is to share huge data via existing cloud, communication technologies (e.g., 5G) and interfaces. Other cloud projects, such as RoboBrain, train robots via the cloud and perform different tasks. CloudSim, an open-source Cloud-based simulation platform, is able to test the performance of humanoid robots on a variety of disaster response tasks [89].

3.1.1 Technology Adoption Readiness Map

3.1.1.1 Digital Automation Platforms and Services

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Smart inspection:** - observe, learn, and capture knowledge from disparate media and/or real-time data feeds; - high performance inspection for detection or quality control; - concurrent multi-scenarios analysis; - knowledge elicitation & representation - explanatory inference provides information / answer at fingertips	**Preventive maintenance:** - maintain self-sovereign identity; - interpret human intention for engineering design and analysis; - knowledge fusion and refinement - decentralised design for planning and optimisation; - make engineering recommendations with human in the loop	**Proactive enhancement:** - give recommendations with rationalisation and provenance for production improvement; - transfer knowledge between systems e.g., virtual personal assistance (VPS) - create, improve and evolve services and components
Technologies	• Petascale Computing • **GPU-accelerated Computing** • **Edge computing** • **Serverless computing** • **Narrow AI/Machine learning/Deep Learning for object recognition and differentiation** • **Machine reasoning** • **Nature Language Processing (NLP)** • Software-Defined Storage • Hyperscale Computing • Cyber physical systems • Multi-objective optimisation • Modelling & simulation • **IoT sensors and wearables** • Ultra-High Definition (UHD) camera • **Virtual Reality** • Human-centric interfaces • Info search • Geospatial information systems (2D/3D) • **Chat bots** • **Computer vision e.g., video content analytics** • **Real-time Programmable Logic**	• **Exascale Computing** • **General AI for decision making, reasoning, and planning** • **Cognitive computing** • **Assistive Technology** • Homomorphic Encryption • Seamless and pervasive multi-modal communications • Social cyber physical systems • Augmented Reality • Blockchain • Wearable computing (e.g., smart textiles) Semantic technology	• **Neuromorphic Computing** • Deep Neural Network ASICs • **Common-sense AI for proactive improvement** • **Virtual Assistant** • **High performance blockchain**

	Controllers (PLC) integration		
Application Scenarios/Use Cases:	**Digital Identity for Intelligent Services** Digital profiling, automated identification, feedback loop with human for optimisation, and apply knowledge across multiple space-time for new services in logistics, retails, traffic & crowd management, smart cities, modern life styles, etc. **Digital Service Engineers for Maintenance Repair and Operation (MRO)** With IoT sensors and artificial intelligence to offer personalised assistance, to learn and acquire knowledge through observation, and to make recommendations of appropriate services based on acquired knowledge. **Smart Building Environment** Automate analytics of building performance (e.g., to inspect building for safety and compliance), drive performance and cost optimisation of their real estate portfolio by surfacing performance anomalies, recommend preventative maintenance, predict energy consumption, and etc.		

* Technologies in black and bold are recommended for industry deployment and innovation in the short run (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in the long run.

Table 1: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Digital Automation Platforms

The below chapter details the various stages of technologies development and adoption by users over time.

- Now to 2 years: Technologies such as narrow AI, machine learning, and deep learning will enable systems to observe, learn, and capture knowledge from disparate media and/or real-time data feeds. Technologies such as IoT sensors and wearables, Ultra High Definition (UHD) camera, computer vision, real-time programmable logic controllers (PLC) integration, GPU-accelerated computing, edge computing will enable high performance inspection for fault detection and quality control.

- 3 to 5 years: Technologies such as exascale computing will significantly improve system response speed. General AI will help the systems on decision making, reasoning, and planning. Cognitive computing will help to interpret human intention for engineering design and analysis. Technologies such as seamless and pervasive multi-modal communications and semantic technology will help the systems for knowledge fusion and refinement.

- Beyond 5 years: Technologies such as Deep Neural Network ASICs will address the hardware design of computing devices and make AI-based computation more efficient and effective. Super AI algorithms will enable systems to be more proactive for creation of service components and enhancement.

3.1.1.2 Autonomous Systems

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Autonomous Bots/Vehicles – Land**		
	Conditional Automation - auto steering and monitoring - semi-auto for dynamic tasks - human take over when needed	**High Automation** - auto steering and monitoring - fully auto for dynamic tasks - more auto driving modes/conditions; - with simultaneous manipulation capabilities	**Full Automation** - auto steering and monitoring - all driving modes/conditions that can be managed by a human driver
Technologies	• Perception-detection • **Route planning and learning for simple uncrowded environments** • **Deep Learning** • **Augmented Reality**	• Perception-tracking • **Route planning and learning for unstructured and semi-crowded environments**	• Perception-prediction • **Route planning and learning for complex, unstructured and human environments**
Application Scenarios/Use Cases:	Autonomous systems including autonomous vehicles, mobile bots, machines or devices which can navigate, plan routes, and complete tasks indoor and/or outdoor autonomously with less human invention		

* Technologies in black and bold are recommended for industry deployment and innovation in the short run (e.g. Now to 2 years), and technologies in blue and bold are recommended for research & development in the long run.

Table 2: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Autonomous Bots/Vehicles – Land

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Autonomous Bots/Vehicles - Marine (surface and underwater)**		
	Assisted Automation Station keeping and navigation (surface)	**Partial/Conditional Automation** Station keeping, localisation and navigation underwater; mapping	**High Automation** Decentralised autonomous systems with full communications
Technologies	• **Acoustics (e.g., ultrashort baseline)** • Sonars • Communications • Battery	• **Bio-inspired underwater vehicles (e.g., stingray)** • Soft Robotics • Advanced and multi-modal sensing for perception and localisation	• **Hybrid vehicles/ propulsion systems** • Air-land-water vehicles
Application Scenarios/Use Cases:	Autonomous systems including autonomous boats, ships, machine or devices which can move in the water (surface or underwater) with a certain degree of autonomy		

* Technologies in black and bold are recommended for industry deployment and innovation in the short run (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in the long run.

Table 3: Technology Readiness Map, Technology Capability Map, and Use Cases for Autonomous Bots/Vehicles - Marine

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Autonomous Bots/Vehicles – Air**		
	Assisted Automation Sensor-aided flight navigation under remote control; localisation and mapping	**Partial/Conditional Automation** Autonomous navigation through defined waypoints; no remote control; longer duration	**High Automation** Automatic flight path generation; automatic 3D mapping with texture
Technologies	• LIDAR • Computer Vision • Inertial Measurement Unit (IMU) • Battery • 3D reconstruction with photogrammetry • Multi-sensory fusion • User interface design	• **Hybrid fixed Wing/Multi-rotor** • Local cognitive intelligence	• **Novel designs (e.g., flapping wing)** • **Self-awareness and advanced cognitive capabilities** • **Self-organisation and planning**
Application Scenarios/Use Cases:	Autonomous systems including pilotless plans/flights, drones, or flying machines or devices which can fly with or without remote controls.		

* Technologies in black and bold are recommended for industry deployment and innovation in the short run (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in the long run.

Table 4: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Autonomous Bots/Vehicles – Air

The below chapter details the various stages of technologies development and adoption by users over time.

- Now to 2 years: Technologies such as route planning, object detection, and deep learning will enable robots auto steering, monitoring and complete dynamic tasks with less human intervention. Other technologies such as computer vision, and sonar will help robots to sense the environments.

- 3 to 5 years: Autonomous systems will be able to conduct route planning and learning in unstructured and semi-crowded environments. Hybrid fixed wing and route planning help mobile robots to auto navigation.

- Beyond 5 years: Technologies such as route planning and environmental perception will enable autonomous systems to be more intelligent with predictive controls. Novel designs (e.g., flapping wing) will improve intelligence and efficiency.

3.1.2 Technology Capability Map

3.1.2.1 Digital Automation Platforms and Services

- Now to 2 years: Digital automation systems will be capable of real-time sending and detection: i) conduct high performance inspection for defects detection, ii) process real-time data feeds collected from a various IoT sensors, iii) conduct concurrent multi-scenarios analysis, knowledge elicitation/representation, and explanatory inference.

- 3 to 5 years: Digital automation systems will be capable of self-learning with automated knowledge fusion and refinement, decision making, reasoning, and planning. They will become sufficiently intelligent to offer further improvements using human-in-the-loop engineering recommendation algorithms.

- Beyond 5 years: Digital automation systems will be more proactive in offering auto recommendations for production improvement with rationalisation and provenance, transfer knowledge between systems, and create & evolve service components.

3.1.2.2 Autonomous Systems

- Now to 2 years: Autonomous systems will be able to monitor the environment and automatically steer in simple uncrowded environments. They can fulfil tasks in unfamiliar environments with remote controls from human.

- 3 to 5 years: Autonomous systems will be able to conduct route planning in unstructured and semi-crowded environments. Robots can navigate underwater autonomously through defined waypoints without remote control.

- Beyond 5 years: Autonomous systems will be able to complete dynamic tasks autonomously and navigate in air-land-water. Systems will have autonomous control including automatic flight path generation, automatic 3D mapping with texture, etc.

3.1.3 Use Cases

3.1.3.1 Digital Automation Platforms and Services

Organisations can make use of digital twins as a digital service platform to create their business operating models for project planning, simulation, and optimisation. It integrates various models, data feeds from IoT devices, and AI algorithms for operating conditions analysis. Various application scenarios include:

- **Digital Identity**: Within the next 2 years, the systems will enable use cases such as proactive health monitoring, identification of manpower shortage, mass sentiment analysis, and crowd monitoring and controls. Within 3 to 5 years, semi-automated consumer service bots such as digital tutors, health advisers, legal/ financial agents, and city planners will speed up digital workforce reconstruction. Beyond 5 years, personalisable machines will enable customisable retail services with human-in-the-loop capability for further improvement.

- ***Digital Service Engineers for Maintenance Repair and Operation (MRO):*** Leveraging on vision-based analytics with IoT sensor and device data, autonomous analytical tools can provide advanced insights that are useful across industries. Within 1 to 3 years, smart agents will enable systems to conduct real-time inspections, diagnose failures, and capture knowledge from disparate media and/or real-time data feeds. Within 3 to 5 years, human-centric intelligent auxiliary systems will facilitate humans to read instructions, capture data, and navigate precisely. Beyond 5 years, virtual personal assistance (VPS) will provide proactive recommendations with rationalisation and provenance for maintenance.
- **Smart Built Environments:** Systems can use artificial intelligence to offer personalised assistance to service engineers, to learn and acquire knowledge through observation, and to make recommendations of appropriate services based on acquired knowledge. Within 1 to 3 years, digital automation platform can leverage vision-based analytics, augmented reality, and IoT sensors for augmented building inspection. Within 3 to 5 years, semi-automated virtual agents will use data-driven approaches for optimisation; e.g., Building Management System (BMS), Automatic Meter Reading (AMR), etc. Beyond 5 years, the digital system will be more proactive to surface performance anomalies, recommend preventative maintenance, and predict performance e.g., energy consumption.

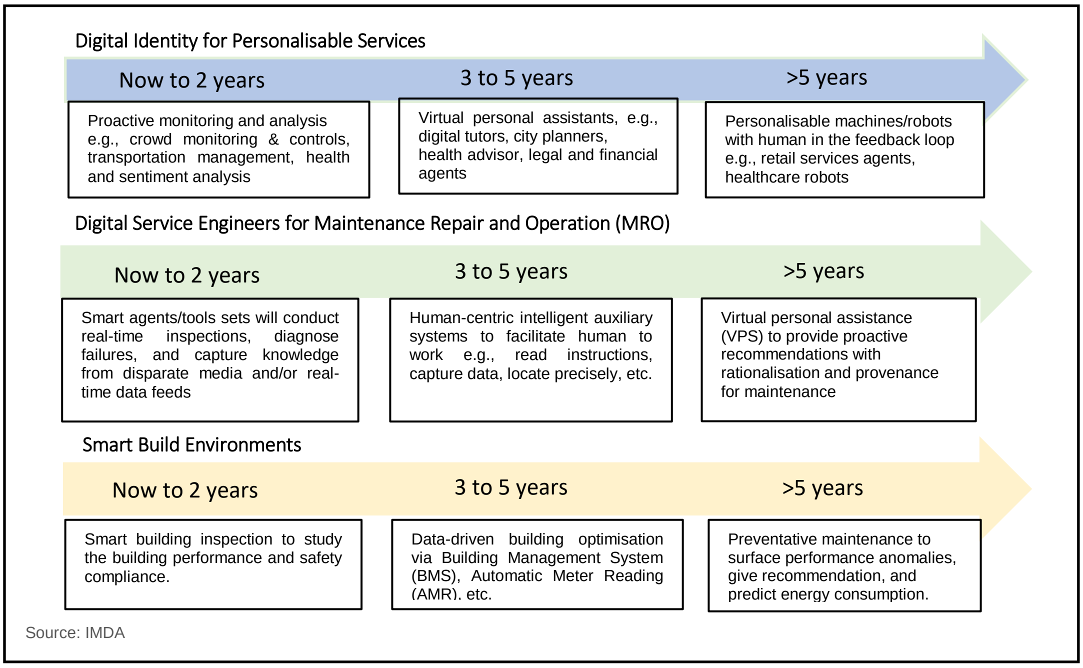


Exhibit 6: Digital automation systems use cases

Digital automation systems like Digital Twins [90] can help an organisation to identify potential improvements, create new revenue, and lower down operation cost. While Digital Twins are compelling for improving quality and knowledge management, the organisation will also need to address issues such as cost, complexity, data rights, etc. It requires designers to understand how real operations connect with the current state and respond to effective design changes in the Digital Twins system.

