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Strategies for the trade-off of Scientific Goal Achievement vs. Robotic Survivability in Extreme and Hostile Environments

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Chapter 1

Background

1.1 Introduction

In 2006 it was confirmed that, since 2004, the Greenland ice sheet has been receding at an accelerated rate, possibly due to the effects of global warming, of -239 ± 23 $\text{km}^3\ \text{yr}^{-1}$ compared with an average of -80 ± 12 $\text{km}^3\ \text{yr}^{-1}$ between 1997 and 2003 (Chen et al., 2006). Such acceleration of the Greenland ice sheet, alone, is resulting in significant increases in run-off meltwater which, in turn, is estimated to be contributing to sea level rise by approximately 0.57 ± 0.1 mm yr^{-1} (Ringot and Kanagaratnam, 2006). Glaciologists and Environmental Scientists, including those at Aberystwyth University, have a significant interest in determining the mechanics of such ice sheets and the extent to which global warming is affecting their rate of recession. In order to model successfully the movements of glaciers and ice sheets, data is needed regarding the physical structure of the ice and the meltwater channels under the surface. Currently, such data is gathered manually by teams of scientists during the early melt-season on the Greenland ice sheet, mainly using ground penetrating radar, and during the summer months at the calving-fronts of glaciers using swath bathymetry and terrestrial laser scanners.

In addition to the financial costs involved when sending teams of scientists to such remote, Arctic areas there are significant dangers and hazards for any human expedition, both at the calving-fronts of glaciers and on the ice sheet, such as the extreme temperatures, meltwater moulins, crevasses, rising and falling ice, etc. Robots are ever more being used for the surveying of such extreme environments; however, they bring their own problems such as the requirement to navigate and avoid obstacles including crevasses and sastrugi, the inability to use some hardware components such as magnetic flux compasses due to the direction of the Earth's magnetic field at the poles, limited communication options, poor GPS signal quality, prolonged periods of darkness during winter limiting options for the use of solar power and generally a lack of high-level hazard-perception, decision making and planning abilities.

Despite these issues, robotic systems are still seen as a viable and vital option for the exploration of these environments. In 2001 a workshop was held at the National Geographic Society in Washington DC including delegates from NASA, ESA, America, the United Kingdom, France, Germany and numerous other nations to investigate the viability, benefits and potential uses of robotic systems for the exploration of polar regions (Carsey et al., 2001). They recommended that the scientific community invest significantly in the advancement of such robotic systems as they could provide many benefits for both planetary and Earth-based polar robots in various categories, including: the detailed mapping of tedious, difficult and hazardous routes as well as operations in extremely remote or inhospitable areas, sustained operations during polar night, simple instrument placement which cannot justify a full manned traverse as well as the deployment of instrumentation requiring slow traverse speeds where humans would inherently get bored and impatient, the augmentation of manned scientific missions in order to increase the quantity of data gathered and finally measurements where human presence could alter or pollute the environment such as during chemical investigations.

However, they noted that there were still significant challenges involved in the development of any robotic system that would be able to operate autonomously in Greenland or Antarctica for prolonged periods of time. In particular they observed that significant issues would include the capability for controlled position at the metre level, crevasse detection and avoidance, 24 hour per-day operations, route selection and decision making, self-diagnosis and recovery, power, wind, blowing snow, deep snow, sastrugi, operations with optical systems pointed at the sun, communications and articulating, self-stowing solar arrays.

Over the past ten years significant effort has been exerted by a number of groups towards the development of polar robots, covering topics from the automated detection of meteorites with semi-autonomous gasoline powered all terrain vehicles (Apostolopoulos et al., 2000) to light-weight wind-blown inflatable rovers designed for 2,000 km traverses (Behar et al., 2004), yet many of the problems raised in 2001 are still highly relevant today. Paramount to truly autonomous operations is the issue of high-level decision making and planning. If robotic systems are to operate alone, performing valuable scientific data gathering and analysis, they need to have the ability to evaluate the risks and hazards involved in individual missions against the potential science gains in order to decide which missions should be conducted; and in what order.

A robotic system with the capability to decide autonomously to forgo scanning at the edge of a crevasse would clearly be able to gather more data at other scientifically interesting areas, yet the data available at the edge of crevasses may be of significantly more value than, for example, ground penetrating radar data, thus justifying any of the risks involved. Integral to the decision making process for robotic systems is the ability to take into account the robot's own survivability; should a robot sacrifice itself, and therefore other potential scientific data, in order to complete a high-priority mission? This further introduces questions as to what exactly constitutes acceptable risk for robots.

Amongst the environmental factors already discussed, there are a number of issues internal to the robotic system which affect what is considered safe. Examples of such include the remaining power available to the vehicle, the operational efficiency of the sensor packages, further scientific missions that the robot must still perform, etc. In addition to the current state, the conditions in the near or long-term future also need consideration; it may be, for example, pointless to perform a survey if it would mean the robotic system would be unable to return to its base before a storm which has the potential to permanently affect its navigation capabilities. Conversely, it may be vital that the survey be performed immediately, before the storm arrives and adversely affects the scan site. All these factors, and more, need to be evaluated, both in terms of their short and long-term effects, by the robotic system in order for sensible operational decisions to be made.

