Horizon Scanning Series

The Effective and Ethical Development of Artificial Intelligence: An Opportunity to Improve Our Wellbeing

Artificial Intelligence and Robotics

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Artificial Intelligence and Robotics

A contribution to the Horizon Scanning Report on AI for the Australian Council of Learned Academies (ACOLA)

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1. Introduction: Robotics

Robotics is often characterized as the intelligent connection of perception to action [Brady 1984] in engineered systems.

In the sense-think-act cycle of operation in a robot (Fig. 1), exterioceptive sensors such as cameras, thermal imagers and lidars are used to collect data about the operational environment of the robot and build world models. World representations widely used include stochastic lattice models, point clouds, geometric descriptions, topological models, etc. The choice often depends on the sensors available and the nature of the tasks to be executed by the robot. Data from multiple sensors or different types of sensors are combined using probabilistic sensor fusion techniques, and SLAM (Simultaneous Localization and Mapping) algorithms are used to estimate both the world model and the motion of the sensors/robot through the world.

The world model is in turn used to plan robot activities. These may include navigation tasks such as obstacle avoidance and trajectory planning, as well as manipulation and sensory tasks. Robot tasks are planned as sets of atomic actions, and complex robot missions as sets of tasks. Actions are executed using control systems that operate on the actuators and perform state estimation using the proprioceptive sensors of the robot. The sense-think-act cycle is usually repeated at high rates to enable real-time operation of the robotic system and adequate response to fast-changing environments.

For next generation Robotics in the Australian context, top priorities include the development of the core technologies for highly autonomous, competent, and reliable robotic systems that can execute complex missions in challenging indoor and outdoor environments. These robots also need to interact safely and seamlessly with humans and other dynamic agents, and to be deployed in a broad range of application domains that are of strategic relevance to Australia and the world. All of these areas will benefit from the next generation of highly autonomous robots, which integrate core AI technologies into Robotics (see subsection 3 and Fig. 1).

2. Strategic Importance of Robotics for Australia

The rapid development and maturation of Robotics in the last two decades, as well as its deployment across a growing number of domains, have led Robotics to become one of the core digital technologies worldwide. This is reflected in a variety of strategic technology roadmaps prepared by academia, government and the private sector that consistently identify robotics and autonomous systems as high-value and increasingly pervasive technologies with major economic impacts and large projected market growth rates (see, for example, [Williamson 2015, Roadmap 2018]).

Due to its interdisciplinary nature, robotics research covers a very large number of areas, problems and application domains. Key application domains for robots include:

- Field robotics:
    - Large-scale agriculture, but also precision agriculture
    - Resources sector: mining and the energy sector (oil and gas)
    - Construction, inspection and maintenance of buildings, roads and other large-scale infrastructure
    - Autonomous transport of people and cargo (ground, air and sea robots)
    - Robotics for defence, safety, search & rescue, security and law enforcement
    - Robotics and the biosphere (including the areas of biosecurity, biodiversity, environmental research and monitoring, marine research, etc.)
- Industrial robotics for the manufacturing sector
- Medical, health, and assistive robotics
- Space robotics
- Service and consumer robotics

In the following discussion, greater emphasis is placed on technologies for field, industrial and health robotics. These application domains have the potential for greatest strategic economic, societal and environmental impact for Australia.

The fourth industrial revolution, also called Industry 4.0 [Lasi 2014], is being enabled by multiple technologies and factors: advanced automation, the ubiquitous deployment of robotics, digital mirroring of reality, cyberphysical systems, large-scale digital connection of physical assets and the Internet of Things (IoT), big data analytics, machine learning, and high-speed communications.

Similar advances are happening in autonomous ground and air transportation systems, as well as in the deployment of robots in mining, agriculture, health care, and many other sectors. By 2025, the potential economic impact of advanced robotics is estimated to be between US$1.7 trillion and $4.5 trillion; the economic impact for autonomous or near-autonomous vehicles is expected to be between US$0.2 trillion and US$1.9 trillion, while potentially saving 30,000 to 150,000 lives from severe or fatal traffic accidents [McKinsey 2016].

For Australia, estimates indicate that the adoption of advanced automation (covering AI, Robotics, and IoT) will boost the national income by more than $2 trillion over the next 15 years, while creating millions of safer, more meaningful and more valuable jobs [AlphaBeta 2017]. At the same time, there are social and perceptual concerns regarding widespread adoption of Robotics and AI that will need to be addressed [Brougham 2018].

