R & D Journal
of the South African Institution of Mechanical Engineering

Dear Reader

This journal invited authors two submit two themed papers under the guest editorship of Dr Willie Smit. The purpose of the papers is to showcase robotics research in South Africa. While we tried to be as inclusive as possible, we quickly realised that the activity is larger than expected and we were unable to include all the work done in South Africa.

The first paper is an overview of a wide section of the robotics research activities in South Africa. Dr Smit collated the work of 17 researchers from seven institutes and even more research groups, showing how South African institutions are preparing technology and highly skilled engineers for Industry 4.0.

The second paper showcases one very close international collaboration and deals with open source technology readily available for South African researchers and industry alike.

The two papers are:

> E. Boje, R.L. Christopher, J. Fernandes, J.H. Hepworth, R.B. Kuriakose, K. Kruger, T. Lorimer, N. Luwes, H.D. Mouton, A. Patel, B. Rosman, W.J. Smit, R. Stopforth, B. van Eden, T. van Niekerk, H. Vermaak, D. Withey. A Review of Robotics Research in South Africa. *R&D Journal*, 35:75-97, 2019.
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> N Limpert, P Wiesen, A Ferrein, S Kallweit, S Schiffer. The ROSIN Project and its Outreach to South Africa. *R&D Journal*, 35:98-104, 2019.

Yours truly,

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A Review of Robotics Research in South Africa

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Abstract: Robots are increasingly being used in the industry. Businesses that use robots can produce products and provide services at lower costs and with higher quality. Some industries, like automotive manufacturing, have become dependent on robots. The impact of robots on society and the greater economy is not clear. Robots threaten the jobs of low-skilled workers and even middle-skilled workers. While researchers and governments are trying to understand the impact of robots on the economy, it is commonly accepted that robots will be used more widely across all industries.

With this in mind, it is useful to consider the current research in robotics at South African research institutions. This paper is such a review. It is not exhaustive, but it provides a sense of the robotics research being done in South African research institutions.

It appears that research institutions do not work on common themes, yet many research groups relate their work to Industry 4.0. The review suggests that each research group is working on topics of interest to them. The implication of this is that a wide variety of robotic themes are being researched in South Africa.

1 Introduction

Robotics can be defined as "*the technology or science of the design, construction, operation, and use of robots and similar automatic devices.*" [1]. Most people agree that the aim of robotics is to use robots to make life easier and better for humans. The dream is to have robots that act and behave much like humans [2].

Society is structured in a way that it provides for those individuals that contribute to the economy. The challenge that society faces with robots is that they make our life easier by doing our work, but by doing our work, we need to find other ways to contribute to society. While robots will make life easier for humans, we need to reinvent society so that we find a new place for humans in it [3].

Robots, like all technology, are not neutral. They have positive and negative impacts on businesses and society. Researchers and governments are trying to understand what these impacts are and what they might be. The impact of robots on the South African society will be different from what it is for first world countries because South Africa has a higher unemployment rate and is not as developed.

It is useful to look at the robotics research currently underway at South African research institutions. One can review the research outputs of these institutions to get an overview of what is being done. However, the research outputs often focus on specific aspects of projects and do not give an overview of the long-term research goals of a research group. Therefore, this review presents an overview of current research.

The contributions from the institutions are divided into two sections: "Theoretical Research" in section 2 and "Applied Research" in section 3. Section 2 contains research that is not linked to an industrial project that is currently underway. This section includes basic research and research that will contribute to projects only a few years from now. Section 3 contains research on specific industrial projects that are currently underway. The paper ends with a conclusion in section 4.

2 Theoretical Research

This section contains some of the theoretical research that is currently done at South African research institutions. The research discussed here is not done with particular projects in

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mind. It is more general research that can later be applied. The subsections are ordered alphabetically by research institution.

2.1 Central University of Technology

Manufacturing has undergone a paradigm shift from the days of water and steam powered engines. Advancements in science and technology have [4] been the root cause of this shift. The latest trend in industrial revolution is referred to as Industry 4.0. The term was coined in Germany in 2011 [5] and is based on cyber physical systems, Internet of things (IoT) and Internet of services (IoS).

The impact of Industry 4.0 has been so ground-breaking that governments [6] of United States, France, Germany, United Kingdom, European Union Commission, South Korea, China, Japan and Singapore have endorsed Industry 4.0 and have incorporated them in some form to their government plans for the immediate future.

Adhering to this global shift is essential for South Africa as it will define the landscape of the country going into the future. Traditionally, South Africa has been a resource-based economy [7], with focus on mining, agriculture and manufacturing. Therefore, by default, these industries still create the majority of jobs in the country.

However, it is widely stated that in the coming years, there will be a shift from a resource-based economy to a knowledge-based economy [7]. It is of paramount importance that South Africa adjusts to this shift while keeping to its strong suits. In acknowledging this need to shift, The Central University of Technology, Free State has embarked on earmarked projects in SMART Manufacturing and Humanoid Robotics.

2.1.1 SMART Manufacturing

Assembly lines have been the spine of the manufacturing industry for decades. Previously, assembly lines were manned by human beings. However, the advent of Industry 4.0 has resulted in assembly lines being more automated. This necessitates the need for Real-Time Optimization [8] which would reduce the production time and thereby increase productivity. While Assembly Line Balancing is a very wide topic, the studies done at the Central University of Technology, Free State focus specifically on Mixed-Model Stochastic Assembly Line Optimization. This is primarily because of the lack of research done in this field and secondarily due to the shift in the manufacturing scene where industries have moved on from a make-to-stock approach to a make-to-order approach [9].

The university has conducted a case study on a water bottling plant [10] which bottles multiple variants of bottled water. The orders for the bottle are sourced through a web interface which is linked to the Simulink model for the plant. Once the orders are sourced, the optimization model determines the quickest production time based on the constraints like the delivery date, water in tank and number of empty bottles available in stock.

The study has yielded very positive results [11] with the optimization model successfully handling up to twelve parallel orders at a time without latency or compromise on the constraints. The optimization model designed for this purpose can easily be reconfigured to suit the needs of a specific industry. This is of importance as it can be used in the car manufacturing industry, which contributes hugely to the manufacturing scene in South Africa.

There are two extensions of this study. The first of which is in the building of SMART Manufacturing Units (SMU's) and developing of communication protocols [12] that will allow communication between different SMU's. As it stands now, for an SMU to communicate with another SMU, the data needs to be first sent to the central server and be rerouted to the SMU with which communication needs to be established.

This lack of communication protocols [13] can create several issues when designing SMU's, as one key characteristic of SMU's is decentralization. Decentralization is the characteristic by which machines can work independently from central servers and in cohesion with other machines when there is no connection to central servers. This will allow SMU's to continue production even when communication is lost to central servers, albeit limited. A standard communication protocol will also allow SMU's to become contextually aware by sensing and reading in nearby connected SMU's and their states. A communication protocol between SMU's is therefore key to fully realize the ability of machines to become SMART and improve real-time production in SMART factories and cloud manufacturing. Figure 1 shows the communication layers in SMART Manufacturing environment. This specific study aims to develop communication protocols in Layer 3.

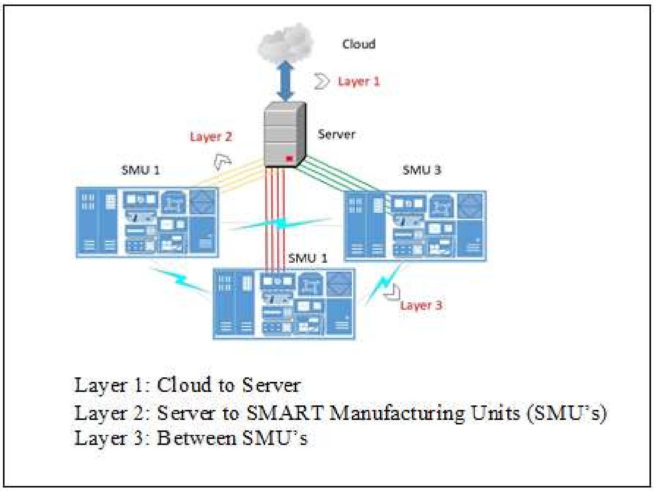

Figure 1 Communication layers in a SMART Manufacturing Environment.

The second extension of this study is in the development of an automated, flexible system utilizing machine vision [14]. With the introduction of such a system to the production line, the complete reprogramming process required for new products needs could be automated with limited loss in production time. Therefore, instead of reprogramming each new position for the robot system, the system takes over real-time control of the robot and carries out the required steps autonomously. The

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benefit with such a system would be that the robot would not need to be reprogrammed for every new routine but is controlled in a real-time environment to carry out new procedures based on external vision sensors. Using a real-time system could remove the need for a fixed programming environment and replace it with an automated changing programming setup. This could result in a system automatically adapting to a new product introduction through real-time machine vision processing techniques.

Here, the test environment is centred using a KUKA robot arm with Robot Sensor Interface (RSI) software installed on it. The vision system is used as a remote detection and image acquiring sensor to the RSI software. It acquired images of components on the pallet and calculated each item position relative to the KUKA gripping device [15]. The centre of the pallet is taken as the default position. This process was done by calculating the centre of gravity for each component. The centre of gravity was needed as it was used as the area to pick the components to ensure stability during moving operations [16]. The Accord.net framework software was implemented and used to calculate the orientation data for each component. This raw and central moments to the blob in question are implemented by the framework for a resultant angle to be calculated [17]. This calculation is very important when the need arises to rotate a component to fit in the new product template. The calculated centre of gravity for different shape components can be seen in figure 2.

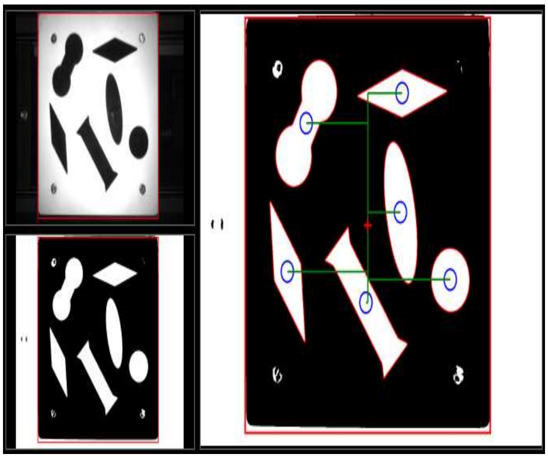


Figure 2 The calculated centre of gravity for each component (small circle in each component).