For many millions of years biological systems have proved to be more than adequate at instinctively making such life-or-death decisions, and this has paved the way for biologically inspired robotics. Such robotic systems use techniques found in nature such as the neuro-endocrine system which adapts to short-term changes in the environment, with effects lasting up to a few minutes, and the immune system which can have effects on the body for months or even years. Some work has already taken place to use neuro-endocrine and artificial neural network control techniques for the long-term survivability of sailing robots (Sauze and Neal, 2008; Sauze and Neal, 2010), with significant emphasis on adapting the behaviour based on the proprioceptive state of the robotic system, in particular the power required over that which is available.

Other Artificial Intelligence methods such as fuzzy logic systems also have the potential to help with such short and long-term decision making (El-Nasr and Skubic, 1998). Fuzzy logic systems have seen considerable use in robotic simulations and platforms where there are various differing (and often conflicting) concurrent tasks providing methods for the smooth transitions between such tasks. Examples have included the navigation of robotic systems and the avoidance of obstacles en route (Parasuraman et al., 2005; Fatmi et al., 2006). It is thus clear that fuzzy logic systems have the potential to aid autonomous decision making regarding scientific objective achievement and robotic survivability when there is incomplete, inaccurate or vague sensor data; something often true of robotic systems outside the laboratory, let alone the real-world, harsh, dynamic environments of Antarctica and Greenland.

1.2 Aims and Objectives

Whilst significant work has already been undertaken towards autonomous operation in the Arctic, the focus has never been towards the long-term survivability, decision making capabilities of the robotic systems. We aim to contribute to the development of biologically inspired control techniques, such as neuro-endocrine control and the immune system, for the provision of robotic systems with the ability to make high-level decisions regarding their own survival in extreme and hostile environments. Further, we will make contributions towards the development of fuzzy logic control techniques with the emphasis on achieving the similar trade-off of robotic survivability vs. scientific goal achievement.

1.2.1 Objectives Summary

- To show that biological inspired techniques can be used to successfully trade-off scientific goal achievement over robotic survivability in a real-world survey mission of the Greenland ice sheet.
- To show that fuzzy logic techniques can also be used to successfully trade-off scientific goal achievement over robotic survivability in a real-world survey mission of the Greenland ice sheet.
- To test the hypothesis that biologically inspired control techniques are more appropriate for ensuring the maximum possible scientific data return and robotic survival rates than fuzzy logic control methods.
- To develop a framework for defining what is appropriate in terms of risk to robotic systems when performing scientific survey operations in various environments.
- To make significant contributions to the existing work in biologically inspired control techniques, in particular developing new methods for ensuring robotic survivability in hostile environments.
- To make contributions to the existing work in fuzzy logic based control methods, with emphasis on building new methods for ensuring the survival of robotic systems in hostile environments.
- To make a considerable contribution towards the efforts of Glaciologists in their efforts to understand the Greenland ice sheet through the development of a fully autonomous robotic survey platform.
- To make use of the existing platforms available within the Computer Science department to act as long-term test platforms, which are able to operate fully autonomously in Greenland (or other similar environments), for automated surveying tasks.

1.3 Key Research Question

Through this work we intend to answer the following key research question:

> *"How useful are biologically inspired control methods, such as neuro-endocrine control, artificial neural networks and the immune system, compared to fuzzy logic control techniques, at adapting the behaviour of robotic systems in order to ensure robotic survivability and the maximum possible science data return in harsh and extreme environments?"*

Chapter 2

Literature Survey

2.1 Introduction

We provide a comprehensive survey of the literature relating to robotic systems used in real-world expeditions to Arctic, polar regions including Antarctica and Greenland. We focus on ground-based rover type robots, the most relevant to our research, though give an overview of a number of water-based autonomous and teleoperated robots which have been used in the extreme and hostile environments of Greenland and Antarctica. Presented is a comprehensive overview of each robot's design, composition, capabilities, technical objectives and scientific missions. We conclude with an overview of the current state of the field and, in particular, present issues which still pose significant challenges for the wide-spread use of autonomous robotics in Antarctica, Greenland or any polar region.

2.2 Dante

In 1992 Dante, an eight legged tethered walking robot, was possibly the first to have ever been designed and developed specifically for Arctic environments; we are unaware of any literature before this point relating to such robots. Designed for deployment in Antarctica, Dante was developed with various scientific goals in mind, of which one was to show that robotic systems, and in particular legged robots, could be used outside of the laboratory for real-world exploration (Wettergreen et al., 1993). Specifically, Dante was engineered in such a way that it would be able to rappel down the inside of the volcano Mount Erebus in Antarctica to gather data relating to the composition of rare magma lakes including gas sample acquisition through the on board gas chromatograph, temperature measurements via the infrared thermocouple and the measurement of the radioactivity of materials in the magma lake.