The growing importance of Robotics and AI-enhanced Robotics also implies the need for fostering and growing a national industry in Robotics. While Australia has very strong capabilities in Robotics R&D, the creation of new companies and industries in this area lags severely behind. This leads to various risks, including that imported robots may not be fit for Australian environments, and more broadly the sovereign risk that key industries that are important to Australia's wealth (such as mining or agriculture) may be restricted in their access to foreign robotics technologies.

3. Artificial Intelligence and Robotics

Artificial Intelligence and Robotics have a long history of interaction. Both disciplines emerged in the 1950s from different R&D communities. Robotics arose from the fields of mechanical and electrical engineering, building on control theory, kinematics and dynamics modeling, and system state estimation. Artificial Intelligence, in turn, arose out of what at the time was the new field of Computer Science. Researchers asked questions regarding the nature of intelligence and the possibility of programming computers to solve problems that were traditionally seen as requiring human cognitive skills. Early advances in AI included knowledge representation methods and heuristic algorithms to search large decision spaces.

Starting in the 1980s, the AI and Robotics communities started to develop new approaches and methods drawing from the areas of probability, information, estimation, optimisation and decision theories. This led to break-through advances in robustness and applicability, and to significant cross-fertilisation research between AI and Robotics, a trend that has continued to the present. The last two decades also saw major advances in the area of Computer Vision through the development of next-generation Machine Learning (ML) methods, including Artificial Neural Networks (ANNs) and Deep Learning [Aizenberg 2000], Support Vector Machines (SVNs) [Apnik 1995], hierarchical Bayesian models [Cressie 2011], and other methods. ML applied to robot control has included evolutionary and reinforcement learning methods [Howard 2017], as well as methods that learn behaviours from human demonstrations [Kuderer 2015], and end-to-end vision-based deep learning of sensor-action mappings [Levine 2016].

Major synergies between AI and Robotics are shown in Fig. 1.

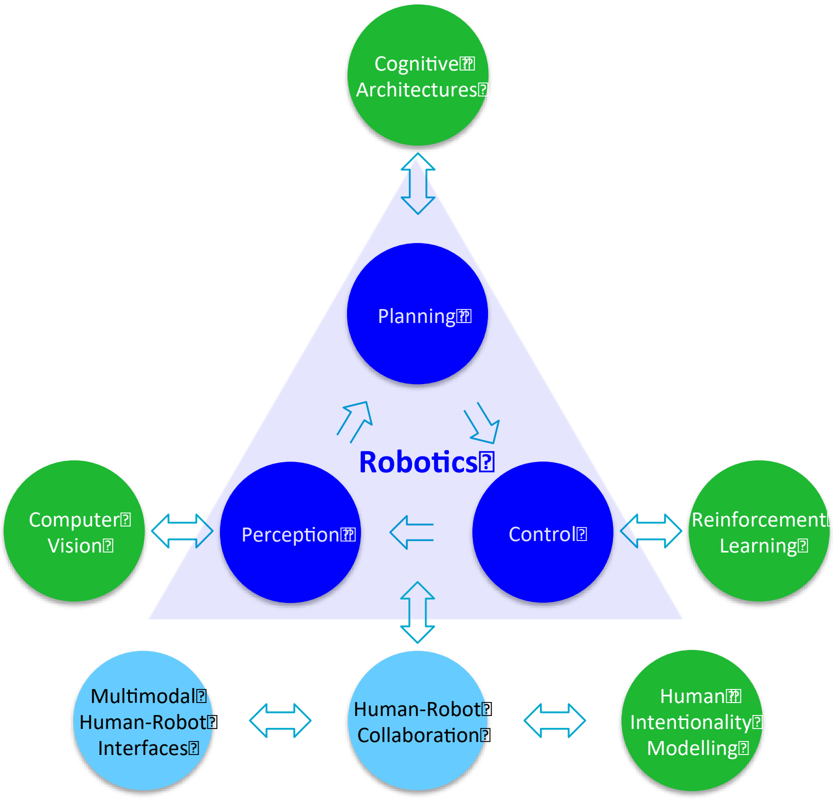

Figure 1. Robotics implements a perception-planning-control cycle (dark blue). Major areas in Artificial Intelligence (green) of high synergistic potential with Robotics include Computer Vision, Cognitive Architectures and Reinforcement Learning methods. Human-robot collaboration is a key emerging area in Robotics, requiring both multimodal HR interfaces and human intentionality modeling and understanding.

4. Strategic Opportunities for AI-Augmented Robotics in Australia

In what follows, we give examples of some of the key areas where substantially autonomous (AI-augmented) robotic systems are of significant strategic importance to Australia.