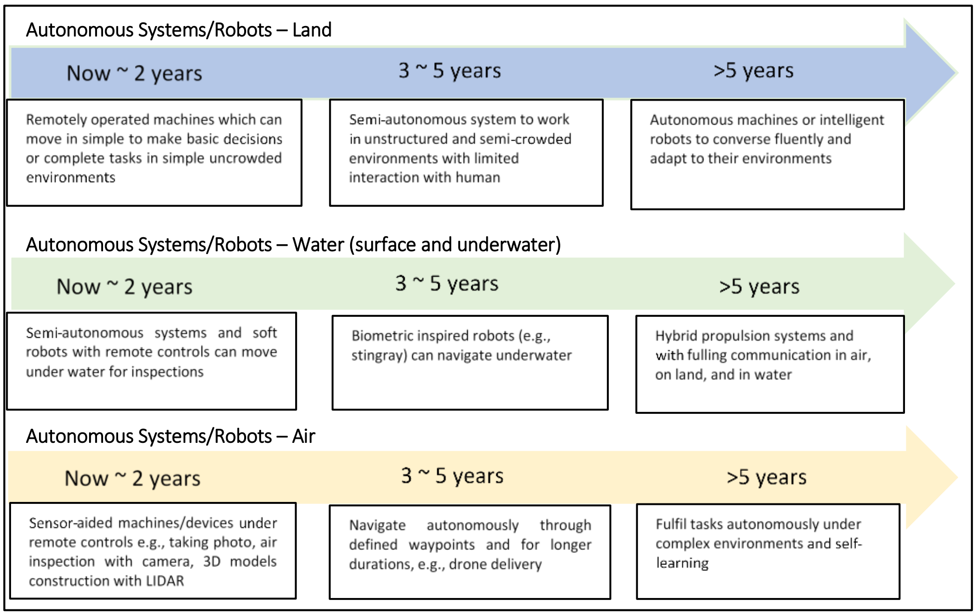
3.1.3.2 Autonomous Systems

Autonomous systems will be capable of self-localisation, navigation, route planning, and environment sensing. They can response to changes and operate in unfamiliar situations. Autonomous mobile robots (e.g., aerial/maritime/surface) will be able to perform air-land-water search, rescue tasks, and exploration in space, sea, volcanoes, etc.

- ***Autonomous Bots – Land:*** Within the next 2 years, autonomous robots on land possess environmental sensing, automatic route planning, and navigation within simple uncrowded environments. Within 3 to 5 years, robots can complete dynamic tasks and navigate in unstructured and semi-crowded environments. Beyond 5 years, robots will become more autonomous and can navigate in complex and unstructured environments.

- ***Autonomous Bots – Marine:*** Within the next 2 years, robots will be equipped with acoustics (e.g., ultrashort baseline) and sonar technologies for environment sensing. Robots with dexterous manipulation can fulfil complex tasks and deal with dynamic situations. Within 3 to 5 years, biomimetic inspired robots (e.g., stingray) can navigate underwater. Beyond 5 years, underwater robots can have hybrid propulsion systems and with seamless communication in air-land-water.

- ***Autonomous Bots – Air:*** Within the next 2 years, sensor-aided machines can fulfil various tasks such as rapid wide-area 3D models reconstruction from LIDAR. Within 3 to5 years, autonomous flights can have automatic ad-hoc waypoints definition in wider areas. Beyond 5 years, they can fly under complex environments with self-learning.



Source: IMDA

Exhibit 7: Autonomous systems use cases

3.2 Intelligent Connected Systems (Machine-Machine)

Two typical intelligent connected systems to be explored in detail here are connected vehicles and swarm bots.

- ***Connected Vehicles:*** Connected vehicles refer to vehicles equipped with various communication devices, which allow them to connect and communicate with neighbouring vehicles, roadside infrastructures, etc. to continuously share mobility information with each other with due consideration of rogue or malicious vehicles. Connected vehicles can connect and communicate with humans, other connected vehicles including aerial transports, traffic signals, work zones, toll booths, school zones, and other types of infrastructures.

Communication technologies are key components of connected vehicles. Vehicles can connect and communicate with others using three main channels:

- Standard telephone connections (5G),
- Traditional short-range technologies such as Wi-Fi, Bluetooth, etc. and
- Vehicle-to-everything (V2X) communication including dedicated short-range communications (DSRC) and Celluar-V2X (C-V2X).

V2X communication technologies are mainly applied to vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication.

V2V communication allows neighbouring vehicles to communicate to share mobility data. Once an individual vehicle receives mobility data about neighbouring vehicles, it can predict whether any crash will occur to avoid it or any dangerous situation that may appear. Depending upon how the technology is implemented, the vehicle's driver may simply receive a warning if there is a risk of an accident or the vehicle itself may take pre-emptive actions such as braking to slow down.

V2I communication allows vehicles to connect and communicate to share information with roadside infrastructures, overhead RFID readers, cameras, traffic lights, lane markers, streetlights, signage and parking meters, etc. Vehicles can send their mobility data to roadside infrastructures for traffic management; infrastructure components can also send warnings or travel recommendations to vehicles.

- ***Swarm Bots:*** Swarm robotics technology is a novel approach to collaborative robots, in which a number of simple robots are coordinated to display a desired collaborative behaviour through the interaction of these robots and their interaction with the environment. This approach is inspired by the biological study of swarm behaviour among insects, ants and other fields in nature.

The motivation behind swarm robotics is the ability to perform tasks that (1) require miniaturisation with distributed sensing for micro machinery, human body intervention; (2) with cost effective design for mining, agricultural foraging; and (3) enable large area coverage in a short time, for post-disaster relief, target searching, military applications, etc. Swarm robotics have an enormous potential in several real-world domains, such as search and rescue, exploration, surveillance.

The following are the enabling properties of the swarm robotics:

- Robustness: ability to cope with the faults or the loss of individual robots;
- Flexibility: ability to operate in a variety of different environments and to perform various tasks;
- Scalability: ability to generally maintain the group behaviour regardless of the size of the swarm.

The research on swarm robotics can be classified into two classes: 1) Collective behaviour based on the patterns, such as aggregation, cartography, migration, self-organising grids, deployment of distributed agents and area coverage. 2) Interaction with entities in the environment, e.g., searching for the targets, detecting the odour sources, locating the ore veins in wild field, foraging, rescuing the victims in disaster areas and etc. Besides these, swarm robotics can also be applied to more complex problems including cooperative transportation, demining, exploring a planet and navigating in a large area, which can be considered as the hybrid of the aforementioned two problems.

In recent reviews of the field of swarm robotics, almost all real-robot experiments presented in the literature have been performed in controlled laboratory environments in which the relevant conditions are defined by the experimenter. Although swam robotics systems aim to operate in complex real-world environments, very few studies have been able to demonstrate their performance in real-world environments.

A challenging issue in building swarm robotic systems is how to design and analyse coordinated algorithms to achieve a desired collaborative behaviour. A swarm robot system can have thousands of individual robotics and thus it is difficult to design coordinated algorithms for a complex problem. Current methodologies for the design include behaviour-based design methods and automatic design methods.

Another challenge is the communication between the individual robots in the group which is generally local with no centralised control to ensure the system is scalable and robust. The communication network depends mostly on the environment, the size of the robots, the budget of the project and on the limitations set by creators.

The last challenge is the limitation in computing capability that enables individual robots to process data, images and messages quickly to make decisions in the face of various complex environments. To overcome this challenge, in-memory computing is one possible computing architecture for individual robotics to do image analysis, context awareness, and data analytics.

3.2.1 Technology Adoption Readiness Map

3.2.1.1 Connected Vehicles

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Basic Connectivity and great analytics abilities:** Be capable of vehicles to vehicles communications, and vehicles to roadside infrastructure communication, and to share data, to use mobility data for traffic safety and efficiency.	**Strong connectivity and greater analytics abilities:** Be capable of communication between vehicles and a broad range of infrastructures, and advanced traffic management system using massive mobility data.	**Intelligent reasoning and decision making**: Be capable of collaboration between vehicles and vehicles, between vehicles and infrastructures in an intelligent and efficient manner.
Technologies	• **In-memory Computing** • V2X communication (DSRC, C-V2X) • **Narrow AI / Data analytics** • Vehicles platooning • **Intelligent traffic advisor** • Driver assistance system	• Strong AI / Big data analytics • 5G • **Context-aware system** • **Intelligent traffic management** • Remote vehicles platooning	• **Advanced context-aware system** • Security • **Advanced traffic management system**
Application Scenarios/Use Cases:	**Connected vehicles for safety**: Vehicles can sense the movement of vehicles and pedestrians in its neighbourhood, and can predict their movement to avoid possible collisions. **Connected vehicles for travel efficiency**: Roadside infrastructures can receive mobility data from vehicles and then can use these data to predict traffic flows and to provide an optimised route for drivers.		

* Technologies in black and bold are recommended for industry deployment and innovation in near term (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in relatively longer term.

Table 5: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Connected Vehicles

- Now to 2 years: The development of AI and computing technologies will promote the utilisation of mobility data to solve traffic issues. AI technology will allow an individual vehicle to identify traffic situations and send warnings to its driver, and computing technologies will speed up the process.
- 3 to 5 years: As massive mobility data is generated, big data analytics technologies are required to mine data from various traffic situations. Intelligent traffic management system will ensure that the transportation sources are utilised in an efficient manner.
- Beyond 5 years: The advancement of AI and data analytics will further enhance the intelligence level of traffic management system and individual vehicles to further improve travel efficiency and safety. Possible scenarios include
    - Efficiency maximisation through user routine, car condition, traffic pattern etc.
    - Efficiency maximisation through multimodal traffic behaviour analysis, across private, public and shared transport media.

3.2.1.2 Swarm Bots

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Collaborative systems with human intervention**: Be capable of collaborative tasks with central control or human intervention. Robots are able to communicate with neighbouring ones, collect data, and execute the activities assigned by the central controller	**Collaborative systems with little human intervention**: Be capable of collaborative tasks with little human intervention, self-organised, and making decisions by individual bots. Robots are able to negotiate with neighbouring ones, generate and execute the activities towards a set of tasks.	**Collaborative systems for complex tasks:** Be capable of self-organised, making decisions by individual bots under complex environments, and adapting organisation structures to tasks.
Technologies	• Machine to Machine communication • Planning and scheduling • Localisation • Narrow AI • Cloud intelligence • Petascale computing	• Multimodal context awareness • **Self-organised systems** • **Context-aware system** • Strong AI • Edge computing • Exascale Computing	• **Context-aware system for complex tasks** • **Self-organised cooperation** • Low cost bot • **Collaboration of heterogonous robotics with different operating systems**
Application Scenarios/Use Cases:	**Micro swarm bots for maintenance and healthcare**:		

	Micro swarm robotics can be used to inspect the engine without removing it from the aircraft. On the other hand, tiny swarm robotics for healthcare can carry medicals to accurately travel to targeted tissues and destroy them. **Swarm bots for logistic**: Swarm robotics can be controlled to collaborative to unload a large number of cargo containers to speed up the logistic efficiency.

* Technologies in black and bold are recommended for industry deployment and innovation in near term (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in relatively longer term.

Table 6: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Swam Bots

- Now to 2 years: The advancement of communication technologies such as V2X and 5G is critical for building connections among a group of bots. On the other hand, in-memory computing is quite important for big data analytics, because more and more data will be created as the number of bots and their interaction increases.

- 3 to 5 years: Context-aware systems will enable individual bots to have good understanding of neighbouring bots' behaviour and the changes in the environments. On the other hand, self-organised system is the key technology that ensures the individual bots display collaborative tasks in a distributed manner.

- Beyond 5 years: Self-organised cooperation is the key technology that enables swarm bots to complete collaborative tasks in a distributed and efficient manner, which includes intelligent forms of decision making, such as organisation, delegation and resolving troubles in a self-complete manner. Further, the collaboration of bots (or with other humans) with different operating systems, design, etc. is critical to a wide range of applications of swarm bots.

3.2.2 Technology Capability Map

3.2.2.1 Connected vehicles

- Now to 2 years: V2X communication devices such as DSRC, C-V2X will be widely installed to ensure the connectivity between vehicles to vehicles, and between vehicles to roadside infrastructures. On the other hand, vehicles can use mobility data from neighbouring vehicles to avoid crashes, and can also gain useful traffic information to avoid congestion.

- 3 to 5 years: Vehicles can communicate with a broad range of infrastructures to strengthen connectivity to gain more traffic information. On the other hand, vehicles' mobility data can be deeply mined to efficiently control traffic lights to reduce time delay and queue length at the junctions.

- Beyond 5 years: The transportation management systems can efficiently and intelligently allocate the transportation resources to reduce travel time and improve travel efficiency. On the other hand, vehicles can communicate with a large range of infrastructures so that traveller's needs including safety, food, and entertainment can be met, even if the driver is not familiar with the surrounding environments.

3.2.2.2 Swarm bots

- Now to 2 years: Swarm bots will be capable of collaborative tasks with certain central control or human intervention. They will have the ability to observe the environment with cameras or sensors, and make simple responses. But they will need human intervention or central control to assign tasks for further actions.

- 3 to 5 years: Swarm bots will be able to complete collaborative tasks with little or no intervention. Individual bots will communicate with other bots, the environment, etc. and make decisions to collaborate with other bots.