Dante was approximately 3 m in length and 2 m wide, weighing around 400 kg. It was composed of two frames, each of which held four legs. A separate motor and drive train were used for each frame to control the legs attached, ensuring intrinsic gate when walking. If necessary, all legs could be raised independently, for obstacle avoidance or where there may have been a lack of foot holes in the wall of the volcano, through the use of separate, independent linear actuators. Dante was further equipped with a laser range finder and a trinocular camera system for perception and modelling of the terrain around the robot.

The robot included various on-board computing facilities and was capable of autonomous, blind operation using contact sensors in the legs alone. However, a tether, including a fibre-optic cable used to multiplex ethernet, two serial lines and seven video channels, was used for control of Dante via a base station erected at the top of the volcano. The tether served a dual purpose as the 'climbing rope' to counteract the force of gravity during descent into the crater.

During deployment between 1st and 2nd of January 1993, Dante successfully rappelled to approximately 10 m below the rim of the volcano using teleoperation before the fibre-optic cable snapped due to the cold temperatures. This caused the end of the mission, with Dante never reaching the bottom of the crater. As such no gas samples were acquired. However, Dante had made significant advances for walking robots, in particular demonstrating that they could be used, not only outside of the laboratory, but in the harsh and extreme environment of Antarctica. Although not specifically related to Arctic robots, in 1994 Dante II was successful in rappelling to the bottom of the Mount Spurr volcano in Alaska and performed supervised autonomous and teleoperated surveys for five days before finally toppling over during the return ascent, bringing an end to the mission (Bares and Wettergreen, 1999).

2.3 SARA & ROBY

In 1992, a programme for technological developments was defined in Italy as part of the 'National Program for Researchers in Antarctica'. Amongst other priorities, such as calling for proposals relating to new sensors and telemedicine, the programme was tasked with producing proposals for robotic systems; in particular those which could have immediate uses in Antarctica for the support of scientific and logistical operations. SARA (Sottomarino Autonomo Robotizzato Antartico) was envisaged; an autonomous underwater robotic system for the exploration of Arctic waters (Papalia et al., 1994).

The primary objective for SARA was to be a long-term substitute for researchers in Antarctica, capable of performing repetitive, dangerous or "impossible" tasks for humans such as operations during winter or the observation of water-ice interfaces. Three scientific payload categories were considered: a) a standard payload including a CTD probe, acoustic Doppler current profiler and a video camera which would be available on the robot for all missions, b) an optional payload sensor suite including probes for chemical and biological measurements, a sonar, magnetometers, etc. which would be immediately available for use on missions, though not always attached, and finally c) a special payload platform for any scientific instruments not specifically considered in SARA's design, but which could be useful on peculiar or specific scientific missions.

Prolonged operation (30 - 40 hour missions, with the ability to operate underwater indefinitely) was to be supported through the use of a static, partially structured, underwater 'garage' environment where SARA would dock to re-charge batteries, deposit acquired samples, backup or save on-board data and return for collection or maintenance. Two survey modes were identified including a simple navigation method following wave-like constant depth trajectories and a more complex navigation method following a pre-programmed grid of survey lines at a constant depth of up to 1 km.

It is unclear as to whether SARA was ever developed or deployed due to a lack of literature after the initial proposal. However, ROBY, a teleoperated underwater vehicle was deployed in December 1993 for a number of related tasks as part of the IX Italian Expedition of PNRA (Programma Nazionale di Ricerche in Antartide) (Bono et al., 1994). ROBY was of specific significance to SARA as it was used both to identify possible locations for the underwater garage area, and also because it provided a means of testing various sensors and equipment in the extreme, cold Arctic waters. ROBY successfully achieved 18 separate teleoperated dives in Antarctica over approximately 20 hours reaching a maximum depth of 150 m.

ROBY was of significant use, showing that whilst the lead-acid batteries planned for use in SARA were not adversely affected by the low operating and storage temperatures, and that the oceanographic sensor which was connected via a RS-232 channel worked as expected, magnetic flux compasses failed due to the low intensity of the Earth's magnetic field at the poles and the film in the camera system became stiff and brittle with the extreme temperatures. In addition, whilst testing equipment for SARA, ROBY was used to achieve a number of scientific objectives, including the study of the distribution of benthos along the coast from Gerlache Inlet to Adelie Cove and the monitoring of the operating conditions of a sediment trap placed on the seabed at a depth of 40m. Further, various dives were used to study the ice-sea interface permitting further study of the effects of ice on marine life.

2.4 TROV

As part of research into methods of control for planetary robots, NASA were working on the use of virtual reality as means of telepresence. Using Antarctica as a planetary analogue they developed TROV, an underwater vehicle based on a modified Phantom S2 by Deep Ocean Engineering (Stoker et al., 1995). It was propelled by four electrically powered thrusters mounted such that driving them differentially allowed the vehicle to turn. Further, a pair of high-resolution video cameras were mounted on a pan-and-tilt platform at an appropriate distance, close to that between human eyes, to allow 3D models to be built from the data. Finally, a manipulator arm was also attached to allow for the sampling of marine biology.