The results of the test showed that the system performed optimally and completed all given tasks without any issues occurring. The accuracy and speed of the system were notable with “everyday” calibration in a changing environment.

2.1.2 Humanoid Robotics in SMART City environment

To handle rapid urbanization, there is need to find new ways to manage complexity, increase efficiency, reduce expenses, and improve quality of life. The new ways are rooted in the concept of 'SMART City'.

SMART City research is focused on research that can produce new technology, products, devices, structures, methodology contributing towards the development of a Sustainable City of the Future. This research explores the possibilities of the Industrial Revolution and in particular Industry 4.0.

A big part of Industry 4.0 and combined with SMART City would see a need for humanoids. A humanoid robot is a robot with its body shape built to resemble the human body. The design may be for functional purposes, such as interacting with human tools and environments, for experimental purposes, such as the study of bipedal locomotion, or for other purposes. In general, humanoid robots have a torso, a head, two arms, and two legs, though some forms of humanoid robots may model only part of the body, for example, from the waist up. Some humanoid robots also have heads designed to replicate human facial features such as eyes and mouths. Androids are humanoid robots built to aesthetically resemble humans.

As of now, a 3D printed the fully functional head, hand and arm have been manufactured as shown in figure 3.

Figure 3 A 3D printed fully functional head, arm and hand developed as part of the humanoid robot project.

2.2 Council for Scientific and Industrial Research

The Council for Scientific and Industrial Research (CSIR) has been active for more than a decade in the area of artificial intelligence (AI) software research and development (R&D) applied to mobile, autonomous robots, those that operate in relatively unconstrained environments and that can move, make decisions, and take actions, both autonomously and under direction. This has involved R&D in perception, navigation, planning, control, computer vision, and machine learning.

The Mobile Intelligent Autonomous Systems group at the CSIR has the primary objective to undertake focused research to build capabilities in Robotics and Autonomous Systems in support of industry, to aid in the re-industrialisation of the country. The secondary objective is to develop SET skills and capabilities to grow the group so that it can meet the ever-increasing needs for robotics and AI related work.

With these objectives, the group strives to develop systems to augment human capabilities and promote human-machine collaboration, where applicable, and to develop systems that are learning machines that can adapt to the environment they are in, and the tasks they are given so that they can better assist the humans that they are working with.

The group has two main research themes. The first is the Autonomous Mapping and Inspection theme where the ability to map, navigate and explore in unstructured environments is developed. The second theme is the Intelligent Work Cell that entails building ability in mobile manipulation systems in support of Industry 4.0, showcasing pick and place, object detection and recognition, and the ability to adapt to new tasks and environments.

A summary of some current systems from both themes is given, including mobile robots for autonomous 3D exploration and mapping, multi-robot cooperation, context-aware real-time action (CARTA), the CSIR Hybrid Autonomous Mobile Manipulator Platform (CHAMP), pick and place on CHAMP and in simulation, place recognition and kinaesthetic teaching. These systems are intended for GPS-denied environments and are typically applied on light, mobile machines operating with limited, battery power. The use of battery power means that system computational resources must be designed for low power consumption. Example target environments include applications in manufacturing and inspection, and also underground mines. The system software is built using custom, CSIR-developed software, along with open-source software packages.

The CSIR is also involved in robotics research projects in computer vision, machine learning, and autonomous navigation, to push the boundaries of relevant artificial intelligence.

2.2.1 Methods

These robot systems are based on the Ubuntu distribution of the Linux operating system. Ubuntu is an open-source operating system, currently at long-term support revision, 18.04. In addition, robotics community software is used, including the Robot Operating System (ROS) which gives mechanisms for interprocess communication, time-sequenced transformations, and visualization, libpointmatcher [18] for point cloud registration, the Point Cloud Library (PCL) [19], OpenCV [20], and Octomap [21].

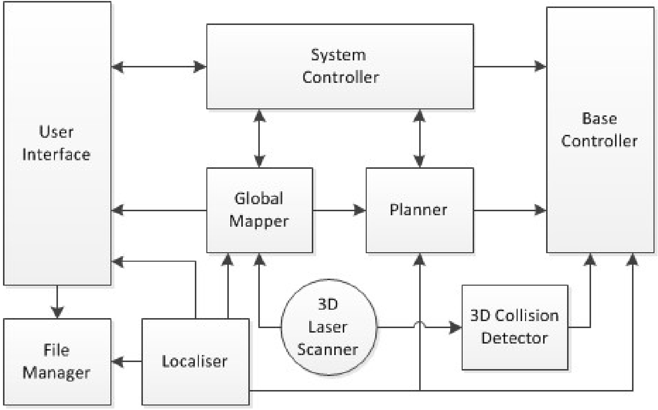


Figure 4 Basic system for 3D exploration and mapping.

Custom software developed to implement the robot systems includes software for localization by odometry, simultaneous localization and mapping (SLAM), path planning, path following control, collision detection and avoidance, and user interface. The basic block diagram for an autonomous 3D exploration and mapping system is shown in figure 4.

Sensors used include 2D and 3D laser scanners, RGB-D cameras, stereo vision camera, inertial measurement unit (IMU), and wheel odometry.

Autonomy requires advanced computing. Resources used include Intel core-i7 CPUs and NVIDIA Jetson family mobile GPUs. The CPU boards run the bulk of the autonomy software and the mobile GPUs run deep neural networks for image analysis and object recognition.

For this work, the robot platforms are typically purchased externally, and computing resources, sensors, and software are added in-house. Examples of robot platforms are given in figure 5. The PackBot 510 robot (figure 5a) has a 3D Velodyne HDL-32E laser scanner mounted on the pole attached at the robot rear. The Pioneer robot, figure 5b, uses a 2D laser scanner and a 3D RGB-D camera.

In addition, research work is performed to push the boundaries of relevant AI technologies, including: a) method development for SLAM in dynamic environments using low-cost sensors [22]; b) path planning using robot kinematic models [23]; c) computer vision and machine learning applied to image and scene analysis [24], d) posture control for a hexapod robot [25]; e) robots for disaster management [26]; f) an overview of robot vision [27]; and, g) image processing towards automated identification of nanoparticles in SEM images [28].

2.2.2 Project Descriptions

A number of experimental systems have been developed. Examples from both themes have been included in the following subsections.

Autonomous Mapping and Inspection

Autonomous 3D exploration and mapping: autonomous exploration and mapping in a GPS-denied environment, typically within a building [29] (see figure 6). The robot has no prior indication of the obstacles in the environment. The operator has a visual display of the robot camera feeds and has control over the three robot operating modes: a) autonomous, where the robot chooses and drives exploration routes; b) semi-autonomous, operator directed with autonomous route selection and traversal; and, c) manual, the robot is operator driven via joystick. The software includes built-in checks to ensure effective operation under unforeseen circumstances such as a failure of communication between the robot platform and the operator console.

Context-Aware Real-Time Action (CARTA): a robot system that brings object recognition capabilities to a mobile robot. It allows the robot to move autonomously within its environment and then take real-time actions when a preselected object is detected. In this case, upon recognising an object of interest, the robot moves to autonomously capture inspectionstyle images of the object from multiple angles. This system uses mobile GPUs and the YOLO software [30] for object recognition.

Multi-robot mapping: autonomous exploration and mapping using multiple robots to cooperatively share the exploration and mapping task. The robots are provided with complimentary exploration goals and combine their mapping scans to determine an overall map of the explored area.

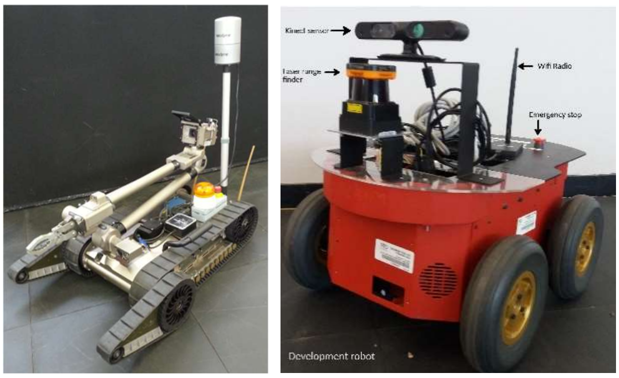
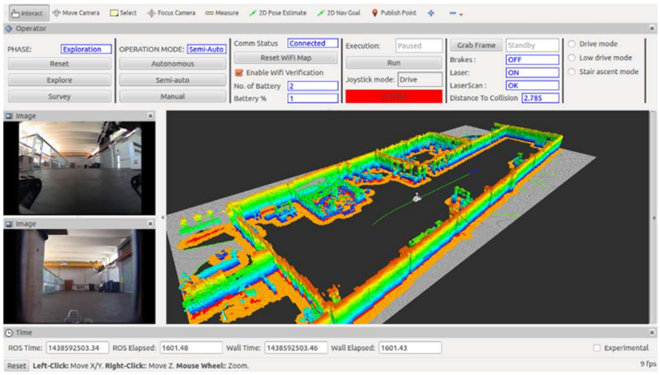


Figure 5 Robot examples: a) PackBot 510; b) Pioneer.



PHASE: Exploration
OPERATION MODE: Semi-Auto
Comm Status: Connected
☑ Enable Wifi Verification
No. of Battery: 2
Battery %: 1
Execution: Paused
Joystick mode: Drive
Standby
Brakes: OFF
Laser: ON
LaserScan: OK
Distance To Collision: 2.785
ROS Time: 1438592503.34 ROS Elapsed: 1601.48 Wall Time: 1438592503.46 Wall Elapsed: 1601.43 ☐ Experimental
Left-Click: Move X/Y. Right-Click:: Move Z. Mouse Wheel:: Zoom.

Figure 6 Autonomous 3D Mapping operator console.