- Beyond 5 years: Swarm bots will be capable of complex tasks with various requirements. They will be able to collaborate with other bots (or with other humans) with different operating systems, design, etc. They will be self-organised, and can adjust their organisation structure according to tasks and environments.

3.2.3 Use Cases

3.2.3.1 Connected Vehicles for Improving Safety

Connected vehicles could significantly prevent a large number of traffic accidents that occur each year, and therefore significantly reducing the number of fatalities and serious injuries [91]. Safety applications implemented within connected vehicle systems would enable drivers to possess a 360-degree awareness of potential hazardous situations. By making use of data received from surrounding vehicles, novel technologies such as in-memory computing could accelerate computation speeds of complex AI algorithms to predict possible crash scenarios and therefore avert an accident. In-car warnings could alert drivers of imminent crash situations; such as, merging trucks, cars positioned on the driver's blind side, emergency braking of vehicle ahead. By communicating with roadside infrastructure, drivers could be alerted when they are entering a school zone, presence of obstacles along the roadside, etc. [92]. Furnished with an influx of flashing lights and alarms in the vehicle cabin, much engineering work is also being conducted to ensure that the driver would not be presented with an overload of information that would only become an additional source of distraction. Connected vehicle systems shall be similar in many ways to other wireless networks that create a dynamic transportation network based on an open platform to allow new and creative applications with open standards to develop new products, services and applications.

3.2.3.2 Connected Vehicles for Enhancing Travel Efficiency

As recorded in the Year 2013 by the Environmental Protection Agency's Inventory of U.S. Greenhouse Gas Emissions and Sinks, the transportation sector contributed 27% of the country's GHG emissions. Real-time data generated by connected vehicle systems would allow both drivers and transportation managers to make green transportation choices. This may be achieved by recording and sharing mobility data (e.g., location, velocity, etc.) with roadside infrastructure via V2I communication [93]. Intelligent transportation systems shall then utilise these data to predict when vehicles would arrive at a stop line, and then optimise the traffic light signalling system (e.g., switching to a green light so that the traveling time of vehicles may be reduced). In addition, real-time information regarding traffic conditions made available to motorists would optimise fuel-efficiency by eliminating the overall number of stops [94]. Drivers would also be able to avoid congestion by:

i) selecting alternate routes, ii) opting for public transit, or iii) rescheduling their trip – to enable more eco-friendly journeys. Provided with real-time information, drivers may have a realistic idea of when transit vehicles will arrive, and so they would be able to improve bus and train connections. As a consequence, the perspective of public transportation may be made to appear more appealing to the average commuter.

Traffic efficiency may also be improved by connected vehicle systems. To illustrate, total traveling time may be reduced by providing a near-optimised route according to using vehicles' mobility data. Connected vehicles also provide real-time traffic data sharing, which makes optimisation of travelling routes or transportation resources allocation possible [95].

3.2.3.3 Micro Swarm Robots for Maintenance and Healthcare

Rolls-Royce has been developing miniature swarm robots that are able to crawl inside aircraft engines to detect and repair problems. Miniaturisation technology was employed to ensure that the robots are sufficiently small to enter aircraft engines without removing the engine from an aircraft. A set of collaborative, miniature robots, each of which is around 10mm in diameter, were deposited in the centre of an engine via a 'snake' robot to perform a visual inspection of hard-to-reach areas. These robots carry small cameras so that they are able to provide live video feedback to the operator, and then the technician would be able to rapidly perform a visual inspection of the engine without having to remove the component from the aircraft. As mentioned by a Rolls-Royce engineer, "If we did it conventionally it would take us five hours; with these little robots, who knows, it might take five minutes". Maintenance can be improved by speeding up inspections and eliminating the need to remove an engine from an aircraft for repair work to take place. Rolls-Royce also plans to use robotics to perform internal patch repairs. Another ongoing research project of Rolls-Royce on swarm robotics aims to permanently install a network of periscope-like INSPECT bots inside engines for constant spot maintenance. In addition, the specialist engineers will control remote bore-blending robots to assist with complicated maintenance tasks.

Another area where swarm robots could be deployed is in the healthcare sector. Nanoparticles are remarkably small and are able to leak into blood vessels and move to targeted organs/sites. They can be further configured into a swarm robotics system by altering their coating, charge or size. Once a group of nanoparticles is well coordinated, they can be controlled to travel to cancer cells to deliver medicines and activated to destroy targeted tissue effectively. With the development of swarm robotics technologies and AI technologies, medial swarm robotics can gain more intelligence and capabilities to more accurately destroy targeted issues.

3.2.3.4 Swarm Robots for Logistics

The potential logistic applications include automated warehouse management, robotised shipping container terminals, robotised public transport and small packet delivery drone swarms. All these examples are already in use in a limited scale. To perform complex collaborative operations for a swarm of robotics, one may need to plan joint operation, schedule sub-operations, and coordinate the routes and actions of individual robots so that they do not interfere with each other. For example, in a container ship terminal, the task of unloading thousands of cargo containers from a container ship can be planned to produce a partially-ordered set of tasks, each identifying a container and its destination in the terminal storage area. The unloading task has some requirements; for example, the top most containers must be unloaded first, and the balance of the ship cannot be compromised by, for example, unloading the whole starboard side before proceeding to the port side. The individual tasks are assigned to specific container-handling robots at the right time, depending on their current location and the requirement of the subtasks. An optimised routing plan is produced for each container-handling robots by taking account of their locations, capability, and safety issues.

3.3 Psychological-Collaborative Systems (Human-Machine)

This chapter shall illustrate several practical implementations of Psychological-Collaborative Systems that are already available today, and also a plausible forecast of their evolutions in the next five years and beyond. We will discuss intelligent human sensing cooperative robots followed by perceptive humanoid robots.

Machines exist solely to benefit human beings, either by amplifying human capabilities (discussed in the section Digital Autonomous Systems (Intelligent-Machine)), or by working together with human operators on different tasks to achieve a shared objective. Hence, human-machine robotic systems are required to be associated with cognitive insights to be able to recognise relevant patterns from large volumes of data in order to make optimal decisions. In addition, future human-machine systems need to have the ability to read, interpret and respond to emotions emanating from human beings. Intelligent human-machine systems of the future are envisioned to possess Emotional, Cognitive and Affective (ECA) capacities that shall prove to be instrumental in enabling better synergy between human beings and machines to enhance productivity and operational efficiency in various industries that are relevant to Singapore.

In particular, two types of human-machine systems shall be discussed: a) Intelligent human sensing robots, and b) Perceptive humanoid robotic system.

- Intelligent Human Sensing Robots

For decades, industrial robots have been utilised within manufacturing workspaces to accelerate production and boost accuracy, and at the same time reducing human labour and human errors. In the emerging field of *Intelligent Human Sensing Robots*, or collaborative robots (aka cobots), it offers the added advantage towards a flourishing digitalised logistics warehouse industry (e.g., Amazon, DHL) of replacing human operators through full automation. The contributions of both “human and machine” may be jointly optimised by exploiting the strengths of both. This category of advanced robots are usually lightweight and highly complex autonomous machines capable of operating safely with human co-workers in a shared work environment.

Cooperative robots are designed to work *with* humans, and not *for* humans. They not only support and alleviate the load off the human operator, they also provide maximum productivity through a conjoint work flow. Traditional robots have been commonly designed and programmed to administer very specific individual tasks that are subsequently taken over by human operators. Intelligent Human Sensing Robots, on the other hand, provide far greater flexibility in shared workspaces (i.e., does not require a safety-fence) that are able to handle multiple tasks that are inter-changeable with the human operator. Advanced robotic automation further enhances operational efficiency as human workers are freed to perform more intricate and interesting roles within the organisation.

The implementation of automated technological solutions has been steadily accomplished with increasing levels of sophistication in digitalised warehouses. Labour is a critical element of any logistics operating model, and automation technology is transforming every aspect of how logistic companies operate. Hitherto, there has always been a trade-off between service levels and costs. The emergence of human-machine automation breaks down this equation by allowing for better service while simultaneously cutting costs. Where larger and heavier industrial robots have been utilised to replace human operators in production lines to perform difficult or dangerous tasks, their smaller lightweight cousins can be used for a wider range of tasks.

In every workspace, safety is of paramount importance. To ensure that safety is never compromised, robots are equipped with human sensing capabilities to ensure close cooperation need to be developed first and foremost. Direct contact with human beings could likely result in a collision, and hence injury to humans. Consequently, the risk assessment accomplished by the robot manufacturer must also cover the envisioned industrial workplace.

Advanced sensing is required for physical human-robot interaction (PHRI) [96] which integrates the strength and accuracy of a robot with the human operator's ability of task recognition and ad-hoc decision-making skills. Traditionally, industrial robots have usually not been equipped with force or torque sensors to control the contact forces applied. This is the reason why industrial robots have to be fenced up securely within a workspace to ensured safety towards human operators. In order to realise effective cooperative robotics in a workspace, it becomes necessary to measure and control the external forces applied by the robot's end effectors. Please refer to reference [97] in Appendix B for additional details.

Sensor modalities used by mobile robots for automated planning algorithms have conventionally included geometric beacons, SONAR, and laser rangefinders. Associated with these sensors are localisation algorithms such as the Kalman Filter and Monte Carlo Localisation (MCL) based algorithms representing a vast majority of localisation algorithms used in practice today. Intelligent Human Sensing Robots use observations from on-board depth cameras for both localisation, as well as for safe navigation. The depth images observed by the depth camera are filtered by Fast Sampling Plane Filtering (FSPF) [98] to extract points that correspond to planar regions. A 2D vector map is used to represent the long-term features (like walls and permanent fixtures) in the environment as line segments." Please refer to reference [99] in Appendix B for additional details.

Supported by artificial emotional intelligence technology, robots would be able to discern certain key emotional states that are indicative of danger or fatigue. For example, the perception of fear in either the human being's facial expression or speech could indicate danger. In one scenario, the robot could be programmed to enter into standby mode and await reactivation from a human operator to prevent injury to the human operator or damage to property. In another scenario, if drowsiness or fatigue is detected, the robot may take measures to reduce the speed of work or to allow the human operator to regain his alertness (e.g., alert the supervisor, flash an indicator light, spray cold air, etc.). Please refer to Chapter 3.4.4 for additional details regarding emotional artificial intelligence. The cognitive intelligence aspect of machines is equally important to the emotional and should not be disregarded. Please refer to Chapter 3.4.6 for more information on cognitive computing and "intentioneering" [100].

Finally, the communication interface between man and machine ought to be uncomplicated and straightforward to operate. Cognitive computing technologies, such as automatic speech recognition and natural language understanding would assist to bridge this interface.

- Perceptive Humanoid Robotic System (Humanoids)

Until recently, robotisation in the labour market had been mainly associated with industrial robots to be large heavy-duty machines designed to perform specific tedious and repetitive tasks with cold precision. On the softer side are perceptive humanoid robots and social robots that are developed to perform much more "human-like" tasks. An important factor that distinguishes humanoid robots from traditional robots is their ability to perceive, understand and respond to human behaviour emotions. As emotions play a significant role in human behaviour, humanoid robots rely heavily on artificial intelligence to analyse the emotional state of a human (via computer vision, audio/voice input, sensors and/or software logic). It can initiate responses by performing specific, personalised actions to suit the mood of the customer. A benefit of detecting emotions/states is for a system to act more sympathetically.

Recent years have witnessed accelerating technological development in AI that has propelled numerous organisations to embrace robotic systems in customer service. Roles such as contact and maintaining lines of communication with customers are normally fulfilled by human staff who have undergone substantial training in "people skills" (i.e., emotional intelligence); that is, being friendly, being a good conversationalist, making customers comfortable and feel at ease. Industrial robots – in their form and shape, and lack of any emotional intelligence – would certainly cause considerable alarm and uneasiness to customers.

Perceptive humanoid robots are designed to bridge the gaps that exist between humans and robots that prevent effective communications from taking place. As far as possible, these machines are built to resemble the exterior human body physique. Most designs are generally comprised of a torso, a head, two arms and two legs; or parts thereof (i.e., some designs are modelled from the upper body only). The most distinguishing characteristic about humanoid robots from the majority of industrial robots is that the former category is usually imbued with advanced emotional intelligence algorithms.

One of the first humanoid robots that entered the market in 2014 is “Pepper” by Softbank Robotics [101]. Pepper was marketed to be “The World’s First Personal Robot that Reads Emotions”. Its primary objective is to develop and cultivate relationships with humans, and not to perform domestic chores in the home. Using state-of-the-art algorithms derived from facial expression recognition, emotional speech recognition and attitude determination of a person’s head, Pepper has demonstrated encouraging real-world outcomes in the effective recognition of four of the principal human emotions: joy, sadness, anger and surprise. Embodied with artificial emotional intelligence, Pepper is able to react suitably in response to the person’s emotional state – it responds with delight to a happy person, and provides comfort when sadness is detected.

Apart from the home, perceptive humanoid robots have proven to be useful in other areas as well. Emotions are integral to customer acquisition, retention, and loyalty, and so the adoption of humanoid robots in the retail industry is anticipated to be highly profitable. By employing recommendation algorithms (e.g., trained using neural networks) to customers based on their purchasing history, the robots are able to deliver an enhanced shopping experience to them. As compared to static information kiosks, robots equipped with natural language processing (NLP) [102] and speech processing capabilities (i.e., automatic speech recognition (ASR), speech-to-text (STT), and text-to-speech (TTS)) would enable better communication and interaction with customers. Using the same robot to illustrate, Pepper was reported to process MasterCard orders for customers at a Pizza Hut outlet in Singapore. These intelligent robots are adaptable and are able to spontaneously amend their answers based on customers’ reactions to provide optimal forms of communication. Pepper was also employed as a virtual concierge at hotel lobbies. Customers would therefore respond to these robots with much more confidence and comfort, and not regard them to be cold impersonal machines as they have commonly been portrayed to be. Please refer to reference [103] in Appendix B for additional details.