Unlike SARA, TROV was not designed to be completely autonomous. Stoker et al. suggested that any robot going to extreme and hostile environments on Earth, and indeed those going into space, would be unlikely to operate without human intervention. As such, they suggested that any control technique should allow humans to deal with the high-level planning of missions, science targets, etc. whilst the robot dealt with low-level closed-looped tasks such as station keeping, navigating to requested locations and collecting samples and sensor data.

The team found that, for the primary scientific mission of obtaining estimates of the densities of the dominant benthic fauna along video transects in McMurdo Sound, the use of telepresence for robot control had considerable advantages over conventional teleoperation methods. In particular, they suggested that the use of stereo imagery to generate 3D models significantly enhanced biologists' ability to identify the shapes, sizes and spatial relationships of species when compared to 2D camera systems. However, they noted that there were still significant problems with their control interface; in particular the lack of feedback from their manipulator arm made it difficult to grasp and uproot soft organisms without causing damage, and that the control interface currently required two operators.

Despite being a remote, telepresence-controlled water-based vehicle, the TROV proved once again that it was possible, in terms of the engineering ability, to deploy robotic systems into extreme and hostile environments such as Antarctica. Further, it showed that the use of such vehicles can often be highly advantageous for performing real science objectives.

2.5 Nomad

Later, in 1998 the three-year "Robotic Antarctic Meteorite Search" project at Carnegie Mellon University started with the aim of developing a completely autonomous planetary robot capable of operations in Antarctica with the specific task of identifying, classifying and acquiring samples of meteorites. The resulting unmanned ground vehicle, named Nomad, was the first true attempt at sustained autonomous operations in Antarctica, or any polar region, over ground.

Nomad was a four-wheeled rover with individual electronic drive motors for each wheel. Occupying 2.4 m^3 when fully deployed and weighing approximately 725 kg, it had a nominal speed of 0.15 $m\ s^{-1}$. The primary scientific instrumentation included a 3-DOF manipulator arm for deployment of the 300 nm - 1,100 nm spectrometer and CCD 512×494 wrist camera. Nomad also featured a 3-CCD 640×480 24-bit colour camera for detecting potential meteorites for further study with the spectrometer and wrist camera. All power was provided for by a 2 kW gasoline generator (Apostolopoulos et al., 2000).

The project investigated various aspects relevant to autonomous operations in Arctic environments, including navigation and obstacle avoidance through both stereo vision and laser scanning techniques. During testing, before and during deployment, the team found that the vision system was insufficient for navigation and obstacle avoidance due to the lack of any surface features on blue ice in Antarctica. However, the laser range finder used (a SICK LMS 220) proved successful in all but one circumstance when there was falling snow and, as such, was chosen as the primary method of obstacle detection and avoidance (Moorehead et al., 1999).

The navigation system for Nomad used DGPS for centimetre accurate localisation whilst waypoints were generated using two algorithms. One algorithm supported various search patterns for optimal coverage of large areas in order to find interesting rocks that may have been meteorites, and an A^* algorithm was used for optimal path planning and obstacle avoidance both to those potential meteorites and also during the execution of patterned searches (Shillcutt et al., 1999). Various coverage patterns were considered, including a 'simple rows' or 'back and forth' pattern and a spiral pattern. Whilst Nomad was powered from a generator, further consideration was given to alternatives such as a sun-following pattern for potential solar-powered rovers. The team found that the main factor affecting the performance of their navigation algorithm was not differing surfaces (gravel vs. ice) between their test sites in Pittsburgh and Antarctica. Instead, the tuning parameters only required adjustment to prevent oscillation and path deviation due to changes in speed.

During testing in Antarctica, Nomad performed patterned searches and classifications of 42 rocks over a total area of approximately 2.5 km^2, taking 16 hours over the course of 10 days to complete. It was largely successful, correctly classifying 69% of rocks identified using a Bayesian classification method, and found a total of five new meteorites. The authors note that, in all cases, Nomad required teleoperation for the final placement of the manipulator arm due to the extreme cold temperatures affecting the contact sensor (Apostolopoulos et al., 2000).

Having been successful, Nomad was later re-used in the 2005 LORAX project as a proof-of-concept for autonomous polar astrobiological exploration (Pedersen et al., 2005). A number of modifications were made to Nomad, including the addition of a UV fluorescence sensor for analysing single microbes in ice samples and a ice-coring and sample handling mechanism. Software modifications were also proposed including the use of median filtering and range gating to eliminate false positives from the laser scanner with respect to falling snow. Further, the LORAX project was able to use the stereo vision for navigation given that snow, as opposed to ice, has enough texture from surface variation. It was noted that the generator power supply would be insufficient for sustained operations and the exhaust fumes could contaminate any biological samples acquired.