Intelligent Work Cell

The CSIR Hybrid Autonomous Mobile Manipulator Platform (CHAMP): Most of the projects for the intelligent work cell are implemented on the CSIR Hybrid Autonomous Mobile Manipulator Platform (CHAMP), see figure 7. The platform was custom built to fulfil the need for a mobile manipulator in our laboratory. A Barrett Whole Arm Manipulator (WAM) with 7 degrees of freedom (DOF) was mounted on the Powerbot base. The system description can be seen in [31].

Pick and place exercise on CHAMP and in simulation: This code was developed for the intelligent work cell project. The pick and place code can be launched using the Vicon TM Motion Capture System [32] or the Tabeltop object recognition (ork) package [33]. The code can be demonstrated in simulation or on CHAMP.

The objects used for the pick and place demonstration are from the ycb database [34], conforming to other research labs doing similar research.

This project was to identify an item when the user clicks on the item in the User Interface (UI), Rviz [35], to pick up the item and place it in a position chosen by the user.

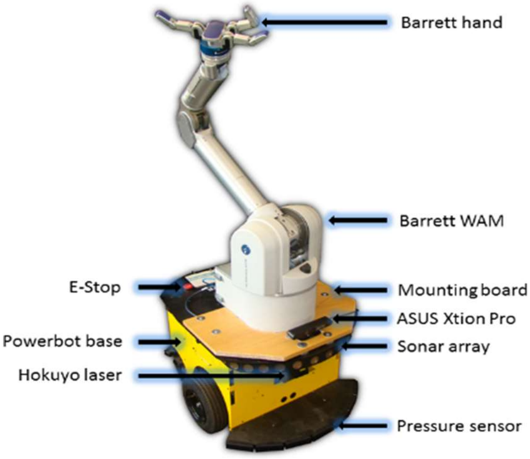


Figure 7 CHAMP robot platform.

CHAMP has been modelled in a Gazebo simulated environment [36]. This allows for safe and quick development before implementation on the platform. See figure 8 for the Rviz display and figure 9 for the Gazebo environment.

In the simulation, the arm can do planning using the MoveIt ROS package [37], but the base has not been included in the planning yet. The base can be driven around manually in the simulation. The base planning with MoveIt will be incorporated in next development phases.

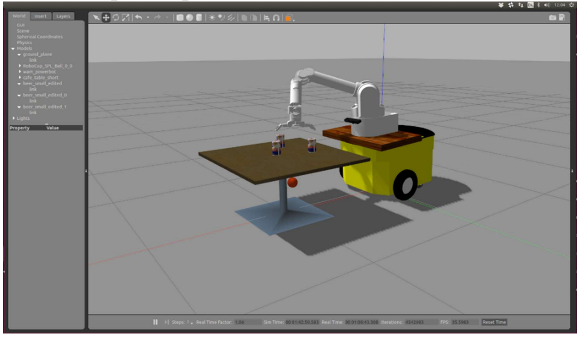


Figure 8 Pick and place performed in simulation, the Rviz display.

Place recognition: This package can identify either the lounge or kitchen space in the Gazebo simulated environment (see figure 10).

The Tensorflow [38] with GPU capability was used for this deep learning model to train on data gathered in simulation. See figure 11 for an example of the results of this convolutional neural network (ConvNet) that was trained using the VGG16 transferred weights.

Kinaesthetic teaching: Kinaesthetic teaching is to carry out a physical activity to demonstrate to a robot how to perform a skill. There are different methods to do this. One method would be through visual demonstration, another would be for a human to physically move the robot according to the required actions needed and a third option would be to use a haptic device as proxy for the robot to follow its movements.

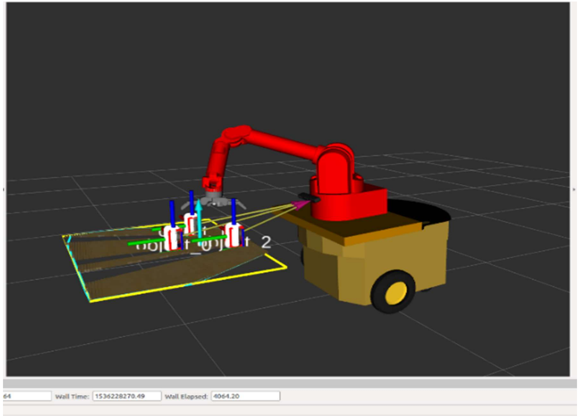


Figure 9 Pick and place performed in simulation, the Gazebo display.

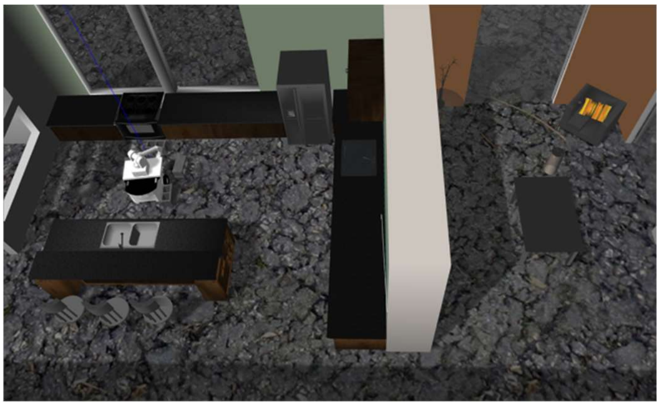


Figure 10 The kitchen and lounge space in simulation.

We chose to continue with a haptic device and the more common field of study and implementation that makes use of such devices is the medical field to perform minimally invasive surgery. The device is used to control actions of the robot platform.

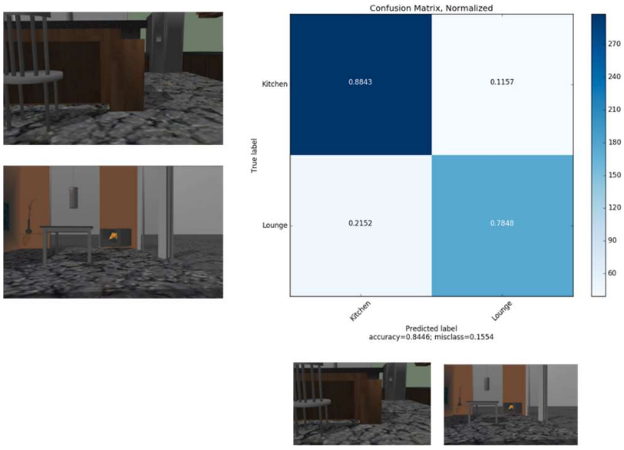


Figure 11 Examples of results for the Convnet trained for place recognition.

The hardware and software have been set up to record and play back the motions performed by the haptic device with the WAM following the motions. The system is ready for higher-level projects to make use of it. See figure 12 for the system setup.

Figure 12 The kinaesthetic teaching setup.

2.2.3 Conclusion of CSIR work

The CSIR is actively involved in software R&D for autonomous robotic systems. For this work, robot platforms are typically purchased and then computing resources, sensors, and autonomy software are added, in-house. Autonomous 3D exploration and mapping, Context-Aware Real-Time Action (CARTA), Multi-robot mapping, CHAMP, pick and place on CHAMP and in simulation, place recognition and kinaesthetic teaching are examples of relevant systems. The CSIR does the custom AI software development along with cutting-edge AI research in mobile, autonomous robotic systems.

2.3 Nelson Mandela University

In recent years, the manufacturing sector has had to explore new and innovative avenues to enhance their productivity to meet the needs of an ever-demanding global marketplace. Business models have thus emerged that aim to harness the potential of technological trends brought about by the fourth industrial revolution. These models principally imply a “mass customization” approach that adopts fully integrated production systems that are both smarter and more autonomous than their traditional “mass production” counterparts. The implementation of new technology, however, always brings with it fresh concerns about the safety and wellbeing of personnel, plant equipment and the environment. This is particularly true within the field of mobile robotics where there is a gradual shift away from driven - towards driverless vehicles. Though such a transition comes with the promise of improved productivity and more accurate and timely deliveries, it also means there is an increased risk of accidents [39].

The observance of standards remains voluntary; however, compliance may be enforced and regulated at a national level by the relevant authorities. Compliance with technical standards is in particular beneficial when it comes to global distribution of robotic technology since barriers to trade quickly disappear. Concerning driverless vehicles, several regional and international standards address the technology including ANSI B56.5-2012, EN1525, EN1526 and ISO3691-4. Chiefly, EN1525, which is a harmonized European standard, deals with the safety of driverless industrial trucks and their systems and can be used to obtain conformance with the Machinery Directive 98/37/EC among other emission and power standards [40]. The Machinery Directive requires manufacturers to define operational limits for their machines, including the stipulation of clear guidelines for use. It also requires them to perform a hazard and risk assessment followed by the implementation of safe design features, technical protective measures and information on residual risks [41].

2.3.1 A safety system for a semi-autonomous industrial Automated Guided Vehicle (AGV)

In this work, a safety system is designed, implemented and tested in order to meet the stringent requirements of the Machinery Directive 98/37/EC. The first step involves the determination of all possible hazards associated with the vehicle according to EN ISO 12100; next, the risk is estimated for each hazard according to IEC 62061 and ISO 13849-1. As an example, figures 13 and 14 depict the risk graphs used to determine the risk associated with one particular hazard - a “head-on collision”. The result of the assessment for this hazard is a required Performance Level - PLd and a Safety Integrity Level - SIL2.

The proposed safety system was designed and implemented through a systematic approach resulting in quality assurance throughout the AGV’s life-cycle. Figure 15 gives an overview of the process that was followed throughout the design and implementation of the system.

The AGV consists of a number of sub-systems, as shown in figure 16. These include a 48V DC power bank and distribution system, a drive system - composed of four identical wheel assemblies each having a 48V Festo stepper motor and drive, a central PLC (S7-1516F PLC) control system that supports Profibus and Profinet fieldbus communication, a LiDAR-based navigation system (SICK NAV350) interfaced to an industrial PC running a ROS node and a SICK safety PLC. Fieldbus communication permits real-time retrieval of data from the sub-systems for the purpose of fault prediction and analysis. To ensure that the AGV is operationally safe, the risk associated with each hazard is eliminated through the implementation of appropriate design and technical countermeasures selected to mitigate each stipulated hazard. Countermeasures include a collision-avoidance system composed of two SICK S300 safety scanners fitted on opposite corners of the chassis. These create a 2D detection field all around the vehicle. The vehicle also features two onboard e-stops, battery enclosure limit switches and one remote e-stop found on the AGV’s wireless control pendant. Misalignment of any of the safety functions results in an immediate stoppage of the robot and diagnostic reporting on the SCADA system.