4.1 Autonomous (Driverless) Ground Vehicles

Current ground unmanned vehicles are extremely limited in their autonomy capabilities. Driverless vehicles, such as Google cars, have demonstrated impressive performance in well-mapped roads, but are unable to operate in off-road terrain. More broadly, current ground robots are also very limited in the type of terrain they can traverse. Wheeled or tracked vehicles are largely confined to roads or relatively smooth, solid and open terrain. Estimates indicate that 30 – 50% of the Earth's land surface is not accessible to ground vehicles, because the terrain is too steep, too heavily vegetated, too cluttered or too marshy.

Autonomous unmanned ground vehicles (UGVs) that can operate in cross-country conditions are highly relevant for applications such as long-distance transportation, mining, agriculture, biosecurity and biodiversity assessments, science surveys, safety, and others. Technology advances are needed in the combination of localization and mapping methods, motion planning, obstacle detection, obstacle avoidance and situation awareness, as well as in translating these technologies into operational and useful platforms that can increase productivity and safety across a wide range of applications [Kunze 2018].

4.2 Unmanned Aerial Vehicles (UAVs)

UAVs, popularly known as drones, are a core technology for a future digital society. They are especially critical for Australia, which has a small number of large populations centres, while most of the continent has an extremely low population density. Currently, the civilian UAV market is booming, with the vehicles being primarily used to generate data at local scales.

In the future, UAVs will become essential to providing transport, delivery services, medical supply services, biosecurity assessments, agricultural surveys, border surveillance, etc. on a continental scale. Australia has a competitive advantage in developing UAV technologies and exploiting these to the benefit of the country, and there have been recent Australian government actions to have the regulatory agency, CASA, collaborate with UAV research groups in the country to develop appropriate standards for operation of fully autonomous aircraft in civilian airspace.

4.3 Next-Generation Manufacturing

Recent manufacturing trends are re-defining business strategies across the sector [Lasi 2014]. The increasing adoption of sustainable practices, stronger demand for personalised products, blurred boundaries between manufacturing and the services sector and an interest from Australian producers in high-value activities across global supply chains, are all imposing both opportunities and challenges for the domestic industry. Manufacturers are seeking alternative solutions to seize global opportunities.

A broad area of opportunity for Australia is the development of assistive technologies to enhance workers, rather than replace them through automation, an approach that has the potential to be a profound enabler for economic success [Brea 2013].

Across many areas of manufacturing and technology, we are seeing a move from production lines of identical items to a new wave of increasingly flexible, adaptive, and customised products. Some of this is being driven by rapid prototyping and construction techniques. Diversity is provided by libraries of selectable “base components” that are assembled into bespoke solutions. One area that is particularly well positioned to benefit from this shift is robotics.

In contrast, conventional automation, such as that used in automotive manufacturing, is driven by the need to automate specific mass manufacturing tasks. However, economic drivers for Australia demands less focus on large volume production, and more concentration on mass personalisation of products. This macroeconomic environment predicates a national quest for affordable assistive automation solutions that support high variety: low volume production runs that are easy to implement, highly flexible, and adaptable to operational processes, equipment and human resources already in place.

Recent advances in Robotics and Artificial Intelligence are enabling a converging trend of transferring robotic capabilities directly to human workers, facilitating teamwork between humans and robots, and augmenting worker's perception by putting digital information directly at their disposal. This approach leads to three types of systems:

- *Worker augmentation systems* that make work easier for humans, increasing product quality, raising labour productivity and contributing in maintaining a high-skilled workforce.
- *Tele-supervised robots* that work for humans, increasing worker safety, expanding the worker's field of action, and facilitating work in small-scale environments.
- *Robotic co-workers* that work with humans, increasing manufacturing productivity, raising responsiveness and providing smart and safe automation.

These new technical capabilities, initially leveraged from advances in assistive mining technologies, are putting Australia in the forefront of an upcoming new industry around assistive systems. It will also serve as a foundation for the next phase of the manufacturing evolution in Australia in alignment with future megatrends, a phase that will see a full digitisation of manufacturing settings.

Radically new opportunities exist for synergies between AI and Robotics in advanced manufacturing. AI-enabled systems can design the "next generation" of robots. Ongoing advances in increasingly-integrated multifunction sensing, actuation, and energy storage materials, combined with emerging multi-material additive manufacturing technologies (e.g., 3D printing) will allow new smart, powerful robots to be created [Mengüç 2017]. The resulting robots will be ready to respond to extremely challenging field conditions, for example in search and rescue and disaster response.