2.6 Tumbleweed Polar Rover

In 2002 NASA's JPL (Jet Propulsion Laboratory) was conducting research towards the development of a rover capable of performing a long-range polar traverse, specifically in Antarctica, with the aim of performing "large-scale science data gathering" (Behar et al., 2002). Their primary objective, as with other rovers discussed, was to use the Arctic terrain as a terrestrial analogue for a range of planetary environments; specifically Mars and Europa, the sixth moon of Jupiter. The priorities for the project were to have a rover with a simple design that was lightweight, low power, low volume and thoroughly tested in terms of autonomy. The authors noted that crevasses presented a significant challenge, one that lightweight rovers with large areas of terrain contact may be able to surmount in certain circumstances, and as such autonomous identification of open and bridged crevasses was deemed essential.

In 2004, the NASA/JPL Tumbleweed Polar Rover, designed to be propelled by wind power, was field tested in Greenland (Behar et al., 2004). The Tumbleweed rover consisted of a 1.5 m diameter nylon bag with rubber studs applied to the outside. Inside, a 1.2 m Lexan$^{\text{TM}}$ tube, within which the electronics and sensor package were housed, was orientated along the preferred axis of rotation. The electronics included an Iridium modem with integrated GPS receiver, an omni-directional Iridium antenna, an active GPS antenna, a 900 MHz serial transmitter, a LCD, a lithium battery pack, a small air pump and a central motherboard holding the primary storage medium, processing unit and various sensors.

The on-board sensors included two pressure transducers (one for ambient and the other for monitoring the membrane's internal pressure), a thermocouple for measuring the ambient temperature and two 2-axis accelerometers to determine the orientation of the Tumbleweed. The Tumbleweed would gather all sensor data once a second and, after pre-determined time period, attempt to transmit it via the Iridium modem. Additionally, every four seconds, the data was transmitted via the 900 MHz radio for on-site debugging purposes.

During the field tests in Greenland, the Tumbleweed rover completed a 130 km autonomous traverse reaching a maximum speed of 17 km h^{-1} and averaging 7 km h^{-1}. Unfortunately, 19 hours and 45 minutes into the mission the rover came to a rest and failed to progress further due to low winds. It remained active and sent sensor data back via Iridium for a further 10 days. Due to the low cost and expendable nature of the rover the team decided not to attempt recovery. The authors noted that, after plans to test a longer 2,000 km traverse from the South Pole to the coast of Antarctica in February 2004, their next step would be to equip the rover with a more significant science package; primarily a sounding radar. This would then allow the collection of data on the topography of the ice sheet, the thickness of ice and accumulated annual snow layers, the depths of isochronous scattering layers in the ice and the nature of the ice-basement interface. The team noted, however, that crevasses detection was still an unsolved problem and a significant challenge.

2.7 MARVIN I & II

As part of the Polar Radar for Ice Sheet Measurements (PRISM) project, the University of Kansas developed the Mobile Arctic Robotic Vehicle for Ice Navigation (MARVIN) rover. MARVIN I was a modified MaxATV skid-steer, amphibious, tracked, all-terrain vehicle (ATV), chosen after consideration was given to various other platforms such as the use of snowmobiles, ATVs, Amphibious ATVs, RC Tanks and custom made vehicles (Akers et al., 2004).

MARVIN I had a number of sensor modules including a laser range finder (a heated SICK LMS 221) eventually to be used for autonomous obstacle detection, gyroscope, RTK-GPS for way-point navigation, temperature sensor, pan-and-tilt camera and a weather station. The primary goal of MARVIN I was to pull a ground penetrating radar array in Antarctica and Greenland. A simulation of the rover was heavily tested before deployment using the MSC.visualNastran simulation package.

During the first deployment in Greenland during 2003, MARVIN I, although capable of simple straight-line GPS navigation in an obstacle free environment, was initially teleoperated (Stansbury et al., 2004) in order to test the operating envelope of the sensors and equipment, including a 24 hour test of the GPS system to identify the availability of GPS signals at the polar regions. During second field trials in 2004, MARVIN I used straight-line GPS navigation so that it was able autonomously to move across the ice sheet following pre-defined paths such that radar data could be collected. Unfortunately, due to the increased temperatures during summer, the rover regularly got stuck in softer snow, the camera's pan-and-tilt motor failed due to vibrations and the transmission failed due to excessive weight and, possibly, because of a buildup of ice on the axles.

The authors noted during testing that slow arcing turns on snow in Greenland were easily accomplished by MARVIN I, but that sharp turns resulted in the vehicle slowly burying itself. However, they concluded that due to the nature of the task, towing a sled, it was, in any case, undesirable to perform tight turns. The scientists also noted that a concern for anyone operating in polar regions is that of crevasse detection, something they intended to pursue in future projects.

In order to address the issues identified with MARVIN I, MARVIN II was developed (Akers et al., 2006). Built from a RangeRunner ATV, the new vehicle had a greater ground clearance (22.9 cm as opposed to 12.5 cm), a more powerful 32 bhp diesel engine and hydrostatic differential drive with built-in speed sensors. The advantages of such a drive system included the ability to turn by adjusting independently the speed of the two drive motors, as opposed to braking completely one side. This meant that the vehicle could turn whilst moving, rather than on the spot, and so prevented the issues where the vehicle would dig itself into the snow. It further allowed for more accurate path following, ensuring overlapping radar readings (Gifford et al., 2009); something of importance when performing surveys of the ice. MARVIN II, whilst able to perform simple obstacle avoidance, was still incapable of detecting crevasses.