Beyond external safety features, the safety program on the PLC was designed in a well-structured manner to keep the system’s response time as low as possible and to ensure detection and reaction to every possible hazard. For additional safety and network security, password protection and program signature generation have also been incorporated.

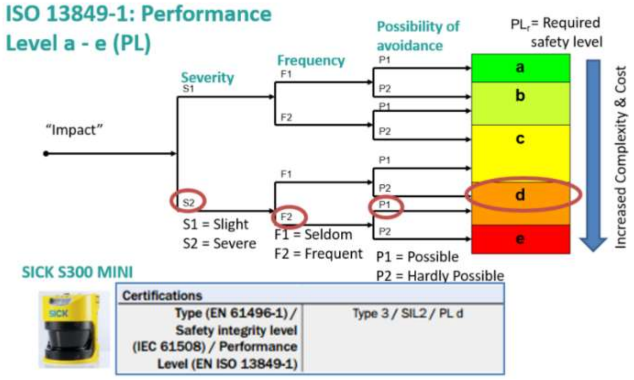


Figure 13 Risk assessment for “head-on collision” according to ISO 13849-1.

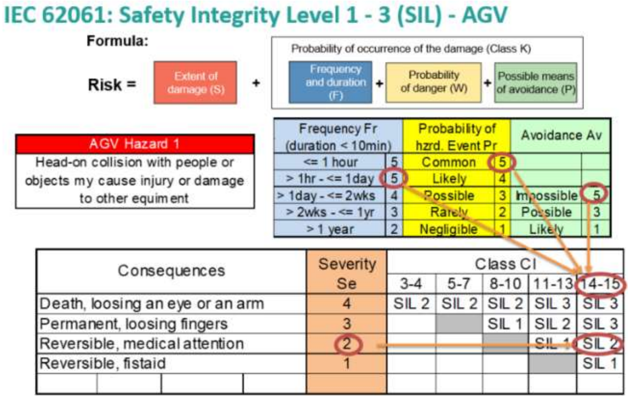


Figure 14 Risk assessment for “head-on collision” according to IEC62061.

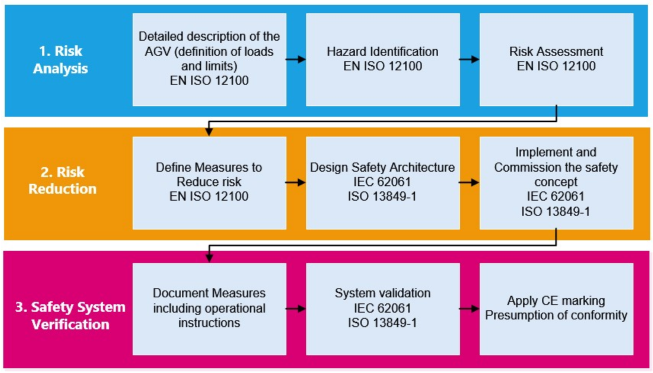


Figure 15 Roadmap for design and implementation of the safety system.

The work furthermore presents a promising technical approach based on a combination of failure modes and effects analysis (FMEA) and fault tree analysis (FTA) to investigate safety and reliability issues in AGVs used in intelligent material handling schemes. The outcome is a dynamic system that can automatically compute fault modes from gathered data and update maintenance schedules for the purpose of preventative or predictive maintenance [42]. The approach also permits the rapid determination of the root cause of system or mission failure due to, for example, mission allocation failure, laser navigation system failure, system failure due to overheating, over-current, wire-breaks, braking system failure and failure of the power system. Lastly, critical to safe operation is the safe re-introduction of the AGV into normal operation mode on start-up. A verification system is thus developed that ensures the integrity of vital robot sub-systems upon vehicle start-up and re-entry into the production process.

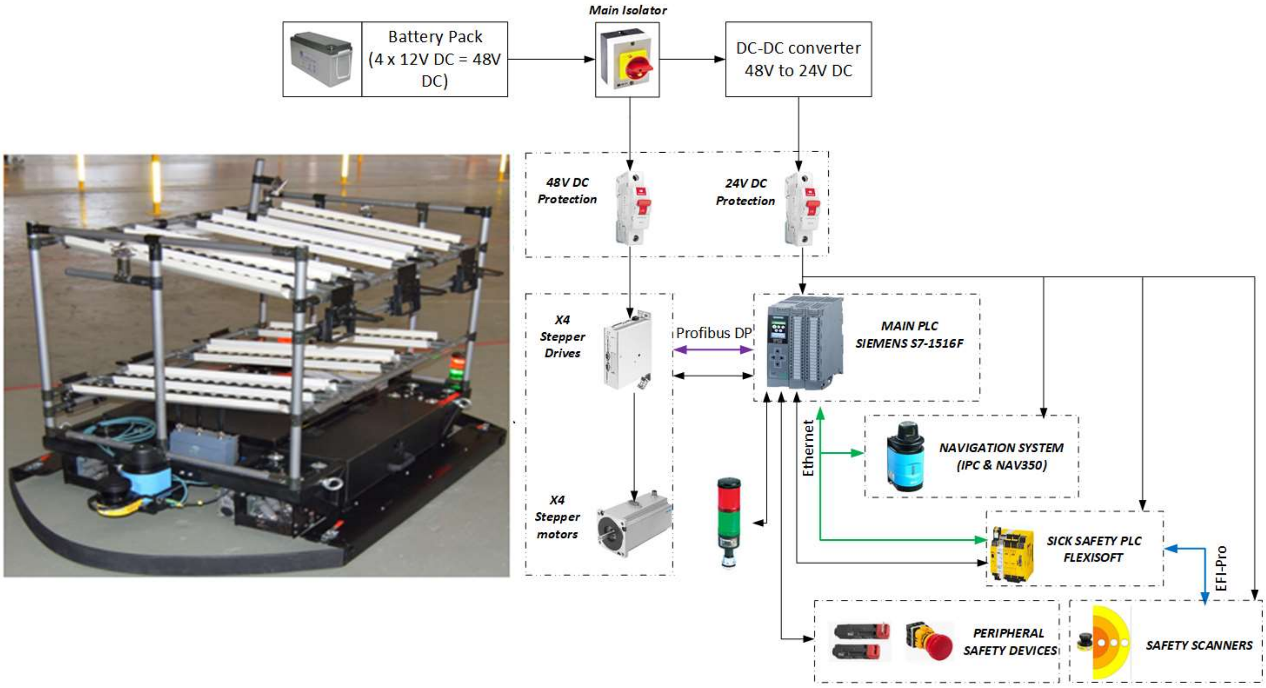


Figure 16 Overview of integrated AGV system.

2.3.2 Conclusion of NMU work

Functional Safety is applicable to almost all areas of industry. This work applied the principles and standards of Functional Safety and reliability analysis in the design of an industrial AGV. The result is a reliable AGV that has an acceptable level of risk and that is ready for deployment in a busy production environment.

This work has been conducted in partnership with the CSIR and the AMTC.

2.4 Stellenbosch University

Robotics are researched in several groups across various departments in the Faculty of Engineering. The groups working on robotics include the Electronic Systems Laboratory (ESL), the Solar Thermal Energy Research Group (STERG), the Biomedical Engineering Research Group (BERG), and the Mechatronics and the Automation and Design (MAD) Research Group. Some faculty members that are not part of these groups also do research in robotics. This paper does not give a comprehensive review of robotics research at Stellenbosch University. Instead, the following subsections highlights some of the theoretical research topics in robotics.

2.4.1 Computer vision

Cameras are becoming one of the primary sensors of mobile robots. They provide rich data sets. Combined with SLAM technology, they can be used for navigation. Especially in GPS-denied environments (e.g. factories, warehouses, underground mines) they can be a powerful sensor. However, metric methods often suffer from accumulation of localisation errors [43], [44]. The alternative is appearance based methods such as FAB-MAP [45], [46], but since they have no metric information, it may be difficult to integrate any metric information. At Stellenbosch University, modelling and experimental work is underway to understand the errors resulting from these methods [47]. These investigations may provide insight into near optimal selection and arrangement of sensors for various applications.

2.4.2 Modern manufacturing systems

The Mechatronics, Automation and Design (MAD) Research Group operates within the Department of Mechanical and Mechatronic Engineering at Stellenbosch University. For the last decade, the MAD group has conducted research into the control and design of modern manufacturing systems. Since 2017, the group's research has focussed on the achievement of the Industry 4.0 (I4.0) vision – a highly connected world of smart systems and humans, which leverages real-world data and the internet to gain insight and add value to business processes. Industry 4.0 relies on the advancement of enabling technologies, such as cyber-physical systems, the Internet of Things, cloud services, and data analytics. Within the manufacturing domain, the role of robotics in Industry 4.0 environments is especially interesting.

Robotics for Industry 4.0

Robotics has been identified as a key enabling technology for the realization of the I4.0 vision [48]. While the contribution has been labelled as "autonomous robotics" or "collaborative robotics" [49], it generally refers to the integrated and intelligent use of robots in production environments. Recent research and development, both in industry and academia, have focused on two issues:

1. "Smarter" robots – related to enhanced robot autonomy in two aspects: the ability to learn and adapt through artificial intelligence; and the support for integration in heterogeneous and dynamically changing environments.
2. Enhanced human-robot interaction – related to the safe and effective sharing of production workspaces and tasks between robots and humans.

The robot digital twin

The concept of the digital twin has emerged as an important structural component of Industry 4.0 environments. While different definitions and classifications exist for the digital twin (e.g. [50], [51]), it can be described as a virtual representation of a real-world entity, to facilitate its integration with digital systems. In the context of Industry 4.0, digital twins offer a mechanism for the integration of the important enabling technologies. The MAD Research Group is exploring two ways in which the digital twin concept can advance robotics towards the I4.0 vision: to provide the infrastructure for advanced analysis, control and integration with other digital systems; and to enable advanced collaboration between robots and humans – as depicted in figure 17.