Natural language processing is a range of computational techniques in AI that assists machines to interpret and understand human language. Machine understanding of natural language conceptually begins from the analysis and representation of the language at the word or concept levels, and can be roughly categorised into three paradigms: i) bag-of words, ii) bag-of-concepts, and iii) bag-of-narratives [104]. Computational models attempt to emulate the function of the brain with respect to the processing of human language by relying on lexical semantic features and grammatical inference in order to bridge the cognitive gap.

An interesting new application of humanoid robots resides in the arena of entertainment robots. Mesmer robots, by a company Engineered Arts, serve primarily in commercial spaces as robotic entertainers and performers. To detect the body language of people, they apply technologies derived from emotional AI. Please refer to Chapter 3.4.4 for more information.

In addition to the above technologies, the research directions for humanoid robotics include further development of the cognitive system using AI, improving the grasping behaviour of end-effectors (duplicating the motion of a human hand to possess 27 degrees of freedom), the fusion and integration of multiple sensors, collision avoidance, and last but not least, to enhance the exterior appearance of the robots to more closely resemble the physical appearance of humans.

3.3.1 Technology Adoption Readiness Map

3.3.1.1 Human Sensing Robots (Cobots)

The system capabilities and technologies required to enable these robotic systems are below. Enabling technologies such as Neuromorphic computing [105], a core emerging technology that is expected to mature in the next few years and would prove to be beneficial to Psychological-Collaborative Systems (apart from other systems) shall be discussed in more detail in Chapter 3.4.

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	**Advanced Sensing & Automated Planning Capabilities:** - Robust detection of humans for safety purposes - Advanced force control End-effectors - Automated route planning and navigation	**Advanced Sensing for Shared Human-Robot Workspaces:** - Increased implementation of shared workspaces - Enhanced safety in terms of human-robot interaction. - Improved productivity	**Advanced Sensing for Seamless Joint Workflow:** - Optimum productivity
Technologies	• 3D Sensing Cameras • **Cognitive computing** • **Automated planning** • **Affective Computing**	• Human behaviour prediction • **Advanced Emotion Analytics** • **Physical Human Robot Interaction** • **Exoskeleton**	• **Neuromorphic Computing** • **Intention Influence** • Robot knowledge sharing • **Brain computer interfaces**
Application Scenarios/Use Cases:	Future robotic systems shall be equipped with a variety of sensors and advanced algorithms that permit robust detection of human presence along with their behaviour. The development of these technologies progressively improves the collaboration quality between man and machine over the next 5 years.		

* Technologies in black and bold are recommended for industry deployment and innovation in near term (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in relatively longer term.

Table 7: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Human Sensing Robots (Cobots)

- Now to 2 years: Technologies such as 3D sensing cameras and automated planning will improve autonomous path planning and navigation of robots around workspaces. Cognitive computing will improve decision-making capabilities, and decrease operational complexity through more user-friendly machine interfaces. Affective computing technologies will instil emotional intelligence into machines and in so doing raise safety levels at the shared workplace for human operators.
- 3 to 5 years: Ensuring that safety is sustained and productivity improved, while maintaining a well-controlled physical interaction between human operators and the end-effectors of a robot, can be accomplished through advances made in the domain of physical human robot interaction (e.g., advanced sensing/force control). Advancements in emotion analytics will allow the machine to progressively learn and adapt to the emotional patterns of human operators it usually cooperates closely with, and thus further enhance the quality of safety within the workplace. In a similar vein, the ability of machines to predict human behaviour, and then provide seamless responses, will certainly accelerate job processes at shared workplaces.
- Beyond 5 years: Intentioneering involves the development of “common sense” into machines and represents the next higher level of automation. Robots programmed with common sense would significantly improve the machines’ capability to function as equal peers to human operators in terms of efficiency and productivity at various job processes.

3.3.1.2 **Perceptive Robots (Humanoid)**

The system capabilities and technologies required to enable these robotic systems are below. Enabling technologies such as Neuromorphic computing, a core emerging technology that is expected to mature in the next few years and would prove to be beneficial to Psychological-Collaborative Systems (apart from other systems) shall be discussed in more detail in Chapter 3.4.

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
Capabilities	Extension of Human Capabilities	Advanced Perception of Emotional Intelligence	Human-like Perception of Emotional Intelligence
Technologies	• 3D Sensing Cameras • **Advances in SLAM** • **Personal recommendation systems (based on human preference).** • **Wearable sensors**	• **Emotion sensing** • **Soft robots**	• **Neuromorphic Computing** • **Deep learning accelerator**
Application Scenarios/Use Cases:	Robotic Caregiver/Companion type of systems that are able to converse and psychologically understand the needs of a human.	Robotic Mediator type of systems that are able to follow the basic constructions of human law and norms of society. This leads the robot to have the capacity to act as a mediator between humans though, it does not impose any regulation and merely acts as an aid to reach a conclusion.	Robotic Authority type of systems with their improved emotional, legal, and moral understanding, can act as a part of the social hierarchy. In several instances, they can act as an authority.

* Technologies in black and bold are recommended for industry deployment and innovation in near term (e.g., Now to 2 years), and technologies in blue and bold are recommended for research & development in relatively longer term.

Table 8: Technology Adoption Readiness Map, Technology Capability Map, and Use Cases for Perceptive Robots (Humanoid)

- Now to 2 years: The proliferation of 3D sensing cameras and advances in SLAM algorithms is expected to enable humanoid robots to be able to sense the environment and navigate around obstacles without difficulty. Equipped with a variety of wearable sensors (e.g., CCD/depth cameras, medical devices, biometric sensors, etc.) and programmed with personal recommendation algorithms based on human preferences, these robots shall provide novel functions from an integration of various readily available technologies.

- 3 to 5 years: Advances in emotion sensing technologies (e.g., facial expression recognition, gesture recognition, speech-based emotional processing) would enable more emotionally intelligent robots that are better able to perceive and understand human beings. The design and fabrication of end-effectors utilised in soft robotic systems would be beneficial to humanoid robots. Being in close proximity and physical contact with human beings, these robots must be built with end-effectors that will not cause injury to people.
- Beyond 5 years: Neuromorphic computing technologies are ideal computing architectures to be implemented into perceptive humanoid robots. Such architectures possess sufficient computing power to run sophisticated artificial intelligence algorithms in real-time, while at the same time offering significant lower power consumptions as compared to their von Neumann counterparts. Algorithm runtime speeds may also be substantially accelerated through the utilisation of deep learning accelerators.

3.3.2 Technology Capability Map

System capabilities will continue to evolve as technology matures out of proving grounds.

3.3.2.1 Human Sensing Robots (Cobots)

- Now to 2 years: Intelligent human sensing robots shall be equipped with more advanced sensing and automated planning capabilities. Consequently, these bots shall find greater adoption in an increased number of applications within the manufacturing and logistics industries as human operators feel safer and become comfortable working around these machines.
- 3 to 5 years: As safety margins are enhanced and productivity gains become more and more evident, the implementation of shared workspaces utilising these robots across industries is expected to be increasingly widespread.
- Beyond 5 years: Optimum productivity can be expected when these robots are able to rapidly and robustly detect human operators and impose the correct safety actions while performing various tasks. Therefore, human operators do not feel unsafe collaborating with these robots, and the workflow between man and machine can be executed seamlessly.

3.3.2.2 Perceptive Robots (Humanoid)

- Now to 2 years: Perceptive humanoid robots are expected to exhibit functions that extend the capabilities of human beings. Considering the recent advances in emotional AI, humanoid robots [103] will be able to better understand the needs of a human and therefore be able to hold adequately rational and comprehensible conversations. Such systems could act as stress-managing companion robots similar to robotic caregiver type of systems. Such robots have proven effective at assisting the elderly and also to patients in post-surgical procedures as caregiver systems [106] [107] [108] [109]. Programmed with advanced cognitive-behavioural intervention algorithms, the robots are gaining popularity within clinical applications, especially in paediatric care. Emotional AI need not be limited to robotic systems only, but companionship or caregiving could be embedded into any type of system; ranging from smartphones to vehicular systems, etc.
- 3 to 5 years: Advances in emotional intelligence technology may enable humanoid robots to evolve from machines that provide companionship into machines that demonstrate the capability of mediate between humans in situations of stress or conflict. In the medical domain,

these robots could exhibit could assist physicians with the diagnosis of depression or dementia.

- Beyond 5 years: For limited instances, humanoid robots may assume positions of authority to prevent humans from engaging in unlawful actions. For example, in cases of traffic violations, robotic traffic operators may be allowed to override a vehicle's operation when safety is a concern.

3.3.3 Use Cases

3.3.3.1 Human Sensing Robots (Cobots)

DHL predicted that the implementation of robotics will be the norm in the logistics industry by the year 2022 [110]. Mobile piece-picking robots work alongside human operators to perform high frequency picking processes such as: i) packaging, ii) sorting, iii) labelling, and iv) assembly. It is clear to appreciate the usefulness of these machines in the optimisation of picking processes; but the widespread adoption of these robots into most warehouses have as yet to be considered to be viable due to various highly-complex difficulties that are technological in nature. As technology continues to improve, however, the prospect of human-machine collaboration being implemented and operational in future warehouses is becoming increasingly more viable and realistic. Relying on human-friendly follow-me picking carts to transport heavy and bulky payloads between multiple locations proves to be much more efficient and ergonomic; and it also frees the human operator from physical demands and injury.

In package delivery, logistics personnel assisted by semi-automated truck convoys effectively reduces delivery times by permitting a larger quantity of packages to be transported in a single trip. The last fifty metres of delivery oftentimes prove to be the most cumbersome part of the delivery journey. This is where the delivery person is required to park the vehicle, locate the parcel to be delivered, and then carry it to the door using an elevator or a flight of stairs. Rather than this, making use of automation via delivery drones and/or specialised automated guided vehicles would transform the last fifty metres of delivery into a very efficient time-saving procedure; and especially if all machines (i.e., truck, drone, automated guided vehicle, etc.) can be in communication with one another.

Big names in the automotive manufacturing industry (e.g., Mercedes-Benz, BMW, Audi, Daimler, Ford, and Nissan) have seen a prevalent adoption of cooperative robotic systems in their manufacturing facilities. A solution blended between man and machine, these systems have been utilised to process and assemble various machine parts (e.g., to loosen bolts on cylinder head cam brackets, or installing engine block intake manifolds). They, therefore, serve to mitigate inefficient production processes (due to an aging workforce, e.g., in Japan) and also assist to minimise spending on relief workers.

3.3.3.2 Perceptive Robots (Humanoid)

The use cases of perceptive humanoid robots are: 1) Services and retail: by providing an enhanced shopping experience for shoppers using recommender algorithms; 2) Entertainment: to provide entertainment to home users or in shopping malls for retail; 3) Home: i) as companionship or caregiver bots to human users, ii) connected home and housing, iii) home security, iv) home monitoring; 4) Medical care: i) in hospitals as robotic caregiver systems to post-surgery patients, ii) to assist in providing paediatric care, iii) telemedicine; 5) Eldercare: to provide mobility assistance in eldercare; 6) Tourism: i) in hotels, ii) travel agencies; 7) Food & Beverage: in restaurants; and 8) Finance: in banks.

The use cases of emotional AI are numerous and diverse. A list of 14 use cases [111] that have been growing over the last 2 years are as follows: humanoid robotics, retail, video gaming, medical diagnosis, medical therapy, automobile safety, autonomous vehicles, fraud detection/credibility analysis, manpower recruitment, education/training, employee safety, connected home, and public service.

3.4 Key Enabling Technologies

3.4.1 Exascale Computing

Exascale computing refers to a supercomputing system that is capable of computing at least one exaFLOPS, or a billion billion calculations per second [112]. This will provide a thousand-fold computing power increase over the current petascale computing system, and may be used for advanced computational tasks such as weather and climate simulation, nuclear simulation cosmology, quantum chemistry, brain simulation, fusion science, etc. It is useful for scientific and engineering problems that require complex mathematical models and enables multidisciplinary design and optimisation, reducing prototyping time and costs. Cummins [112] used advance simulation to build diesel engines faster and less expensive; Goodyear was able to design safer tires in a shorter amount of time, Boeing was able to build more fuel-efficient aircraft, and Procter & Gamble was able to create better materials for home products.

Exascale computing offers high-speed response time for large scale computation for big data analytics and are able to serve thousands of requests concurrently using parallel and distributed computing techniques. In the big data domain, there exist a wide range of large scale and complex issues that require temporal and spatial data analytics, nonlinear interactions across multiple biological and physical processes, and data management pipeline involving data assimilation, multidisciplinary correlation and statistical analysis, etc. Digital Twin systems or applications can leverage the computing power of supercomputers for the computation-intensive simulations such as 3D Computer Fluid Dynamics (CFD), or robots to acquire knowledge and process large amount of data sets via supercomputers installed within cloud-based data centres. Robotic systems can also leverage on the intelligence of remote supercomputing systems to process large amount of data sets or share the knowledge with other robots for learning, improving and self-healing. There have been significant investments being made in the research and development of exascale computing systems. For example, it has been estimated to exceed US$1 billion in US, with an annual operating cost of tens of millions of US dollars. Technical challenges of exascale computing include energy efficient circuits, high performance interconnects, high capacity memory access, parallelism and resilience in programming, application scaling, and software environments for performance tuning, correctness assessment, and energy management, etc.