2.8 Cool Robot

More recently there has been a significant move towards the use of mobile robots for the deployment of scientific instruments. In order to achieve this a number of desired qualities have been identified, including the requirement for full autonomous navigation over distances as great as 500km over a period of two weeks followed by two to three months of stationary data collection before return. This posed significant issues with the state-of-the art where Arctic rovers were generally gasoline powered.

The Cool Robot was designed for this purpose and was a four-wheeled, battery-powered, lightweight rover (Lever et al., 2005). It weighs approximately 75 kg and has the ability to carry a payload of 15 kg. It is 1.4 m × 1.14 m × 1 m and has a maximum speed of 0.8m s^{-1}. The Cool Robot builds significantly on earlier work by the team towards the mobility assessment of lightweight rovers over deep snow (Lever et al., 2006a).

Significant work towards the Cool Robot focused on the long-term power requirements for prolonged autonomous operation. The Cool Robot design used five solar panels in a box shape to capture both direct solar radiation from the Sun, and that which was reflected by the snow. In addition, a dynamic power system was developed with the ability to adjust the power output of the solar panels and batteries as the robot's control system and drive motors required. However, at the same time the power system was able to request that the rover slow down when the available power was insufficient.

Two tests were conducted in Greenland during August 2005. In the first test, the Cool Robot was given a set of GPS way-points to navigate without any power management. The rover successfully operated for five hours until the battery power dropped below 43 V. During this time the Cool Robot was more than capable of driving on the soft snow surface. In the second test, the power system was fully integrated and the rover successfully operated, with only four of the five solar panels due to a hardware fault, for eight hours before the test was stopped when the rover attempted, due to a bug in the navigation algorithm, to make a second trip around the test course (Lever et al., 2006b).

As a result of their work, Ray et al. concluded that inexpensive mobile robots are capable of reliable, long-term operation on the Antarctic and Greenland ice sheets and that solar-powered robots are feasible for summertime science campaigns, though not wintertime where there are prolonged periods of polar night (Ray et al., 2007).

2.9 Arctic Crawler

As part of work towards robotic mobile sensor networks for use in Arctic environments for the gathering of scientifically useful data, in particular weather conditions such as wind speed and barometric pressure as well as measuring solar radiation, a fleet of 'Arctic Crawler' prototype rovers based on a snowmobile chassis were developed (Williams et al., 2008). These snowmobiles were modified to each include a Connex 400XM Gumstix with wireless 802.11g ethernet and bluetooth. Further, each also had a Robostix board including an Atmel ATMega 128 RISC micro-controller, providing SPI and i^2c, serial ports, general purpose input-output (GPIO) pins, pulse-width modulation (PWM) outputs and a analogue to digital converter (ADC) unit. The rovers each include a 0.3 Megapixel wireless camera for processing of real-time images and a GPS unit.

Each of the robots included a path-planning algorithm, obstacle avoidance techniques and a single-camera terrain, slope and pose estimation technique (Williams and Howard, 2008; Williams and Howard, 2009; Williams and Howard, 2010). Finally, a DAMN architecture was used to combine the competing outputs for each behaviour model in order to navigate. A* and Rapidly-exploring Random Trees (RRTs) were used for the generation of paths and a pure pursuit algorithm was used to follow the generated path.

The authors noted that even with the stable nature of the snowmobile chassis the potential for the rovers to roll over was a significant concern. As such, a fuzzy logic slope assessment scheme was developed, using the single camera pose estimation technique, to keep the rover on level terrain.

An important aspect of the work conducted was to show the dynamic and collaborative abilities of the robots. The authors simulated an Arctic environment for their rovers through the Player/Stage/Gazebo environment. Using a market-based algorithm the rovers were able to distribute the various scientific tasks, provided to the robots by a human scientist, amongst themselves autonomously.

2.10 Yeti

Ground penetrating radar has been used on larger human-driven Tucker Sno-Cat vehicles for the detection of crevasses, giving operators approximately two seconds notice in order to stop the vehicle and examine the situation further. In 2008, Yeti was designed to use ground penetrating radar to detect crevasses (Trautmann et al., 2009).

Yeti is a four-wheeled, differentially-steered, battery-powered autonomous robot of approximate size 1.1 m × 1.1 m × 0.76 m. Weighing approximately 71 kg it is capable of speeds up to 2m s^{-1} with a maximum range of 16 km. It was designed to be capable of operations in temperatures as low as -40 °C and wind speeds up to 60 mph. The sensor suite includes a GPS, 3-axis accelerometer, 3-axis gyroscope, wheel encoders, motor current sensors and a optical velocity sensor. The main scientific equipment is a SIR-3000 ground penetrating radar. Of particular interest is the design of Yeti; it uses a passive pivot, linking the front and rear wheels, to allow it to maintain four-point contact when navigating rougher terrain such as sastrugi.