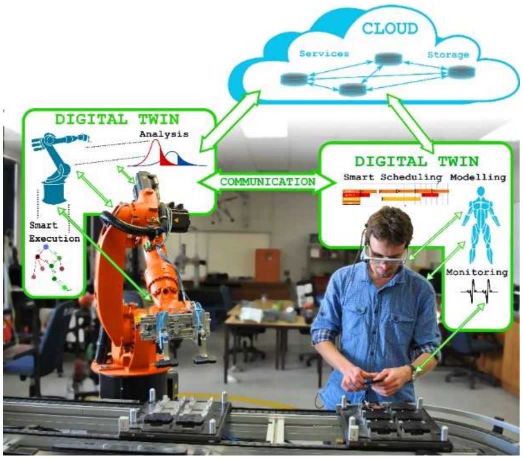


Figure 17 Digital twins for Industry 4.0.

Advanced analysis, control and integration

The digital twin of a robot can utilise, or be used to build an accurate digital model of the physical robot with near real-time sensor and controller data. This digital model can be used for near real-time emulation, remote monitoring, and fault detection and diagnosis. Furthermore, such a model can be used as a basis for analysis – either through data analytics or simulation. Ultimately, the digital twin also provides a mechanism to "close the loop" by adjusting the robot's control processes according to the insight gained through analysis. The MAD Research Group has developed a six-layer architecture for the implementation of digital twins, and performed an evaluation within the manufacturing context [52], [53].

The digital twin also supports the integration of robots by offering a mechanism for digital communication. The digital twin acts as a digital administration shell, which can facilitate communication with other I4.0-enabled system entities. This is critical for the enhanced integration of robots and humans within connected production environments, as is discussed in the next section.

Advanced human-robot collaboration

Collaborative robots (or *cobots*) are industrial robots with built-in safety features that allow them to share their workspace with human workers. These safety features are present in both the robot hardware design and control. Cobots are structurally designed to reduce the risk of potential injury to humans during operation – sharp points and edges, and pinching points are avoided. Cobot controllers typically embed safety features within a specified operation mode. In this mode, the speed of the robot motion is reduced, and force and torque parameters are continuously monitored to ensure they remain below specified thresholds.

While cobot technology has come a long way in ensuring the safety of human workers in the workspace of robots, there still exists potential for the enhancement of human-robot collaboration. For instance, cobots allow for the "safe" collision of robot and human – while this safety is critical, the intelligent avoidance of collisions, and subsequent adjustment of robot motion would allow for more effective collaboration. The MAD Research Group is exploring the use of a collaborative robot digital twin to facilitate intelligent robot-human collaboration.

2.5 University of Cape Town

Robotic manoeuvrability is still incomparable to the locomotion of animals and presents a large impediment to attaining true autonomy. Current robotic systems can adequately perform steady-state (constant velocity) motions such as walking and running but are unable to accelerate to high-speed on unsteady terrain as will be required for future, time-critical missions such as search & rescue.

The Rapid Acceleration and Manoeuvrability (RAM) Group in the Mechatronics Lab at UCT utilises mathematical modelling, sensing, trajectory optimisation and mechanical design to understand transient locomotion in animals and robots. This work has illuminated the various mechanical factors which limit performance of legged systems as well as the constraints current control algorithms impose on the development of highly agile robots.

2.5.1 Motion Capture

In the spirit of bio-inspired robotics, the RAM Group has selected the cheetah (Acinonyx Jubatus) as a model animal to study the biomechanics of legged manoeuvrability. However, the biomechanics of this animal was scarcely studied as most work was done at constant velocity [54]. Further, the hunting behaviour which contains large accelerations has only been studied at a macro level using GPS collars [55].

In order to obtain more information about the kinematics of the cheetah spine and tail, we have developed a novel harness-based motion capture system [56]. The system contains a stereo camera pair, as well an IMU/GPS system which are combined with a 3D kinematic model using an Extended Kalman Filter. The output is depicted in figure 18. This system, though successful, is still quite invasive for the animals. More recently, we have employed high-speed cameras in conjunction with a Deep Learning neural network (Deeplabcut) to provide 3D skeletal information from cheetahs without the need to place markers on the animals [57]. The operation of the network is depicted in figure 19.

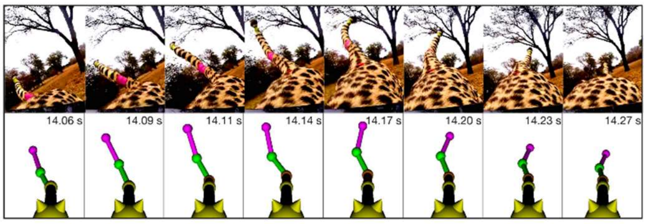


Figure 18 The harness-based system fuses camera, IMU and GPS data to the kinematics of the cheetah tail and spine [56].

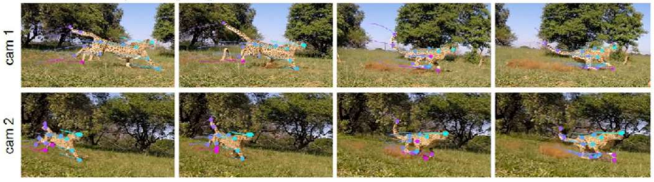


Figure 19 The Deep Learning algorithm (Deeplabcut) detects the cheetah from six different views, and these are fused to create a 3D skeleton [57].

2.5.2 Trajectory Optimization

The locomotion of animals has for several years been described using optimal control. This has resulted in interesting works which study a range of topics from energy economy in humans [58] to various gaits for steady-state locomotion in quadrupeds [59]. However, rapid manoeuvres represent a significant departure from these previous works due to two main factors: aperiodicity and contact-schedules. Firstly, the transient nature of the motions such as acceleration, gait termination and turn initiation breaks the assumption of periodicity, which makes the problem size larger and more complex. Secondly (and most importantly), these motions do not rely on a fixed gait pattern (eg. heel, toe and then swing) which can be easily scheduled as done in previous work [60].

Contact-implicit trajectory optimization is one method which includes the contact-mode schedule as part of the optimisation formulation [61]. These methods have enabled us to study rapid acceleration in quadrupeds [62] and rapid deceleration in biped robots [63]. However, these methods rely on a first-order integration scheme which limits their use for short-time horizon problems. More recently, we have increased the accuracy of these methods using orthogonal collocation [64], which has enabled the optimization of large, long-time horizon trajectories [65] as depicted in figure 20.

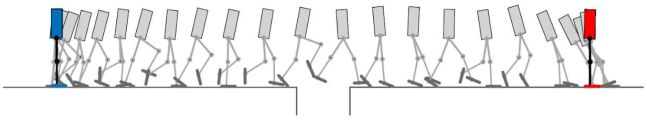


Figure 20 A bipedal model is optimised to generate a motion starting and ending at rest without specifying contact order [64].

2.5.3 Mechanical Design and Morphology

Animals employ a diverse array of morphologies such as specialised legs, actuated spines and tails to perform agile manoeuvres. With this realisation, what should the future agile robotic platforms look like? Should we be blindly emulating animal morphology through mechanical designs? Our group opts to first understand the underlying mechanism in animal locomotion before applying it to robotic designs.

The cheetah characteristically flicks its lengthy tail during rapid manoeuvres and similar motions have been shown to stabilise high-speed turns [66] and rapid accelerations [67] in a wheeled-robotic platform (Dima). Using the aforementioned trajectory optimization methods, we investigated the optimal design for quadruped spines when rapidly accelerating [68] and leg bend direction for rapid manoeuvrability [69]. These methods have also informed the design of a novel biped robot (Baleka) specifically developed for rapid acceleration as depicted in figures 21 and 22 [70].

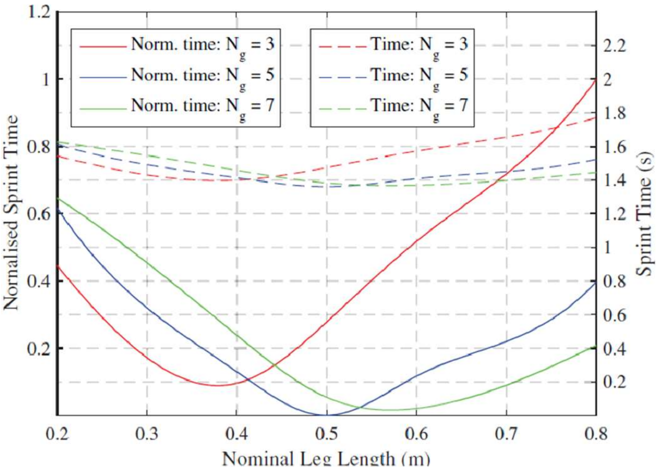


Figure 21 Extensive trajectory optimization of a rapid acceleration and braking manoeuvre was employed to inform the design of the robot's drivetrain [70].

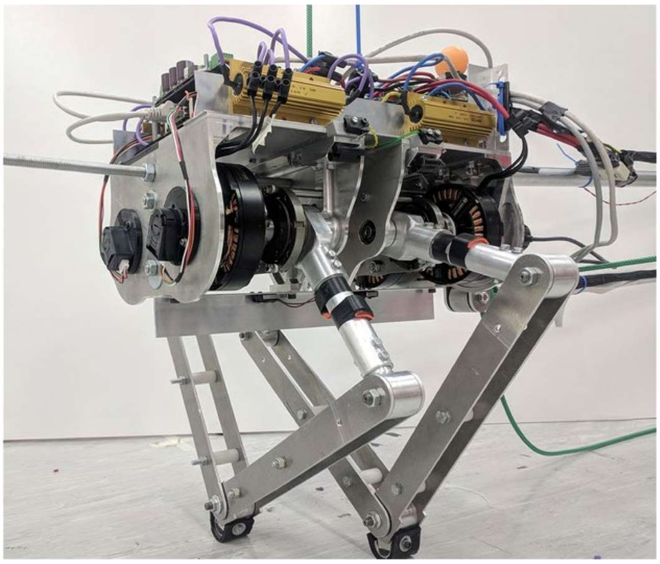


Figure 22 The completed bipedal robot, Baleka.