In the past few decades, the advancement of computing architectures and techniques – e.g., Instruction Set Architecture (ISA) versus MIPS (Microprocessor without Interlocked Pipeline Stages), CISC (Complex Instruction set Computer) versus RISC (Reduced Instruction Set Computer), and fast memory technologies such as HBM (High Bandwidth Memory) and eDRAM (embedded DRAM), possible on-chip architecture such as SMP (Symmetric multiprocessing) and NUMA (Non-Uniform Memory Access) – have greatly improved the capacities of the computation. Numerous challenges still remain, such as energy consumption, system cost, and parallelisation for using massive computer cores effective and efficiently to run applications [112]. By June 2018, the fastest supercomputer on the TOP500 supercomputer list is the Summit, capable of 122.3 peta floating-point operations per second (PFLOPS) of Linpack benchmark. It was developed by IBM, the US. It consists of 9,216 IBM POWER9 22-core CPUs, 27,648 Nvidia Tesla V100 GPU, and high speed NvLink, and it is the first computer to reach exascale speed, achieving 1.88 exaFLOPS during a genomic analysis. The second fastest supercomputer is the Sunway TaihuLight which reaches 93 PFLOPS based on China-designed 40,960 SW26010 processors. In June 2018, Fujitsu has produced the initial version of the ARM processor that will be used in Post-K, Japan's first exascale supercomputer. According to the joint announcement, by Fujitsu and RIKEN, the prototype chip will be used to start "functionality field trials".

They expect the processor to "deliver performance far surpassing that of general-purpose processors for many supercomputer applications. Deployment of Post-K system is expected to take place in 2021.

While international competition in building the first exascale computing system proceeds, there are rapid expansions of the cloud computing and services. The pay per use models of clouds attracted large numbers of users and a variety of cloud-based services, applications and APIs have been developed in a short period of time. Some cloud vendors such as Amazon, Microsoft, Google, etc. are providing hyperscale computing-as-a-Service besides the other cloud services such as Software-as-a-Service, Platform-as-a-Service, and Infrastructure-as-a-Service. It made it much easier to access high performance computing resources or supercomputing power via the clouds. With the proliferation of IoT and the shift from personal computers to mobile devices such as smart phones, tablets, smart watches, etc. more data sets are generated by sensors and mobile devices via wireless networks and a variety of new apps or services consumed by users in many areas of digital innovation. New services like Augmented Reality, Gamification, and Real-time Analytics are going to drive more hyperscale computing applications and services. In Singapore, the National Supercomputing Centre Singapore (NSCC) use hyperscale computing to improve the speed of a weather forecasting application and use AI to improve the accuracy of image recognition technology. Various initiatives of using supercomputers for science and engineering discovery "support Singapore's mission to use hyperscale computing to power innovation and bolster Singapore's stature as a supercomputing hub". More research and development work are addressing the high speed and low power massive data processing which may make hyperscale computing more accessible and consumable in near future.

3.4.2 In-memory Computing

In-memory computing (IMC) is an application architecture which assumes that all the data required by applications for processing are located in the main memory of their computing environments. In IMC, massive data can reside in Random Access Memory (RAM) for immediate processing, instead of moving a part of data from storage into RAM thousands of times. IMC eliminates the need to move data from storage to RAM before processing, and thus the computation can be sped up by avoiding thousands of times of write/query operations. The development of IMC is motivated by an increasing need for real time massive data process.

IMC enables a significant amount of computational work load to be completed in real time. With IMC, individual vehicles (more generally, edge computing devices) are capable of processing various mobility data and environmental data using advanced data analytical methods to make right decisions without having to rely on the growth of communication capability. In the face of streaming data, data can be processed in memory using a streaming analytics engine and AI algorithms to detect and respond in real-time for use cases such as crash prediction and route recommendation. IMC delivers dramatic improvements in performance, scalability and analytic sophistication over traditional architectures. IMC is enabled by in-memory data grids, event-processing platforms, high-performance messaging infrastructures, data visualisation tools and other technologies. As an additional benefit, it enables distributed intelligence through autonomous edge computing devices. Further, it provides an opportunity to look into the communication security from a different perspective. For example, the attacks like Denial of Service (DoS), which largely relies on jamming communication networks, may have much less impact when the intelligence resides on the edge.

IMC can eliminate that latency. IMC platforms use large pools of RAM to process and analyse data without the need to continually read and write data located on a disk-based database. An IMC platform can easily be inserted between existing application and database layers with no rip-and-replace. On the other hand, an in-memory computing platform that utilises commodity servers can easily be scaled out at any time by adding nodes to the cluster, allowing a business to cost-effectively scale its infrastructure as needed. In addition, distributed architectures can provide high availability and simplified maintenance with data replicated across the cluster nodes.

Driven by IMC, it is possible that big data analytics can be implemented to deliver results in real time. The benefits of big data analytics will also lead to more sensors, IoT systems, connected vehicles, swarm bots, etc. being used, and more data being generated.

There are multiple storage technologies, including standard 3D stacked SRAM [113], STTRAM [114] and ReRAM [115] [116], for which the in-memory computing technology has been demonstrated through prototypes. The technology does not rely on any change in the process/fabrication flow, thereby allowing fast and seamless adoption.

3.4.3 Neuromorphic Computing

Drawing much inspiration from the biological brain, neuromorphic computers are conventional semiconductor-based processors that are designed using modern non-von Neumann architectures consisting of highly connected synthetic neurons and synapses. Neuromorphic processor designs attempt to mimic neuro-biological architectures present in the nervous system, and so they inherently possess the ability to learn and adapt in solving machine learning problems. In a separate vein, neuromorphic computers can be used to model and validate various neuroscience theories.

The domain of neuromorphic engineering is a remarkable piece of interdisciplinary thinking, linking fields as diverse as computer science, electrical engineering, neuroscience and material science. Computer scientists and engineers research on and develop novel neural network mathematical models, and electrical and computer engineers work on analogue/digital/mixed-signals circuitry to implement these algorithms on. Neuroscientists contribute in the form of new theories resulting from their studies on the human brain that may be useful in formulating in the implementation of the algorithms onto neuromorphic computers. Material scientists discover and experiment on new materials that show promise in mimicking biological neural systems.

In the future, neuromorphic computers are poised to become a highly-suitable candidate to implement machine learning algorithms by virtue of their low power-consumption, achieving faster computation speeds by exploiting massive parallelism and having the ability to operate complex algorithms in real-time. Apart from this, neuromorphic computers exhibit exceptional fault tolerance characteristics and reliability in handling hardware errors.

In fact, power-efficiency and small form factors prove to be the strongest motivations for developing neuromorphic computers in recent years [117]. Another major motivation for the development of neuromorphic systems originates from within the study of neuroscience. The study is mutually beneficial as contemporary findings from neuroscience (e.g., the origins of certain algorithmic computations resulting from the cumulative effect of individual neurons and biological architectures) can be used to drive neuromorphic architectural designs, and experimental results performed on neuromorphic computers may in turn be used to validate the neuroscientific theories.

Ever since the first instance of neuromorphic computing in the form of a silicon retina that surfaced 30 years ago, there has been a plethora of real-world applications that has benefited from the adoption of neuromorphic computers. Most notably, image-based applications involving deep learning have benefited the most. Other applications have also gained substantial traction in the utilisation of the technology. Examples include video analytics, speech processing, natural language processing, general data classification, control tasks, anomaly detection, wearable technology and smart sensors driven by the momentum of the Internet-of-Things (IoT), robotic systems, and medical systems.

Use Cases: There exist a plethora of use cases by which neuromorphic computing technology can be applied in [99], such as:

- ***Wearables***: medical treatment or monitoring, pacemakers or defibrillator systems.

- ***Robotics***: very small and power efficient systems are often required for autonomous robots. Thus far, in terms of robotics, the most common use of neuromorphic implementations is for autonomous navigation tasks.
- ***Control tasks***: typically require real-time performance, they benefit from models that utilise recurrent connections or delays on synapses. The most common control test case is the cart-pole problem or the inverted pendulum task.
- ***Image-based applications:*** edge detection, image compression, image filtering, image segmentation, feature extraction. Image classification, detection, or recognition is an extremely popular application for neural networks and neuromorphic systems. Digit detection, general character recognition, recognition of simple shapes or pixel patterns, classifying traffic signs, face recognition or detection, car detection/recognition, detecting air pollution in images, detection of manufacturing defects, hand gesture recognition, human recognition, object texture analysis.
- ***Video:*** object recognition within video frames, motion detection, motion estimation, motion tracking, and activity recognition.
- ***Speech:*** require the ability to process temporal components, and may have real-time constraints. Speech recognition, music recognition, speaker recognition, voice activity detection, analysing sound for identification purposes, noise filtering to translate noisy speech into clean signals.
- ***Natural language processing:*** many require recurrent networks. Sentence construction, sentence completion, question subject classification, sentiment analysis, and document similarity.
- ***Smart sensors:*** for deployment into the environment. A small footprint, and/or low power are common use cases for neuromorphic systems. Humidity sensors, light intensity sensors, sensors on mobile devices used to identify and authenticate users. Anomaly detectors for biological data, and industrial data, applications in cyber security, and fault detection in diesel engines and analogue chips.
- ***General data classification:*** accident diagnosis, cereal grain identification, computer user analysis, driver drowsiness detection, gas recognition or detection, product classification, hyperspectral data classification, stock price prediction, wind velocity estimation, solder joint classification, solar radiation detection, climate prediction, and applications within high energy physics.
- ***Medical domain:*** coronary disease diagnosis, pulmonary disease diagnosis, deep brain sensor monitoring, DNA analysis, heart arrhythmia detection, analysis of electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG) results, and pharmacology applications.

3.4.4 Emotional AI

Emotional AI is comprised of facial expression recognition and speech-based emotion analysis (among other modalities such as text, hand and body movements, etc.). One of the most powerful and universal ways that people convey their emotional states is through their facial expressions. There are a total of seven basic types of facial expressions: i) joy, ii) sadness, iii) anger, iv) fear, v) disgust, vi) surprise, and vii) contempt (please refer to reference [118] in Appendix B for a detailed description of the emotions that human beings are able to feel). Each facial expression may be decomposed into their specific facial muscle movements termed action units (AUs) that have been fully defined in the Facial Action Coding System (FACS) [119]. Common approaches that use FACS to directly detect the facial expression include active appearance models and optical-flow based techniques [6]. Another school of thought attempts to extract features from AUs in order to infer the facial expression. Such techniques include kNN, Bayesian networks, hidden Markov models (HMM) and deep neural networks, etc. Currently, the main trend in facial expression recognition is to use a convolutional neural network. Please refer to reference [120] in Appendix B for additional details.

Emotional AI also encompasses the field of speech-based emotion analysis. Here, unlike the visual modality, speech based technologies infer emotion from a person through speech (instead of the face) using prosodic features such as tone, loudness, tempo, pause length, and voice quality to distinguish speech events. Algorithms utilised in speech-based emotion analysis include extraction of mel-frequency cepstral coefficients, Gaussian mixture models, multi-layered artificial neural networks, etc. Currently, the main trend in speech-based emotion analysis is to use a convolutional neural network. Please refer to reference [121] in Appendix B for additional details.

Unlike facial expression recognition, however, the full rich set of emotion modelling using speech-based emotion analysis may not be possible for a person with limited vocabulary and limited emotional capacity. This should be taken into account while interpreting the emotions. In the future, the development of more robust Emotional AI technologies should be able to model and interpret increasingly elaborate human emotions such as those described in the psychological literature (e.g., Plutchik's Wheel of Emotions [118]).

Currently, the range of Emotional AI technologies is continuing to expand into a diverse spectrum encompassing both cognitive and emotional/affective computing [3] domains. With the progress of emotional AI in future years, the education sector is a likely beneficiary as research in the field of intelligent tutoring systems and e-learning is gradually shifting emphasis from cognitive processes to emotionally-cognitive processes [122]. Emotion recognition permits various behavioural patterns of students to be identified, and in a similar manner, instructors would be able to adjust their non-verbal communication cues (e.g., hand gestures, facial expressions, and body language) to students in smart classrooms that utilise emotional AI [123]. Emotional/affective AI technologies are also revolutionising the automotive industry by enhancing the safety of occupants through monitoring of driver fatigue and distraction levels, and also improving passenger comfort levels by adapting the interior environment based on the levels of comfort/drowsiness/anxiety detected [124].

Other potential applications include: a) call centre/service operations, b) automated chatbots, c) e-governance, d) homeland security, e) classroom education (following cognitive resonance or dissonance), f) engagement surveys, g) general health analysis, h) old age patient monitoring, i) monitoring persons with autism, j) social marketing, k) interactive computer simulations.

3.4.5 Cognitive Computing

Cognitive computing technologies imbue smart products with higher levels of intelligence, and have been the key drivers for knowledge automation work. Cognitive computers are modelled after the biological brain, thus they possess decision-making capabilities on top of learning and natural language processing capabilities so these machines would be able to interact with human beings in a natural manner [124]. The main goal of cognitive computing architectures is to enable artificial entities (i.e., machines) to attain similar mechanisms as human cognition; and they are the functions of: i) reasoning, ii) control, iii) learning, memory, adaptivity, perception and action [125]. Ultimately, it is the yearning for machines to one day achieve (or exceed) human levels of intelligence through the realisation of artificial artefacts (General AI/common-sense AI) built upon them [126].