In order to validate their design Trautmann et al. tested their ground penetrating radar array in various circumstances to identify the effect of electrical interference. They noted that during traverse the radar data was adequate and not affected by the electric motors. However, they observed that their 900 MHz radio antenna, used for communications with the robot, did adversely affect the data. They surmised that, as long as there were very short data bursts of less than 1ms and typical of their data, the signals were unlikely to overlap with the radar scan and so were minimal enough to ignore. Further tests were also conducted to test the mobility of Yeti. The authors noted three cases where the rover could potentially become immobile: a) narrow vertical ridges taller than 50 cm with a width less than the robot's wheelbase, b) loose wind-drift snow and c) step obstruction, particularly larger steps of above 35 cm.

At the time of deployment in 2008, Yeti was configured to perform a set traverse collecting and storing ground penetrating radar data. This data was then post-processed, as opposed to being processed on-the-fly, allowing human operators to then decide if it was safe to proceed with their traverse. The authors claim that the current bandwidth limitations prevent live radar data being sent back to a manned vehicle. This severely limits the usefulness of Yeti at present. However, during deployment, Yeti was sent to collect radar data in a known hazardous zone where there were four crevasses. The data collected showed that three of the crevasses were clearly visible, though the fourth wasn't due to a temporary problem with the radar configuration.

The authors note that future work would be conducted towards real-time processing of the ground penetrating radar data in order to allow the robot to adjust autonomously its survey path, ensuring that any crevasses detected are surveyed to the maximum. They further suggest the need to improve their immobilisation detection, through a trained classifier, in order to prevent immobilisation as opposed to their current approach; detecting only after the robot had lost mobility.

In 2009, Yeti was deployed again with no modifications other than the addition of a frequency modulated continuous wave (FMCW) radar for the autonomous surveying of the Antarctic shear zone. Yeti operated for two days in October 2009, concurrently with human-operated radars. Yeti surveyed the entire 5 km shear zone at temperatures as low as -30 °C with a average speed of 3.2 km h^{-1} (Koh et al., 2010).

2.11 Minty

Most recently in 2010, Minty, a remote-controlled robotic boat, was deployed at the calving-front of the Lille Gletscher glacier in Western Greenland (Neal et al., 2011). Minty was a modified Optimist sailing dinghy equipped with various scientific survey instruments including two swath bathymetry transducers and an interface box, a Crescent Vector 2 GPS, a Furuno PG500 Magnetic Compass, a Teledyne TSS DMS-25 IMU, a SMC 108 IMU, a Riegl Z620 laser scanner and a Nikon D300s camera.

The control system included a Gumstix Verdex Pro with network board, a PIC18F4550 microcontroller, a Linak LA12 linear actuator for steering and a trolling motor. It was capable of operating for up to five hours, being powered by two 110 Ah 12 V lead-acid batteries.

Whilst the plan was to allow for full autonomy when surveying, at the time of deployment only remote control was used. Neal et al. suggested that, whilst the data collected represented an “unprecedented level of detail ... for a small remote control survey vessel”, the data quality could have improved through simple GPS way-point navigation, station holding and the ability to remain a set distance (between 50 m - 100 m) from the calving front of the glacier autonomously. The introduction of these techniques, along with a new hull design, are currently being investigated for future missions.

2.12 Conclusions

It is evident that over the past twenty years significant progress has been made towards the use of autonomous robotic systems for operations in Arctic, polar regions. Most of the work undertaken has been in conjunction with additional scientific missions such as the detection of meteorites, the collection of ground penetrating radar data and the scanning of the fronts of calving glaciers providing valuable scientific data vital for understanding global warming and climate change on Earth, and for gaining a better understating about the universe and its origin. Missions drivers have been two-fold; the desire for greater autonomy, in particular for space and planetary robotics, and secondly the need for scientific data regarding Greenland and Antarctica where human missions are costly and dangerous.

Throughout the last twenty years many different robotic systems have been developed including walking robots for exploring volcanoes, underwater and sea-based robots for scanning of marine life and calving glaciers and ground based rovers ranging from tracked, all-terrain, gasoline-powered rovers, to large inflatable balls to light-weight, wheeled, solar-powered rovers. Many issues have been overcome such as the ability to operate at extreme temperatures, improved vision based systems for use where there are limited features, methods for preventing blowing snow interfering with laser range finder data and even attempts at crevasse detection.

It is clear that, for the last ten years, the state of the art has been dominated by the work of Apostolopoulos et al. with their Nomad rover developed in 1998. Whilst progress has been made in individual areas, none of the future rovers have, as yet, demonstrated such integration and autonomy.