2.6 University of KwaZulu-Natal

The research that has been pursued more recently has been in line with the vision of the Robotics Center, an initiative under the Robotics Association of South Africa (RASA). The research being pursued has purpose and application. Even though there is theoretical research being pursued, this research is included in the applications. Therefore, the research is elaborated in the "Applied Research" section.

2.7 University of the Witwatersrand

The robotics research agenda at the University of the Witwatersrand is largely interested in questions pertaining to robots learning and acting under uncertainty. Specifically, we focus on designing and learning robust representations of both actions (in the form of skills) and state (in the form of abstract symbols).

Towards robustness, we are also largely motivated by the idea of lifelong learning, in that we want systems that are able to continuously accumulate more knowledge and improve performance as they encounter growing numbers of tasks.

The research conducted in this area falls into three primary themes, loosely organised around different levels of abstraction in robotics: motion planning, learning and control, and high-level reasoning.

2.7.1 Motion Planning

Our work in motion planning has focused on rapid replanning in the case of failures, as may be the case when operating in a stochastic environment. To this end, our methodology has involved learning topological representations of the environment, and using this with a form of probabilistic roadmaps to allow for switching between classes of trajectories [71].

In addition, we are currently exploring questions around planning in constrained environments, where constraints could be specified in a combination of task and joint spaces.

2.7.2 Learning and Control

The core of our robotics research pertains to learning in robot systems. Here our work has drawn mainly on ideas from reinforcement learning with a focus on learning knowledge that can generalise across tasks and environments.

A key component of generalisation is the acquisition of skills that can be invoked by a robot in later tasks. A common paradigm for this is learning from demonstration, where a demonstrator such as a human provides multiple sample trajectories from a skill to be learned, and the skill learning is often done via inverse reinforcement learning. We have proposed a new framework, non-parametric Bayesian reward segmentation, which allows for a much more intuitive version of learning from demonstration, where the human is able to demonstrate long sequences of multiple tasks, and the algorithm learns to identify and segment multiple skills from these trajectories [72] (see figure 23).

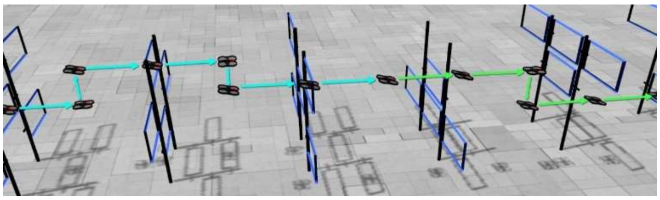


Figure 23 Segmented skills in demonstrated drone trajectories.

Having acquired skills, it is useful for these to be shared across multiple robots. This is challenging when different robots have different morphologies. As a result, we have explored algorithms for transferring skills between robots, by learning abstract latent manifolds describing the capabilities of these robots and using those spaces for skill transfer [73], [74].

Instead of learning skills, another approach to knowledge transfer is to learn the dynamics model of an environment and reuse this to predict how that environment will respond to different actions. This is known as model-based learning, and allows for planners to be subsequently run to solve the task at hand (see figure 24). In this space, we have developed an approach to model learning with Gaussian processes, that allows for rapid task solution when combined with model predictive control methods, even in constrained environments [75].

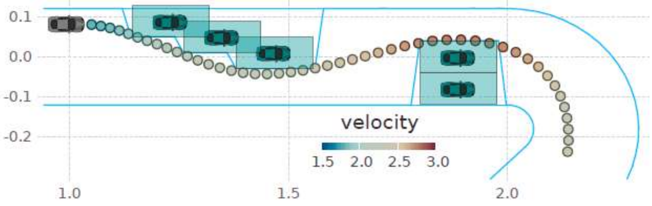


Figure 24 A learned model-based planner is able to avoid novel obstacles.

A final important aspect of learning is how to deal with situations where the robot does not have access to the full state of the environment, specifically the state of mind of a collaborating human (figure 25). In this setting, we have developed approaches based on partially-observable Markov decision processes to infer a proxy for the mental processes of a human in the same workspace as the robot, and use this to improve the manner in which the robot interacts [76], [77].

Figure 25 Simulated human-robot collaboration task.

2.7.3 Reasoning

Having learned a set of skills for operating in some environment, or a more general description of the environment dynamics, one could then use a planner to produce an optimal plan for solving a task in that environment. However, planning in the space of raw inputs is typically intractable. As a result, we propose to learn portable symbols as a high-level abstraction of the raw state space [78]. These can be transferred to new problems, and greatly simplify the problem of planning.

This is a specific case of the more general problem of learning symbols which can be used to facilitate higher-level reasoning in robotic systems [79].

3 Applied research

This section reviews research done on industrial projects. The research is being applied to projects or will be applied to projects in the near future.

3.1 SEAHOG

SEAHOG (see figure 26) has a mass of 80 kg, is tethered, can descend to 300 m, and has five thrusters – one for descend and ascend, and four for horizontal linear and rotational movement. Its five thrusters are magnetically coupled and are BLDC motors with bought-out controllers, it contains three sets of lights, a camera and an ultrasonic transducer. The cover acts as a protection device and also renders the SEAHOG slightly positively buoyant [80].

Various types of Kalman filters have been evaluated on it. Its simulation and control systems design were done with MATLAB. SEAHOG is the third generation of underwater robots developed at RARL in UCT.

A difficult issue when dealing with the kinematics of an underwater robot is the concept of added mass and moment of inertia. The added components are due to water being dragged along while the robot is moving. Although formulas are available for simple shapes, they were found to be too inaccurate. Better results were obtained by doing measurements of periods on a small-scale model fixed to a pendulum swinging in a large enough water tank so that there were negligible boundary effects.

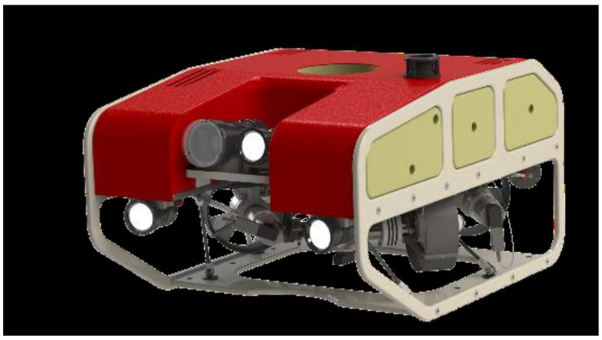


Figure 26 The SEAHOG is an underwater robot developed at RARL in UCT.

3.2 A hexapod robot

This robot went through multiple revisions running on ROS and LabVIEW, but today's version is controlled by a STM32F4 micro-controller (see figure 27). The older versions could display multiple gaits and could grip various objects by switching over to a four-legged gait which frees up the remaining two legs for use as manipulators [81]. It contains three Dynamixel servo motors for angle control per leg, thus 18 in total. The motors use a function called sync write. It allows for broadcasting a serial command to all the motors at once, which allows them all to be controlled simultaneously. Inverse kinematics and dynamics were calculated using MATLAB and implemented in real-time in object-orientated C++ on the micro-controller to control the position of the feet. A path generation algorithm was developed to allow for smooth walking motion. A platform in the centre of the hexapod is PID controlled to remain level in both pitch and roll while the slope it is walking on varies in angle. The robot can be remotely controlled and has batteries so that operation is possible without any external wiring or cabling. Even charging of the batteries is done wirelessly by walking the robot to a wireless charging station, and accurately positioning it.

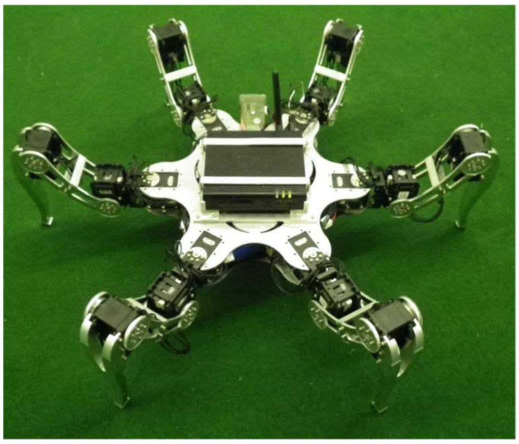


Figure 27 A hexapod designed and built at UCT.

A complex component of the design of this hexapod was the interfacing of multiple different serial communication devices (Motors, IMU and remote) and communicating with each of these high-speed devices simultaneously. This was overcome by using the DMA capabilities of the STM32F4. This allows the main CPU to continue its operations while the DMA performs the sending and receiving of serial data. The DMA then notifies the CPU at the completion of a task through receive and transmit complete interrupts. Using DMA allows for fast communication with all devices with a minimum amount of data being lost.

3.3 A throwable rescue robot

It was developed as the efforts of three Master's projects. Initially work in RARL was focused on a larger robot that could navigate over rough terrain easily, could communicate with trapped victims and use a multi degree of freedom arm to perform complex tasks. This robot was called RATEL. However further investigation around the topic suggests that these larger robots have limitations in disaster sites. They are large, heavy and very complex. They often do not fit into the small voids created by collapsed buildings. To address these and other issues a project was begun to design a low cost, man-packable, throwable rescue robot called SCARAB (see figure 28). This tiny robot can be used by research institutes, police forces, rescue operators, armed response and firefighters for anything from victim location to surveillance. It was designed to carry a variety of sensors, such as microphones, headlights, optical and thermal cameras, and temperature sensors into environments that are too dangerous or confined for human workers [82]–[84].

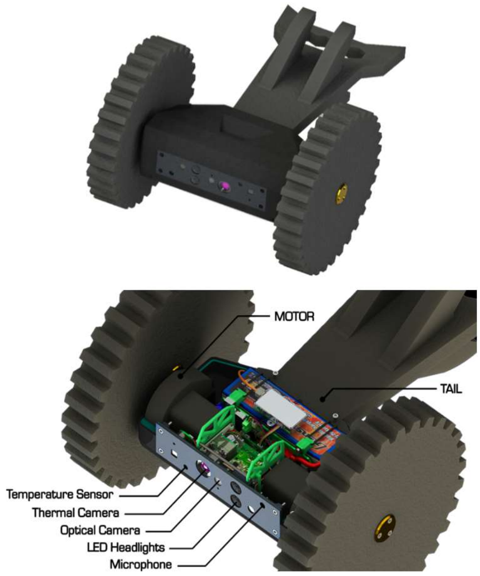


Figure 28 A rendering of the SCARAB, a throwable rescue robot.