The research direction for cognitive computing perseveres towards problems that are easily solvable by humans but remains challenging to machines. These challenges deviate from the conventional axioms that surround Narrow-AI and shifts towards the philosophy established behind General-AI or common-sense-AI [127]. These works include common-sense reasoning about space, action, change and language categorisation, selective attention; integration of multi-modal perception; learning from few examples; robust integration of mechanisms involving planning, acting, monitoring and goal reasoning [128].

3.4.6 Intentioneering

Intentioneering represents the next level of automation for machines to achieve a similar level of cognition and rationality compared to human beings (often referred to as “common-sense AI”) [100]. It may be considered to be intention-synchronised machine learning that offers maximum flexibility for competence-acquisition with a minimum set of restraints by modelling the belief and value systems (e.g., pragmatics, emotions, desires, etc.) that constitute the core and relatively invariant part of human-to-human interactions. In a continuously evolving operating environment, this allows AI to comprehend terms such as “usefulness”, “relevance”, “meaningfulness” and “valuable” from a point-of-view similar to that of a typical human user. The aim is to create a stand-alone ‘human emulator’ module that could constantly monitor the performance of a super-intelligent autonomous system and see if its self-acquired capabilities are beneficial to humans.

3.4.7 Soft Robots

Engineers have begun to explore the design and control of soft-bodied robots composed of compliant materials. These robots are inspired from natural systems such as cephalopods, which achieve amazing feats of manipulation and locomotion without a skeleton storing elastic energy in their soft tissues. In contrast to robots built from rigid materials, soft robots allow for increased flexibility and adaptability for accomplishing tasks, as well as improved safety when working around humans. Soft robots can also transmit assistive torques without the use of rigid external stimuli, as seen in rigid robots.

There are a number of foundational technologies which need to be developed for the widespread development and adoption of soft robots, these include: New malleable materials; Light-weight; batteries; Light-weight actuators; Energy aware computing chips. Advanced robots may use multiple sensor and IoT systems to detect changes in the environment and appropriately respond. Energy aware computer chips can allow soft exosuits to determine how much energy should be provided to help the user complete a certain task, thus ensuring efficient use of energy.

3.4.8 GPU-accelerated Computing

As a type of specialised electronic circuit designed to accelerate a variety of computing applications (e.g., scientific, engineering, analytics, consumer, or enterprise applications) when coupled alongside a general-purpose CPU, Graphics Processing Units (GPU) have witnessed large adoption in numerous devices; namely, embedded systems, mobile phones, personal computers, workstations, and game consoles. GPUs are able to achieve significant improvements in graphical computational speeds over CPUs due to their inherent highly parallel structures and efficient means to manipulate and alter memory intended for images. CPUs by themselves, on the other hand, are only able to process large blocks of memory in a sequential manner.

GPU adopts a SIMD-based (Single Instruction Multiple Data) architecture, which gains high performance through massive parallelism. GPU is also used together with a CPU to accelerate data analytics, AI/deep learning, and engineering applications. For example, Deep Neural Network (DNN) is structured in a uniform way that thousands of identical artificial neurons perform the same kind of computation at each network layer. This makes it possible to utilise a large number of computation units and execute massive tasks effectively in parallel. NVIDIA GPU contains largely independent processors called Streaming Multiprocessor (SM), each SM hosts several Streaming Processor (SP), and each SP runs a thread.

GPUs technologies have been widely used for computer vision, gaming, and recently video processing for Virtual Reality (VR). For example, in VR, GPUs are used to rapidly stitch video from multiple cameras together into a single 360-degree panorama. Image stitching or photo stitching is the process of combining multiple photographic images with overlapping fields of view to produce a segmented panorama or high-resolution image. GPUs are well suited for repetitive image processing and numerical simulations whereas stitching is a complex set of mathematical algorithms. Companies like VideoStitch are using NVIDIA GPUs for such purposes. GPUs are also adopted for high speed data processing in autonomous machines/vehicles. Yamaha Motor Co. has selected NVIDIA Jetson AGX Xavier as the development system to power its upcoming line-up of autonomous machines. The world's first computer created for AI, robotics and edge computing, Jetson AGX Xavier's massive computing performance can handle odometry, localisation, mapping, vision and perception, and path planning critical to next-generation robots.

3.4.9 Assistive Technology

Assistive technology refers to the selecting, locating and using assistive, adaptive and rehabilitative devices for people with disabilities. People with disabilities may have difficulties in activities of independent daily living including toileting, mobility, eating, bathing, dressing and grooming. Assistive technology aims to provide devices to assist people with disabilities to complete tasks they are not able to perform on their own. An example of such devices is assistive feeding devices that enable physically challenged individuals to enjoy a meal without help.

Assistive technology can help people with disabilities to enjoy a better quality life and to participate in more social activities with increased safety. It can leverage technologies such as exoskeletons, soft exosuits, communications, speech, vision technologies, and ability to interpret intention of the patients or communicate via other means (e.g. a mute or visually impaired person), etc. Some use cases of assistive technologies such as a mechanical exoskeleton that make manual labour for factory workers easier. Another example is devices that help Parkinson patients to reduce the tremors so they can have better control and use of their hands.

3.4.10 V2X Communication

Dedicated Short-Range Communications (DSRC) is a key enabling wireless technology for V2X communications. DSRC technology can be used in either a V2V or V2I format, and communicates using transponders known as on-board units (OBUs) or roadside unites (RSUs). RSUs are radio base stations installed at intersections or along the side of the road within a localised area. They can be on lamp poles, traffic light poles, and electronic toll collectors. In V2V, DSRC is used to allow vehicles to communicate with each other through OBUs. This communication allows to vehicles to communicate to share mobility data, traffic messages, etc. In V2I, an OBU in or on the vehicle communicates with surrounding infrastructure equipped with an RSU. This allows roadside infrastructure to send drivers traffic recommendations or warnings, and also allows vehicles to share their mobility data with roadside infrastructures.

DSRC meet all the requirements of V2X communication. However, celluar-V2X (C-V2X) technology which communicates to a cellular network for cloud-based services is a challenger to DSRC for V2X. C-V2X provides enhanced communication range and reliability. C-V2X can combine the capabilities of RSUs and the cellular network to support both short-range and long-range transmissions between vehicles and infrastructure. On the other hand, C-V2X support higher vehicle speeds and high-density traffic. The roadside units will use a high-throughput connection with other cars on the road to build local, dynamic maps using camera and sensor data, and distribute them as needed. DSRC is more cost effective than C-V2X, since C-V2X is a complex technology rooted from base-station implement. In addition, C-V2X products are far from reaching the maturity for industry applications today.

DSRC can be used for vehicle-to-vehicle and vehicle-to-infrastructure communication in Intelligent Transportation Systems, specifically for collision avoidance, improved mobility and improved environmental responses. US DOT has developed a Connected Vehicle Reference Architecture (CVRA) to help guide deployment of components by road operators and automotive, highway, and aftermarket equipment manufacturer and service providers. Each vehicle broadcasts its core state information in a “Basic Safety Message” (BSM) nominally 10 times/sec; this BSM is sent in 360o pattern using IEEE 802.11p technology. Upon receipt of BSM, the vehicle safety host builds a model of each neighbour’s trajectory, assesses threat to host vehicle, warns driver (or takes control) if threat becomes acute.

3.4.11 Self-organised Collaboration

Self-organised collaboration refers to a number of machines working together in which individual machines interact and respond to others’ behaviour and the environment in a collaborative manner without human intervention or external control to achieve the common goal. As a group, the machines achieve collective intelligence which is greater than the sum of each machine’s intelligence. The machines can be mobile or static robots, or any form of machinery with intelligence. They may have different capabilities with built-in specialisation that may be known beforehand or self-discovered as they operate. This heterogeneous group of machines are able to adapt to the environment and can self-reconfigure accordingly. The collective task can be automatically divided among the machines on the fly. The group of machines include those residing the cloud, where distributed compute servers are independent machines that serve as brains of the group. This group of machines can also include human beings who can be treated as unique intelligent-machine systems with special capabilities (which may be unpredictable). The inherent nature of such a group is resilience and robustness to achieve the desired performance even if some members degrade or die.

Self-organised collaboration is currently an active research area. Main applications today include formation control, search and exploration, coverage and patrolling problems, and target searching. But there are many more applications where intelligent-machine systems collectively work more intelligently with humans. The current challenges are addressed by drawing inspiration of how biological beings evolve, adapt and continuous learn through daily interactions with the environment.

3.4.12 Context-aware Systems

Context-aware systems refer to a system that is able to collect information about its physical environment or users that are interacting with it and adapt its behaviour according. Context includes various information that may affect a system's behaviour. It involves a wide range of variables including time, location, temperature, task, process, neighbouring bots and user centric contexts such as user cognitive state, user behaviour and emotional states.

Context-aware systems have various complicated architectures consisting of components for representation, management, reasoning and analysis of context information. Regardless of the complexity of their architecture, they are designed to implement the functionality of 1) gathering context information from sensors, surrounding bots, etc.; 2) storing context information using suitable context model; 3) transforming context information to meaningful data using context aggregation and context interpretation methodologies; and 4) utilising context information for decision making and further response.

Context-aware system has been applied to a broad range of applications including location-aware systems for navigation, tracking and advertising and user-aware systems for customer relationship, etc. In intelligent connected systems, the behaviour of neighbouring bots, human users, and outside environment keep changing. Hence, context-aware system is an indispensable component for intelligent connected systems.

3.5 Future-Ready Systems Contribution to Cloud Native Architecture

As a part of the overall technology roadmap recommendation, Singapore needs to establish a cloud native architecture to assure Services 4.0 and improve access to emerging technology amongst the stakeholders. We believe that Future-Ready Systems will play an important part in ensuring the success of the cloud native architecture. Exhibit 8 highlights how future ready tech will enable cloud native architecture.

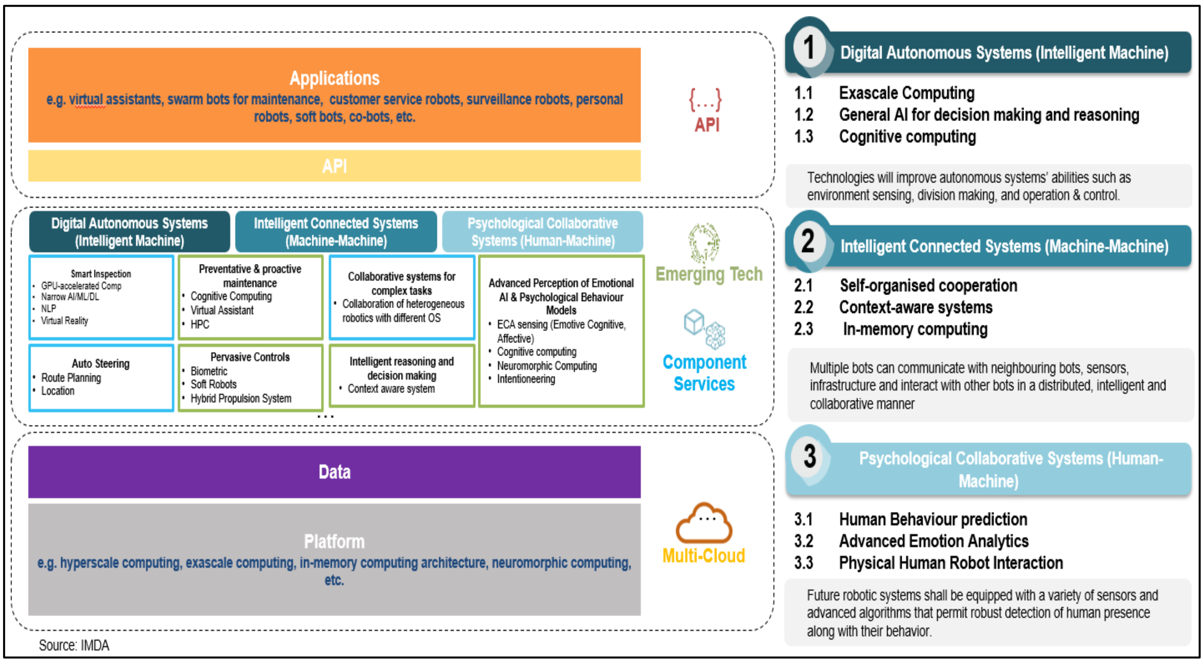
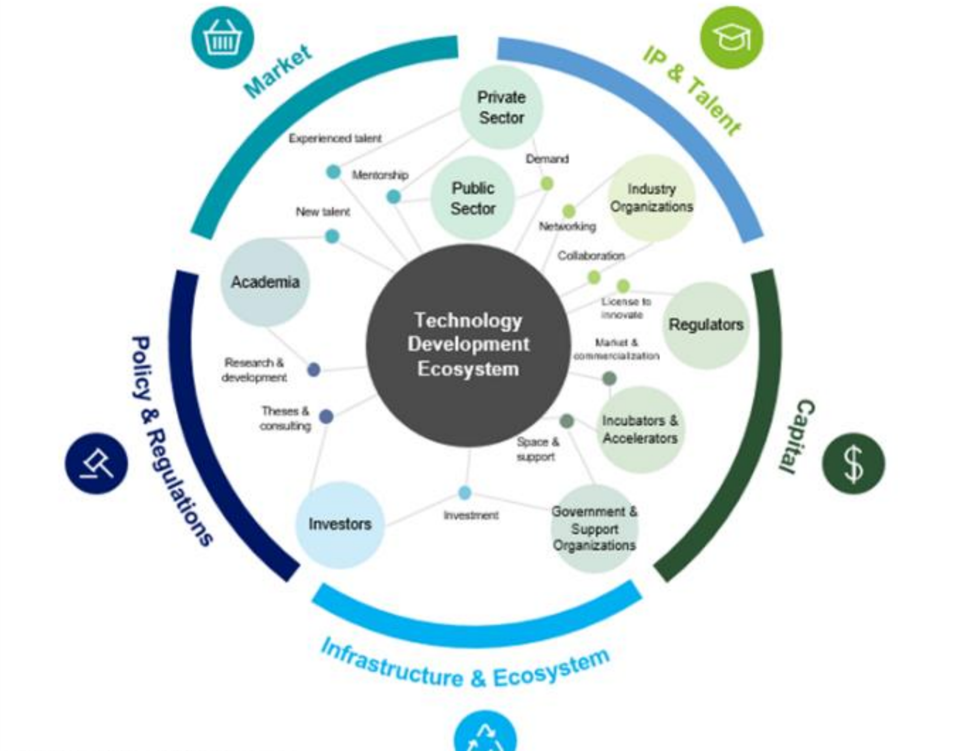


Exhibit 8: Emerging Technology and Cloud Native Architecture: Alignment of Future-Ready Systems

4 SWOT ANALYSIS

Singapore's unique positioning in the global market provides it with specific strengths, weaknesses, opportunities and threats. In order to determine which emerging technologies are promising areas for Singapore to invest in, it is important to have a holistic view of these aspects. The framework shown in Exhibit 9 takes into account key areas in which Singapore may have strengths and weaknesses and/or face opportunities or external threats. Our analysis of the local and global landscape reveal that there are both system specific as well as system agnostic elements to the SWOT analysis. These elements should be kept in mind when developing holistic recommendations for the Singapore landscape.