5. Synergistic Research Opportunities for AI and Robotics in Australia

Some of the key research opportunities for the use of AI technologies in Robotics include (Fig. 1):

- **Understanding the world:** robots today have no rich internal world models to enable higher degrees of competence and autonomy. To understand the world, robots will need to associate semantic information to exterioceptive (visual, lidar, thermal, etc.) and proprioceptive (IMU, joint angle encoders, etc.) data. While significant progress has been done in applying machine learning techniques to computer vision, many of these methodologies have not yet transitioned into field robotics.
- **Broad, robust and persistent autonomy:** while very broad autonomy claims are sometimes made in the popular press about robots, the reality is that today's field, industrial, medical and other domain-specific robots are competent in one or two types of tasks (deep autonomy), and usually fail when faced with unforeseen situations (broad autonomy). Furthermore, practically no research has addressed the challenges of persistent (long-term) autonomy for

robots operating “in the wild” for months or years. Concepts from cognitive architectures and higher-level reasoning methods developed in AI will be fundamental to develop next-generation robotic autonomy levels [SAE 2018, Parasuraman 2000].

- **Autonomous development of control systems:** development of control architectures for robotic systems requires extensive work on system kinematics and dynamics, system identification, and programming and fine-tuning realtime controllers [Chiuso 2016]. Automated development of control systems, either through evolutionary and reinforcement learning methods or through autonomous synthesis of control software, could be a major breakthrough in the speed to deployment of complex robot systems.
- **Human-robot collaboration and intentionality modelling:** for robotic domains such as small-scale manufacturing, medical robots, and health and assistive robots, the ability to have robots collaborate closely with humans is essential [Sheridan 2016]. Multi-sensory (multi-modal) human-robot interfaces (HRI) provide part of the answer, but true human-robot collaboration will also require the robot to be able to model and assess human intentionality through ML methods applied to human gestures, speech, tone of voice, gaze direction and other clues.

Conversely, some of the key research opportunities for the use of robotic systems and technologies in AI include:

- **Robots as highly competent surveyors:** many application domains of AI, from smart cities to large-scale infrastructure inspection, require Big Data, or the collection of massive amounts of data. Air, ground and aquatic robots can collect data systematically over large spatial and temporal scale, and at adaptive levels of spatial and temporal resolution. They can also be retasked in real-time to focus on areas of particular interest.
- **Robots as embodied testbeds for machine learning and cognitive architectures:** much of the work on machine learning and cognitive architectures applied to robotics has relied solely on simulation [Amunts 2016]. Broadly speaking, these approaches do not transition well to actual robotic systems, as there are normally significant gaps between the simulated model and the actual robot system. Using actual robots as embodied testbeds for ML and cognitive architectures, while imposing significant challenges, provides far more stringent performance requirements and realistic scenarios.

It should also be mentioned that areas such as **Ethics** and **Cybersecurity** are common concerns of the AI and Robotics communities.

6. Towards AI-Enabled Robotics in Australia

Some of the key elements that will contribute towards a broad strategy for AI-enabled Robotics in Australia include [SWA 2018]:

- Develop and foster a positive social narrative in Australia around robotics and AI, with an emphasis on how these technologies can:
    - Assist the Australian workforce (increase safety and productivity)

    - Advance the Australian economy (increase diversity and business opportunities)
    - Address Australia’s challenges (resource limitations and environmental sustainability)
- Promote and facilitate the adoption of next-generation, AI-enhanced robotics and automation technologies so as to ensure that:
    - Australian industry remains globally competitive and connected, as a leader in the international automation supply chain
    - The Australian workforce continues to develop high-tech skills that will be in demand globally
    - Australia’s unique domestic technology requirements are satisfied
- Promote and facilitate the creation of advanced robotic and automation technologies in Australia by:
    - Connecting our diverse talent, knowledge and resources in industry, government and academia
    - Unifying and expanding government and industry support and uptake for Australian robotics and automation research
    - Enhancing the capability and capacity of the domestic ecosystem to support this technology

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[SWA 2018] The Sixth-Wave Alliance (SWA) is an initiative of CSIRO’s Data61 business unit through its Robotics and Autonomous Systems Group. SWA’s vision is to be integrated by all the key robotics research organisations and industry partners in Australia, and provide a framework that would enable a high level of R&D

collaboration among the partner institutions, leveraging existing programs and investments vs. trying to replace them. This in turn would allow the SWA to target large-scale, national problems of strategic and commercial relevance to Australia and internationally, far beyond what individual Robotics research groups in the country are able to achieve. The term Robotics is used in an encompassing sense and includes robotics-relevant areas in Computer and Machine Vision, Machine Learning and aspects of Artificial Intelligence.

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