3.4 A two-axis stabilized platform forming part of a tracker

This fits in with Robotics because stabilized cameras are often essential requirements for robots. It contains a camera mounted on a two-axis gyro-stabilized platform for good base motion rejection and whilst automatic tracking of celestial objects is achieved [85] (see figure 29). Its simulation, containing 6 DOF geometry and dynamics, and control systems designs, were done with Simul_C. The implementation was done on a STM32F0 micro, programmed in C++. LabVIEW was used to create a user interface with graphics to present the orientation of the tracker and essential system information.

A remote-controlled vehicle is used to test the base motion rejection of the stabilized platform to a limited extent. It is done by mounting the platform on the vehicle and then steering the vehicle at controlled speed along a pre-determined path with bumps to generate specific base motions. An IMU is part of the vehicle so that the achieved base motion can be measured. By comparing the sightline stabilization and the tracking accuracy with the applied base motion, the performance of the stabilized platform and its tracker can be evaluated. Alternatively, very expensive rate tables would have been required.

A challenge that was required to be overcome in the control system development of the stabilized platform was the gimbal-lock situation encountered when the pitch platform mounting the camera is oriented to point straight upwards. In this orientation, a loss in control action of the yaw DOF during target tracking is experienced when the target moves in a direction parallel to the pitch rotation axis. This was solved by causing the yaw gimbal to rotate by 90° when this condition is experienced in order to regain tracking control of the system. In the next subsequent occurrence of this condition, the yaw gimbal is then rotated by -90° to regain tracking control.

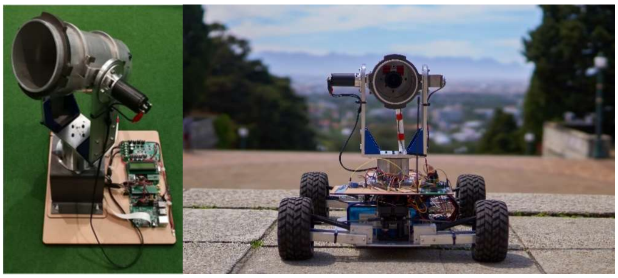


Figure 29 The tracking mechanism can be fitted to a variety of platforms.

3.5 Power line inspection robot research

A power line inspection robot has been developed through a collaboration between University of KwaZulu Natal, Eskom (the South African electricity utility), and more recently University of Cape Town [86]–[91]. The project has spanned academic research across a large range of disciplines through to commercial realisation of the robot. The robot (see figure 30) rolls along the conductor and then gets around obstacles by gripping on the conductor with one arm while the other navigates around the obstacle. The patented gripper arrangement allows the robot to use a hybrid of rolling and gripping as required.

Figure 30 Power line inspection robot navigating around a damper on a 132 kV line.

The initial work on the power line robot was focussed on innovative mechanical design, optimised to overcome obstacles such as vibration dampers, suspension clamps and spacers on typical transmission lines (that is 220 kV and above). At these voltages, electrical clearances are large (although many of the obstacles are also large). Of special interest is that the robot can navigate over jumpers at strain towers where the line changes direction or needs to be kept under strain such as at the line end (see figure 31). (Navigating over suspension clamps at suspension towers is relatively easy.) Because the robot rolls along sections of line that are clear of obstructions at speeds of over 1 m/s, the average inspection speed per span is kept low. During the research phase of the project, work was done on autonomous navigation around obstacles, image processing for component and line identification as a future aid to navigation and inspection, state estimation and design for energy harvesting from the line. At the same time, a software operating platform was developed, and many laboratory high voltage tests (up to 140 kV, figure 32) were conducted to support the design work.

Figure 31 Power line inspection robot climbing from a jumper to the main line on a (220 kV) strain tower.

This project has developed past the “innovation chasm” and is now at a high level of technology readiness (TRL-8). The robot has been demonstrated on live lines and out of service lines in South Africa as well as in New Zealand (out of service 220 kV) and Japan (Training Centre lines). The robot is placed on a live line either by driving along a hot stick from a tower or by manual placement from a bucket truck (figure 33). In order to make it easy for a linesman to handle the robot during deployment and to reduce power requirements, a lightweight version of the robot has been developed. It has carbon fibre arms and body, harmonic drive gearboxes and other innovations to get the total weight below 8 kg. Another pre-commercial innovation is the development of machine learning algorithms to solve image processing problems.

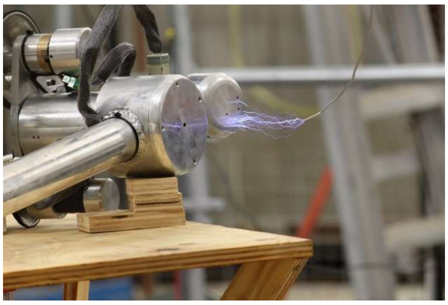


Figure 32 High voltage testing of components.

Figure 33 Manual, live-line placement on 80 kV line from a bucket truck.

3.5.1 A brachiating line inspection robot

What started out as post-graduate research project at the University of Cape Town into swing-up control and brachiation has the potential to be an alternative approach to industrial power line inspection robotics [92], [93]. One of the constraints of the commercial power line inspection robot discussed above is that it must be able to apply enough torque on the attached gripper to allow the robot’s end effector to reach around obstacles in a static manner. Design innovations to reduce the robot’s weight greatly reduce this problem, but a brachiating robot avoids it altogether. A brachiating robot (figure 34) has been designed, built and tested in the laboratory. It has grippers with a half pulley on each side of the gripper as shown in figure 35. When the gripper is closed, the half-pulleys are joined and form a wheel that allows the robot to roll (i.e. drive) along unobstructed portions of the line. Brachiating manoeuvres are only required to overcome obstacles on the line. Currently, research includes feedback design for reliable swing-ups that are robust against uncertain friction, disturbances and other uncertainties, and techniques to swing out of plane to allow the robot to navigate around corners rather than only on straight lines.

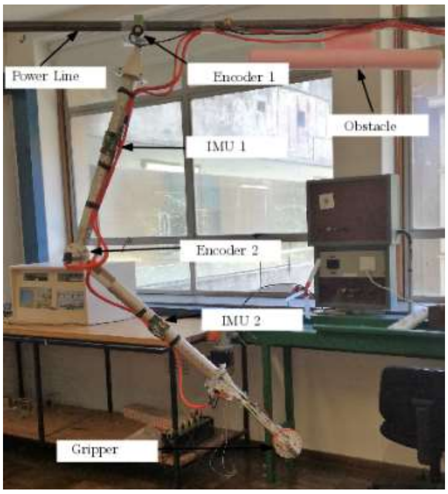


Figure 34 Laboratory prototype brachiating robot.

Figure 35 Brachiating robot gripper/pulley.

3.6 Autonomous marine vessels

The University of Cape Town has undertaken research projects in autonomous marine vessels. These projects have included underwater robots as well as initial projects into the understanding of wave powered surface vessels (the WaveGlider). The WaveGlider employs an underwater component (the glider) that is tethered to a surface vessel (the float). The glider has hydrofoils and vertical motion of the glider as a result of waves results in hydrodynamic forces that propel the vessel forwards. A detailed, three-dimensional model of this coupled system has been developed and studies towards detection of local wave conditions based on IMU data have been undertaken. In addition, local communications for platoon operations of multiple autonomous vessels has been investigated – because of the low antenna heights, the stochastic behaviour of waves between two vessels limits the line of sight and this effect has been characterised.

3.7 Servicing heliostat fields with multirotors

Concentrated solar power (CSP) plants can provide clean electricity and process heat. CSP technologies focus solar rays onto a receiver that contains a working fluid like heat transfer fluid, molten salt or ceramic particles. The working fluid is used for industrial heat, or it can generate steam for a steam turbine that drives an electric generator. CSP is an attractive renewable energy technology because it is possible to store heat which can then produce electricity or provide process heat on demand.

Two CSP technologies are commonly used, the parabolic trough and the central tower with heliostat field (see figures 36 and 37). The working fluid in a parabolic trough plant can reach temperatures up to 460°C while temperatures up to 900°C are possible in a central tower plant.

South Africa has four parabolic trough plants that generate a total of 400 MW of electricity. There is one central tower plant in operation near Upington that produces 50 MW. A 100 MW central tower plant is under construction near Postmasburg. Although there are only a few CSP plants in South Africa, there are many in operation worldwide. The installed capacity of CSP plants in 2018 worldwide was just under 5.5 GW [94].

Figure 36 A parabolic trough mirror.

Figure 37 A central tower surrounded by heliostats.

The central tower plant consists of a heliostat field of tens of thousands of heliostats. The heliostats track the sun during the day to keep the reflection focused on the central receiver. Since there are thousands of heliostats reflecting onto the same receiver, it is very difficult to measure the position of a particular heliostat's reflection on the receiver. Therefore, heliostats are controlled by open-loop controllers. High tracking accuracy with an open-loop controller requires a stiff support structure with accurate and backlash-free drives, and an accurate mathematical model of the heliostat. The process of finding an accurate model for an individual heliostat is called calibration.

Heliostats need to be inspected, cleaned and calibrated quite often. Multirotors are ideally suited for these tasks. The Solar Thermal Energy Research Group (STERG) at Stellenbosch University is therefore researching these applications.

STERG has identified three areas that need to be researched before multirotors will be able to effectively operate in CSP plants. The areas are:

1. long flight times,
2. accurate position estimation, and
3. obstacle detection-and-avoidance.

3.7.1 Long flight times

One of the challenges of using multirotors is the limited flight time. Battery-powered multirotors have flight times that typically range from 20 to 50 minutes. STERG is investigating ways to increase the flight time. A study has been done on using hydrogen fuel cells to power multirotors [95]. The study showed that flight times of 2 to 3 hours is possible for a multirotor that weighs 10 kg.