Exhibit 9: Framework for SWOT Analysis



Source: Monitor Deloitte Analysis

Through the SWOT analysis, strengths and weaknesses (internal environment analysis) of future-ready systems and opportunities and threats (external environmental analysis) for future-ready systems were extracted and summarised in

Exhibit 10. The viewpoints after the extraction are presented below:

STRENGTHS

1. Strong Presence of Technology Companies
2. Strong support by the government on Technology in R&D
3. High Quality Talent Pool
4. Investment in R&D
5. Investment in Technology by Multiple Sectors
6. World Class Innovation
7. Geographic Location
8. Advanced ecosystem for intelligent machines
9. Strong National Robotics Programme

WEAKNESSES

1. Lack of Local Market
2. Lack of Scale of Data
3. Aggressive Overseas Markets
4. High Cost and Lack of Tech Talent
5. Lack of Commercialisation of Future Tech
6. Lack of Scale in Talent in AI

OPPORTUNITIES

1. Presence of Multiple Tech Companies
2. Geographic Location
3. Investment by Private and Public Sectors
4. Global Leader in Self-Driving Vehicles
5. Global Leader in Cloud Computing
6. Utilising Cloud Computing for "as-a-service" Model of Service
7. Strength in Robotics

THREATS

1. Lack of Local Market
2. Outsourcing Technical Jobs to India and China
3. Competing Markets with Larger Pools of Data
4. Aggressive Overseas Markets with Scale
5. Lack of hyperscale computing capability available locally
6. Aggressive Overseas Markets for advanced communications technologies

Exhibit 10: Exhibit summarising SWOT analysis for Future-Ready Systems

4.1 System Specific Strengths

Intelligent-Machine System: Using self-driving vehicles as a metric for autonomous systems, Singapore ranks 2nd globally for self-driving vehicles' readiness. In addition, Singapore has supportive policy and legislation, robust infrastructure and high customer acceptance [129] [130].

Machine-Machine Systems: Using Advanced Cloud Technologies as a metric for connected vehicles as such systems would allow cars to store information on a central server. Singapore ranks 1st in the APAC region due to high-quality broadband, government support, with an emphasis on cybersecurity and strong IP protection laws [131].

Human-Machine Systems: Using Singapore's standing in advanced robotics gives a good understanding of its abilities in this space globally. The National Robotics Programme received SGD450 million over the last 3 years has greatly supported robotics development [132].

4.2 System Agnostic Strengths

Strong Presence of Technology Companies: Singapore ranks second in top Asian locations for tech companies [133].

Strong Support by the Government on Technology in R&D: Smart Nation initiatives focused on assistive technologies, analytics and robots for healthcare [134].

High Quality Talent Pool: Singapore ranks first in Asia Pacific in the Global Talent Competitiveness Index (GTCI) 2017 [135].

Investment in R&D: The Government has committed SG$19 billion to R&D for the Research Innovation Enterprise 2020 Plan [136]; a component of this is the development of the ASPIRE1 the first petascale supercomputer in Southeast Asia [137].

Investment in Technology by Multiple Sectors: The financial and technology industries are investing heavily in new and emerging technologies in order to improve its service offerings**;** Google building third data centre in Singapore with added investment of US$350 million [138] [139].

World Class Innovation: The 2017 Global Innovation Index ranked Singapore as the most innovative country in Asia, 2017 Bloomberg Innovation Index ranked Singapore sixth globally [140].

Strategic Location: Well-positioned within the ASEAN region and in the broader Asian continent, Singapore lends itself as a hub to service intelligence-driven technology. Singapore serves as an ideal launching pad that allows technologies to be tested in this area [140].

4.3 System Specific Weaknesses

Intelligent-Machine Systems: Using hyperscale computers as a metric for digital autonomous platforms gives a view on Singapore's readiness to develop and implement systems in the Singapore landscape; Singapore ranks 19th on a list of 25 countries when looking at hyperscale computers as it only has two of the high-performance computers listed in the Top 500 list [141].

Machine-Machine Systems: Advanced communications technologies can be used as a proxy to determine Singapore's readiness for the development and implementation of swarm bots. Singapore ranks 10th globally for advanced communications technologies; it is still at a trial phase for advanced communications behind the front runners like China, South Korea, Japan and the U.S [69] [70].

Human-Machine Systems: Singapore's global standing in advanced AI provides an understanding of Singapore's readiness for the development and implementation of humanoid robots [132]; Singapore is not listed in the list of top 10 measuring the number of AI professionals working there; whilst there are proactive government initiatives and funding. However, lack of talent and specific skillsets might impede the development of technology [73] [74].

4.4 System Agnostic Weaknesses

Lack of Local Market: Lack of successful start-ups in emerging technology areas compared to dynamic innovation hubs like the Silicon Valley and Israel [142] [143].

Lack of Scale in Talent: Demand far exceeds supply of local technology talent; the government estimates that there are 400 graduates a year with the right qualifications for the tech jobs; for example in FinTech alone 1,100 jobs are added annually [144].

Lack of Scale of Data: Many emerging systems require data to train them and Singapore's size ensues in a lack of scalability compared to, for example, China and India. [145] [146].

Aggressive Overseas Markets: China's MIC 2025 starts by listing the robotics industry, along with AI and automation as important industries which they will invest in. Furthermore, China and the US alone account for 46% of global R&D spending, severely outpacing any other country in this area. Competing with them on the same level is challenging due to the sheer size of both countries [146] [147].

High Cost and Lack of Tech Talent: High cost and shortage of tech talent force Singapore firms to outsource abroad [75].

Lack of Commercialisation of Emerging Tech: It is challenging to bridge the cessation of Emerging Tech due to inability to commercialise, a stagnant market or betting on the wrong technology [10].

4.5 System Specific Opportunities

Intelligent-Machine Systems: Singapore's strength in self-driving vehicles provides it with an opportunity to develop this technology and potentially export these solutions once they have reached maturity [129] [130]. Singapore's strength in cloud technology provides a valuable opportunity for the development of connected vehicles. Given its robust infrastructure and high consumer acceptance of self-driving vehicles, Singapore can successfully develop and implement these technologies advantage it can become a forerunner in this space [131]. Singapore's strength in cloud computing provides an opportunity for it to democratise access to technology by leveraging cloud platforms; the rise of "as-a-service" models of service have proved lucrative to many countries such as Iceland, for example, who provides access to hyperscale computing services via cloud services [148]. This "as-a-service" model of service democratises access to technology and allows for the local development of emerging technology.

Human-Machine Systems: Singapore's strength in advanced robotics provides a valuable opportunity for Singapore to develop humanoid robotics across a variety of industries [63].

4.6 System Agnostic Opportunities

Presence of Multiple Tech Companies: The presence of multiple technology companies such as Amazon, Google, Intel and Facebook provides Singapore with a valuable opportunity to form strategic relationships with these firms to develop local talent and the local ecosystem for emerging technology innovation [149].

Strategic Location: Singapore's strategic location provides an opportunity to become a test-bed for tech companies to test their technologies before expanding to the broader APAC region [140].

Investment by Private and Public Sectors: Provides Singapore with a valuable opportunity to promote innovation and develop local talent as well as support local business who are making an effort to innovate in this space [140].

4.7 System Specific Threats

Intelligent-Machine Systems: Singapore's lack of hyperscale computers will hinder the development of emerging technologies which require high computational power [141].

Machine-Machine Systems: Other markets such as Korea and China are far more aggressive in their approach towards advanced communications technologies and thus threaten to vastly overtake Singapore [70].

4.8 System Agnostic Threats

Lack of Local Market: The lack of a local market threatens development of a flourishing ecosystem in the emerging technology space [142] [143[.

Lack of Scale in Talent: Singapore lacks local talent in the emerging technology space and its dependency on outsourcing such tasks to India and China may leave its population underdeveloped [75].

Lack of Scale in Data: Singapore's lack of scale of data means that it cannot train deep learning systems which can threaten the development AI technologies [145] [146].

Aggressive Overseas Markets with Scale: Aggressive overseas markets with scale and size such as China and the US are racing ahead of Singapore, due to the vast amounts of funding they have invested in the R&D space [145] [147].

4.9 Conclusions from SWOT Analysis

In conclusion, Future-Ready Systems require a focussed set of strategies, with Singapore's unique strengths and weaknesses in mind. This analysis revealed three guiding principles for recommendations, which leverage Singapore's unique strengths and overcome its weaknesses to build Future-Ready Systems capabilities:

1. Given singapore's strategic location and international standing, Singapore should aim to become a hub where Future-Ready Systems are developed, piloted and scaled up by the concerted effort of local and global stakeholders.
2. Singapore should aim to develop technology infrastructure to develop Future-Ready Systems as well as access to maximise adoption; adopting an As-a-Service philosophy in developing and disseminating technology into the ecosystem will greatly help.
3. Singapore should continue building its technology capabilities for Future-Ready Systems – National Competency Programme. While Singapore boasts a strong talent pool, it is hindered by scale and size; focussing on Future-Ready Systems early on will ensure long term sustainability and competitive advantage.

5 RECOMMENDATIONS

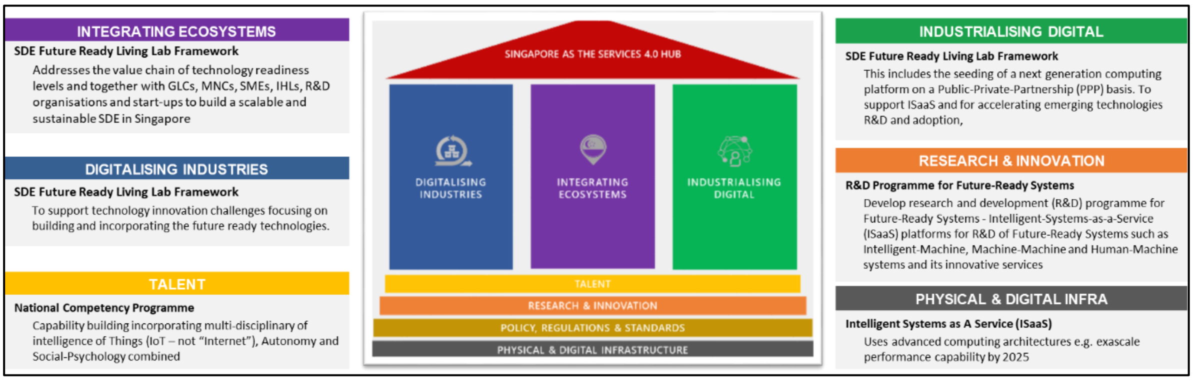


Exhibit 11: Recommendations within the DE House

Singapore's plan in getting ahead on Future Ready Technologies

Three main recommendations have been formulated based on the results of the market study, SWOT analysis and examination of the various Future Ready technologies.