3.7.2 Accurate position estimation

A multirotor does not estimate its position very accurately, at least not to the level required to calibrate a heliostat. Heliostat calibration requires the drone to measure its position (north, east and altitude) to centimetre level accuracy. At the moment, the altitude estimation of the multirotor is limiting the calibration accuracy of a multirotor based system.

Barometers are most often used to estimate altitude, but they do not provide the required accuracy. Air pressure changes with time as the weather changes. Changing weather can cause a pressure trend of more than 1 mbar per hour. This results in the altitude errors of up to 8 meters per hour.

A differential GPS can with reasonable accuracy measure the north and east position of a multirotor, but it provides poor altitude accuracy. The altitude accuracy of a standard GPS is around 20 m, while it is around 9 cm for a differential GPS. The accuracy of a differential GPS is at the limit of what is required for heliostat calibration with multirotors. The altitude measurement inaccuracy can be offset to some degree by using more calibration points.

There are usually practical problems when using other common altitude measurement techniques in a CSP plant. For example, it is difficult to use sonar or LIDAR to measure altitude, as the multirotor may be directly above the ground or directly above the facet of a heliostat, which can be several meters above ground level.

STERG is investigating ways to improve state-estimation of multirotors in general, with a focus on altitude estimation. The group considered gyro-free inertia measure units [96], [97] to improve state-estimation, and sensor fusion [98] to improve altitude estimation. Preliminary results show that fusing data from the barometer and GPS may improve the altitude estimation of a multirotor.

3.7.3 Obstacle Detection-and-Avoidance

The multirotor needs to reliably and robustly detect and avoid obstacles. A CSP plant does not normally have any obstacle in the space above the heliostat field. However, obstacle detection is still necessary, as the multirotor may encounter birds or a service vehicle, like a cherry picker.

In this area, STERG has looked at obstacle detection with a 2D-LIDAR system and obstacle avoidance and path planning with a vector field histogram [99] and with a virtual force field [100].

Another research project investigated the optical flow for obstacle detection [101]. The work showed that obstacle detection is possible with obstacle flow in a simulated environment. This now has to be tested in the real-world.

3.8 University of KwaZulu-Natal

The following research topics have been industry-related research topics that have been in collaboration with other institutions in South Africa.

3.8.1 Accident Investigation

Even though most of the accident investigation research that was explored was more mechanical orientated, there was some research that expected robotic systems. This research has been in collaboration with Accident Specialist and the CSIR. Initially, a vehicle simulator to replicate vehicle motion was designed and developed [102], to allow for kinematic and motion analysis on a software simulator package. Further research allowed for remote control of a sedan into a truck trailer at 100 km/h were considered [103], to identify the damage to the vehicles and platforms, often required for accident reconstruction scenarios. This research resulted in the design and development of a remote control minibus, which was a world first scenario to initiate an accident with the use of autonomous turning manoeuvres to induce the vehicle to be out of control [104]. As part of this minibus platform, low cost dummies were developed to allow an autopsy [105], to record the motion of the dummy's and which allowed for a comparison with the motion of the vehicles [106]. The control mechanism with a dummy is seen in figure 38. A full demonstration video of the tests conducted can be viewed at [107].

Figure 38 Minibus steering control system with a dummy being tested.

3.8.2 Remote Piloted Aerial Systems (RPAS)

RPAS, drones or unmanned aerial vehicles (UAVs) have been a recent research area being considered for different applications. From the development of first principles for flight, control performance [108]–[110] and the development of an optimized vision system for victim identification [111] have been explored. With South Africa being the first country to implement regulations and RPAS licenses that were required [112], collaboration with industry sectors such as ProWings and Starlite Aviation were pursued. Further research has been explored with a dual rotor UAV [113], which showed to have complex control aspects to consider, yet the performance-power comparison was considered. Neural network stability control systems have also been implemented to be used on various RPAS platforms [114]. Research collaboration has been explored with Nelson Mandela University, which has also initiated the Autonomous Operation Group, an RPAS research unit at the institution. The stability control simulations have been tested using X-Plane, where stability has been reached in the maximum harsh weather conditions, with an error of less than 2° fluctuation. The tests conducted to observe the airflow and aircraft manoeuvrability can be seen in figure 39.

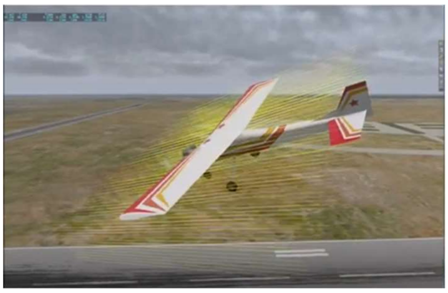


Figure 39 Airflow and aircraft manoeuvrability being tested on X-Plane.

3.8.3 Inspection and Search and Rescue Operations

Inspection and search and rescue operation robotic systems have similar requirements and expectations. Due to the similarity, both of these research avenues have been explored. These avenues being discussed are above the inspection in the manufacturing environment [115], and gas concentration identification [116], [117]. Automated ground vehicles (AGVs) research [118] also allowed for the integration into search and rescue operations.

The vehicles could be of the land, water or air domain. The air domain is discussed in more details under the industrial projects, while the other domains are considered here. The Contractible Arms Elevating Search And Rescue (CEASAR) robot was designed and developed [119], [120], which identified ways to improve communication with the platforms [121] and furthermore identified a means to communicate between robotic platforms [122], prior to the Industry 4.0 focus. Gas danger, concentration identification, with fuzzy logic models [123] were developed for both inspection and search and rescue operations. The models used to identify dangerous gases have the use to be incorporated into equipment used for underground mining purposes. Research has also been explored with underwater vehicles [124], which have many similarities to aerial vehicles. Above water (surface) vehicles have also been explored for search and rescue operations [124], which are being further developed for inspection purposes. Figure 40 shows the Silver SHARK (Solar Hydro Autonomous Research Kruiser), which is being developed for autonomous missions.

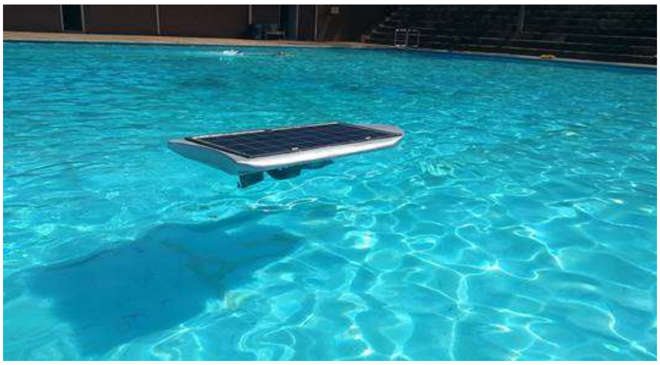


Figure 40 The Silver SHARK being developed for autonomous missions.

3.8.4 Bio-Mechatronics

Different bio-mechatronics research topics were explored, some of which were considered for inter-university collaboration and education. The research progression from exoskeleton systems [125], and the development of new electrodes to be used for electroencephalography (EEG) [126] have been explored, resulting in research being pursued with prosthetic devices.

The initialization of the low cost prosthetic hand research were explored with the Touch Hand 1 [127]–[129], which even though it was a rough design, it had technology being explored into it which consist of a control system from electromyography (EMG) system, with haptic feedback system to the user by means of vibration [130]. The Touch Hand 2 was explored [131], which had a better look compared to the Touch Hand 1, but it was found that the cable driven system had performance issues too [132], [133]. To improve some functionality, the Touch Hand 3 was developed, with the focus at the time on the EMG control methods [134]. The Touch Hand 3 was used as the conceptual hand for the UK collaborators to test embroidery electrodes that they were developing [135]. After this, the Touch Hand 4 was developed, with the focus of functionality, and grip requirements, to make it possible to participate in the 2020 Cybathlon Prosthetics Olympics. For this system, the kinematic models integrating with the CAD models were optimized. Research collaboration has been explored with Nelson Mandela University where the Touch Hand 4 and EMG control is being further developed. Figure 41 shows the Touch Hand 4 being tested by an amputee. Further tests performed and the design process can be seen in a video [136].

Figure 41 The Touch Hand 4 being tested by an amputee.

4 Conclusion

The paper reviews the research done in robotics at various research institutions in South Africa. A great variety of topics are researched. There is a good spread of theoretical research into topics like SMART-manufacturing; multi-robot exploration and mapping; the design of AGVs according to standards of functional safety and reliability; modern manufacturing systems; robotic manoeuvrability; and robots that learn and act under uncertainty.

It does not appear as if there are any research themes that are common between institutions. However, several research institutions explicitly relate their work to Industry 4.0. A few research institutions are looking into ways to integrate robotics into the South African context. One approach to do this is to augment human capabilities with robotics. In this regards, one research group aims to create a workspace in the manufacturing sector where humans and robots can work side-by-side, instead of robots replacing humans. This is a constructive idea in a country that needs to create more low-skilled jobs.

Much of the applied research done by South African research institutions are on projects that are relevant to South Africa. This can be expected, as funding for applied research is often given to address relevant and local problems. Along this line, the following projects are underway or have recently been completed: power line inspection using a robot; accident investigation; and search and rescue in mines and at sea.

South African institutions also work on robotics projects that are of interest to the international community. These include an underwater robot; a hexapod robot; a throwable rescue robot; a two-axis stabilized platform for tracking; autonomous marine vessels; multirotors that service fields of heliostats; and bio-mechatronic projects.

The South African robotics community is a loose and organic community. Each research institution sources its own funding and collaborates with other institutions as necessary. There is not a single structure that coordinates the research efforts of the institutions or that sources funding for strategic projects. It might be beneficial to have such a structure. However, the community has several platforms where it can regularly meet and collaborate. There are regular summits and local conferences on robotics. The RobMech conference is usually well attended. Furthermore, the Robotics Association of South Africa maintains active mailing lists to promote multi-disciplinary and robotics education, research, and collaboration within South Africa.

The review highlights the variety of robotic topics that are researched in South Africa. It shows that robotics research is active and balanced between theoretical- and applied research.

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