- Firstly, Singapore should aim to develop **research and development (R&D) programme for Future-Ready Systems** - Intelligent-Systems-as-a-Service (ISaaS) platforms for **R&D** of Future-Ready Systems such as Intelligent-Machine, Machine-Machine and Human-Machine systems and its innovative services. These platforms should comprise of advanced computing architectures and provide democratised access to newly created APIs including "warm" and "perceptive" human-centric API system technologies. This includes the seeding of a next generation computing platform on a Public-Private-Partnership (PPP) basis. Furthermore, to support ISaaS and to accelerate R&D for emerging technologies and adoption, a roadmap for an advanced computational infrastructure and exascale performance capability (e.g., at least 1 exaFLOPS) should be put in place in Singapore by 2025.
- Secondly, Singapore should set up the **SDE Future-Ready Living Lab Framework** addressing the value chain of technology readiness levels, together with GLCs, MNCs, SMEs, IHLs, R&D organisations and start-ups to build a scalable and sustainable SDE in Singapore. Singapore's strategic location, highly innovative and 'trusted' environment will help attract global investments and talent. This framework should include a series of tech innovative challenges focussing on building and incorporating the Future-Ready Systems. These challenges aim to invite contribution to **ISaaS provisioning platform, create ecosystems, and build sustainable environments to catalyse the development of Cloud Native Architecture and microservices for Future-Ready Systems and sector-specific use cases.** This framework will help Singapore become a hub where Future Ready Technologies is developed, piloted and **exported** by the concerted effort of stakeholders. It requires the effective translation of state-of-the-art technology from laboratory to industry to meet various use cases identified. It will also include, conducting of test trials in sectors, verifications, certifications and standardisation to export to cloud platforms in large-scale ecosystems.
- Thirdly, Singapore should focus on developing a **National Competency Programme** which helps develop talent for the development of Future Ready Technology. Singapore currently boasts a strong talent pool but is constrained in scale. Focussing on training programmes and fostering growth of talent will enable long-term sustainability and competitive advantage. **The competency development program should focus on developing talent at the Junior STEM level as well as continuing education programmes,** thus contributing to the development and deployment of Intelligent Systems capability building along with incorporating multi-disciplinary of Intelligence of Things, Autonomy and Social-Psychology combined.

Exhibit 12 below details the different technologies needed to be developed for the three systems. Each of the aforementioned three programmes should help develop these foundational technologies in order to ensure sustainable development.

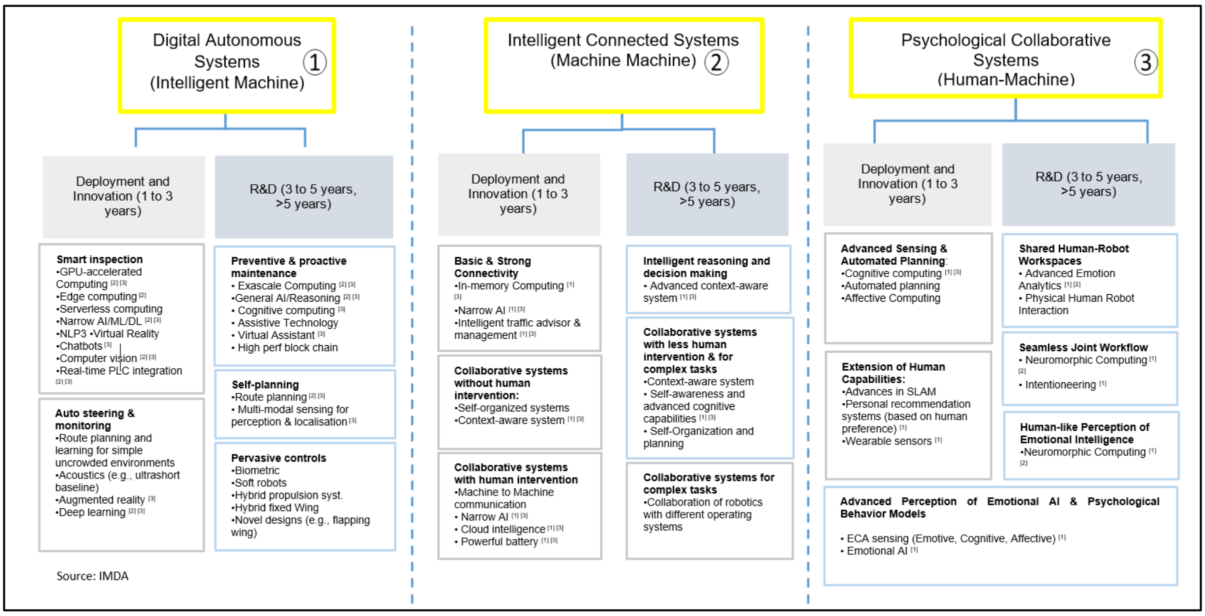


Exhibit 12: Future-Ready Systems and recommendation for various schemes

* Some technologies can also be applied to other systems indicated with superscript [1] [2] [3]

An example of a programme which can result from the recommendations is the "A-bots R&D Programme". Globally, few nations are developing Human-Machine Systems thus providing Singapore with a valuable gap in the market. As part of the Services 4.0 push, Singapore could aim to become a hub for R&D on augmented bots (A-bots) for Future-Ready Systems. These systems can be piloted and exported by the concerted effort of local and global stakeholders. Singapore has several competitive advantages compared to other nations when it comes to developing A-bots: a pervasive high-bandwidth digital infrastructure, multi-racial cultural behavioural understanding, high productivity, pro-business policies, a robust intellectual property (IP) regime and a commitment to ongoing scientific research. This will contribute significantly to the development of Human-Machine Systems which are endowed with capabilities to recognise, interpret and express emotions in human psychological models.

This can form the bedrock for R&D programmes for other systems such as machine-machine systems and intelligent-machine systems. Singapore should continue to devote some resources to the development of intelligent-machine and machine-machine systems. Singapore will still require to continue to perform R&D in these technologies areas for these systems even though stiff competitive landscape exists for Singapore to differentiate itself effectively in these areas.

The combined efforts of these recommendations and the integrating ecosystems paves the way for Singapore to be positioned as the Services 4.0 hub in the region and beyond. To remain relevant, we need to be ready to experiment more with emerging technology developments and remain open-minded and innovative. Our existing infrastructure puts us in an advantageous position to build relevant, emerging technology products for markets around the world.

6 SUMMARY

In summary, Future-Ready Systems require strategies in line with Singapore's unique strengths and weaknesses in mind. The SWOT analysis has culminated in three guiding principles that leverage Singapore's unique strengths and overcome its weaknesses to build its Future-Ready System capabilities.

Firstly, Singapore should aim to become a hub where Future-Ready Systems is developed, piloted and scaled by concerted effort of local and global stakeholders. This entails leveraging Singapore's unique geographic location and highly innovative and 'trusted' environment to attract global investments and talent. This particular principle overcomes the issues relating to lack of scale in talent as well as stimulating the local market. Furthermore, this will reduce outsourcing emerging technology development to other countries such as India and China [75]. In addition to this, by becoming a hub, Singapore may be able to form synergetic partnerships in order to collect vast amounts of data pivotal for the development of emerging technology.

Secondly, Singapore should develop robust technological infrastructure which provides the tools to develop Future-Ready Systems as well as access to the Future-Ready Systems to maximise adoption. Specifically, Singapore must consider adopting the as-a-Service philosophy in developing and disseminating technology into the ecosystem. For instance, Iceland is a role model in providing access to hyperscale computing services via cloud services. This "as-a-service" model of service will successfully democratise access to technology and allow for the local development of emerging technology, once again stimulating the local market. Furthermore, investments in a robust technological infrastructure will help Singapore remain competitive in an increasingly aggressive global market place.

Thirdly, Singapore should continue building its capabilities for the Future-Ready Systems by developing a National Competency Program; while Singapore boasts a strong talent pool but this talent pool is constrained in scale. By investing resources focusing on Future-Ready Systems early will ensure long term sustainability and competitive advantage. Furthermore, a well-functioning ecosystem needs to be developed which requires the market, capital, IP, talent, policy and regulations to work in concert to develop the ecosystem to catalyse growth of Future-Ready Systems in Singapore.

APPENDIX A: GLOSSARY

TECHNOLOGIES	GLOSSARY
Assistive Technology	Assistive technology is an umbrella term that includes assistive, adaptive, and rehabilitative devices for people with disabilities while also including the process used in selecting, locating, and using them. Assistive technology promotes greater independence by enabling people to perform tasks they were formerly unable to accomplish, or had great difficulty accomplishing, by providing enhancements to, or changing methods of interacting with the technology needed to accomplish such tasks.
Cobots	The definition of collaboration is the action of working with someone to produce something and cobots are designed with that in mind, working alongside other employees and not as a replacement to them.
Cognitive Computing	Cognitive Computing are systems that learn at scale, reason with purpose and interact with humans naturally. It is a mixture of computer science and cognitive science – that is, the understanding of the human brain and how it works.
Context-aware Systems	Context awareness is the ability of a system or system component to gather information about its environment at any given time and adapt behaviours accordingly. Context includes any information that's relevant to a given entity, such as a person, a device or an application.
Dedicated short-range communications (DSRC)	Dedicated short-range communications are one-way or two-way short-range to medium-range wireless communication channels specifically designed for automotive use and a corresponding set of protocols and standards.
Digital Twins	Digital twin refers to a digital replica of physical assets (physical twin), processes, people, places, systems and devices that can be used for various purposes.
Emotional AI	Artificial emotional intelligence or Emotion AI is also known as emotion recognition or emotion detection technology.
Exascale Computing	Exascale computing refers to computing systems capable of at least one exaFLOPS, or a billion billion calculations per second.
Exoskeleton	Exoskeletons are wearable devices that work in tandem with the user. They are placed on the user's body and act as amplifiers that augment, reinforce or restore human performance. Exoskeletons can be made out of rigid materials such as metal or carbon fibre, or they can be made entirely out of soft and

	elastic parts. They can cover the entire body, just the upper or lower extremities, or a specific body segment.
GPU-accelerated Computing	GPU-accelerated computing is the use of a graphics processing unit (GPU) together with a CPU to accelerate scientific, analytics, engineering, consumer, and enterprise applications.
Humanoid	A humanoid robot is a robot with its overall appearance based on that of the human body.
In-memory Computing	In-memory computing is the storage of information in the main random access memory (RAM) of dedicated servers rather than in complicated relational databases operating on comparatively slow disk drives.
Intentioneering	Intentioneering represents the next level of automation – where machines have the ability to alter their goals or designed purposes.
Neuromorphic Computing	Neuromorphic computers are integrated chips that are designed to mimic the organisation of living neuron cells and are modelled closely on biological nerve cells, or neurons.
Self-organised Collaboration	Self-organising systems are structures that process where some form of overall order or coordination arises out of the local interactions between smaller component parts of an initially disordered system. The resulting organisation is wholly decentralised or distributed over all the components of the system.
Soft Robots	Soft robots are made from soft, elastic materials and offer unique opportunities in areas in which conventional rigid robots are not viable; for example, for drug delivery, non-invasive surgical procedures, as assistive devices, prostheses or artificial organs. The emerging field of soft robotics draws together materials scientists, mechanical and biomedical engineers, and researchers of intelligent systems with the inspiration for the design from nature.
Swarm bots	Swarm robotics is an approach to the coordination of multiple robots as a system which consist of large numbers of mostly simple physical robots. It is supposed that a desired collective behaviour emerges from the interactions between the robots and interactions of robots with the environment.
V2X Communication	Vehicle-to-everything (V2X) communication is the passing of information from a vehicle to any entity that may affect the vehicle, and vice versa. It is a vehicular communication system that incorporates other more specific types of communication as V2I (Vehicle-to-Infrastructure), V2N (Vehicle-to-network), V2V (Vehicle-to-vehicle), V2P (Vehicle-to-Pedestrian), V2D (Vehicle-to-device) and V2G (Vehicle-to-grid).

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APPENDIX C: WORKGROUP MEMBERS

Prof. Lawrence Wong (Chairman of Workgroup 5)	Deputy Director, Smart Systems Institute, National University of Singapore (NUS)
Mr. Leong Mun Yuen (Co-Chairman of Workgroup 5)	Senior Advisor & SVP, ETPL
Dr. Simon See	Chief Solution Architect, Nvidia Singapore Development Pte. Ltd.
Mr. Cheng Jang Thye	Chief Solution Architect, Fujitsu Ltd.
Dr. Theodore Vassilakis	Chief Technology Officer, Grab
Mr. Sing Khang Leng	Cluster Director, Government Technology Agency (GovTech)
Mr. Chan Chung Kit	Head, Watson CoC, IBM Singapore Pte. Ltd.
Prof. Ang Wei Tech	Professor, School of Mechanical & Aerospace Engineering, Nanyang Technological University (NTU)
Dr. Terence Hung	Chief of Future Intelligence Technologies, Rolls-Royce Singapore Pte. Ltd.
Dr. Fun Wey	Institute of Systems Science, Nanyang Technological University (NTU)
Dr. Ang Marcelo H. Jr	Associate Professor, Department of Mechanical Engineering, National University of Singapore (NUS)
Mr. Sami Hoisko	Chief Technology Officer, Nokia Technology Pte. Ltd.
Prof. Anupam Chattopadhyay	Assistant Professor, School of Computer Science and Engineering (SCSE), Colleague of Engineering, Nanyang Technological University (NTU)
Mr. Poon King Wang	Director, Lee Kuan Yew Centre for Innovative Cities (LKYCIC), Singapore University of Technology and Design (SUTD)

Prof. Lynette Cheah	Assistant Professor, Singapore University of Technology and Design (SUTD)
Mr. Liu Genping	Partner, Vertex Ventures
Dr. Lua Eng Keong	Director, Intelligent Computing Labs, Infocomm Media Development Authority
Mr. Raymond Lee	Director, Infocomm Resource & Technology, Infocomm Media Development Authority
Dr. Li Xiaorong	Executive Manager, Intelligent Computing Labs, Infocomm Media Development Authority
Dr. Chris Chew	Senior Manager, Intelligent Computing Labs, Infocomm Media Development Authority
Dr. Nie Maowen	Manager, Intelligent Computing Labs, Infocomm Media Development Authority
Mr. Praveen Sampath Kumar	Manager, Green Data Centre, Infocomm Media Development Authority