In almost all instances of the robots discussed, some form of human intervention has been used, or ultimately required. The early robotic systems were all teleoperated. Nomad was mostly autonomous, though required teleoperation for final placement of the manipulator arm. The Tumbleweed rover got stuck and was unable to continue its traverse. Marvin was initially teleoperated, though when finally operating autonomously broke down due to the build-up of ice on its axles. The Cool Robot had control system bugs resulting in unpredictable behaviour when following GPS way-points. The Arctic Crawlers required human scientists to dictate the science missions. Yeti required ground penetrating radar data to be post-processed, as opposed to being captured and used online for crevasse detection, and further became immobilised with large step-like snow features. Minty was entirely teleoperated.

Clearly, despite the progress, there are still significant issues which hinder the use of truly, fully autonomous robotic systems today. These primarily include the requirement to detect crevasses, as well as the impending immobilisation of robotic systems. Power is another area that needs further consideration; solar-powered robots such as the Cool Robot are ideal for summertime operations where there is constant, 24-hour sunlight, though during winter, where there is constant 24-hour darkness, such robots would fail. Further, gasoline-powered vehicles clearly suffer a disadvantage of requiring refueling and are inherently polluting making them useless for sampling where biological or chemical samples are required. Most importantly, there is a need for greater autonomy in terms of higher-level decision making capabilities. Robotic systems need to be able to make decisions, such as planning science missions in ways that ensure crevasses or potential areas of immobilisation are avoided until absolutely required, or possibly the deliberate operation in hazardous areas due to increased scientific interest. They must further have the ability to identify scientifically interesting targets during their normal operations and adjust their mission appropriately in order to maximise the scientific data gathered and their usefulness.

Chapter 3

Review of Progress

3.1 Introduction

Provided is a brief overview of the current progress and of the work planned for the next twelve months. Included are plans for thesis development, conference and journal publications and both Aberystwyth and Greenland based experiments.

3.2 Current Progress

3.2.1 Robotic Development

Initially, until February 2011, progress was focused on an impending expedition to Greenland in April 2011. The initial trip was to allow for the collection of vital sensor data required to investigate the feasibility of the chosen vehicle (an Argo 6x6 Amphibious Skid-Steer ATV) and sensor package in Greenland so as to understand better the problems involved in robotic exploration in such remote, Arctic environments. During this deployment there were four primary aims:

- To test the sensor equipment for its ability to function in the extreme environment of Greenland and, in particular, to identify the ability and accuracy of the laser range finder and panoramic camera system at identifying potential crevasses, sastrugi, etc.
- To test the mobility of the Argo vehicle on the snow-covered surface in Greenland, including identifying the potential for the skid-steer system to perform slow, arcing turns required for towing ground penetrating radar (GPR) arrays.
- To gather GPR data, collectively with terrestrial laser scans, to build 3D models of the surface above and below the ice sheet.
- To gather and test a snow penetrometer, attached to the Argo vehicle, in order to perform simple grid-like surveys of ice/snow thickness, stress, and strength.

Significant work was undertaken towards the development of the robotic system over the first few months of the PhD, including the development of a simple low-level control system capable of integration with C/C++, Java and the Player platform. The development required the integration of various sensors and computing equipment into the vehicle including a 3-axis accelerometer, fully integrated inertial measurement unit (IMU), magnetic flux compass, global position satellite (GPS) receiver and antenna, SICK LMS111 heated laser range finder, panoramic camera, wheel rotation sensors, PIC18F4550 micro-controller and Gumstix embedded Linux modules for the low-level control of the Argo. The low-level Argo was largely based on previous work (Clarke and Blanchard, 2010), though included significant enhancements to try and ensure reliable operations during expeditions to Greenland. Additional scientific equipment was added including a terrestrial laser scanner

(TLS), snow penetrometer and a dual-core rack-mountable computer for science data storage and processing.

3.2.2 Greenland Data Gathering

Unfortunately, in mid February, it became clear that the trip to Greenland, as initially planned, would not be viable due to personal circumstances. In particular, it would not be possible to send the robotic Argo platform until April 2012.

However, it was still vital to get data relating to the performance of the sensor equipment in Greenland. As such, in order to compensate, focus moved from finishing the final details of the Argo ready for deployment, to the development of a simple box style device which could be strapped to the back of a ski-doo during human driven GPR survey missions. This box included various sensors identical to those on the physical Argo, including an IMU, LMS111 laser range finder, USB uEye camera, and a eeePC for sensor data gathering and storage.

The box was shipped to Greenland in April 2011 and, at the time of writing, is still there. It is expected to return by June 2011. At this point, data collected can be analysed; it is anticipated that the box will provide significant insight into the operating conditions of the sensor equipment and robotic platform. Further, data gathered can be used towards the development of visual navigation, obstacle detection and crevasse avoidance techniques.

Such techniques will help significantly with identifying and categorising the various risks involved in individual missions the robot may be required to undertake, and so will therefore contribute towards the development of an overall strategy for trading-off scientific goal achievement and robotic survivability.

3.2.3 Literature Survey

Over the last month, the focus has been directed towards understanding the efforts of others, the problems which may be faced in such environments and gaining a better understanding of how our work can contribute towards rectifying such problems through an on-going literature survey. A general outline of the survey, with conclusions and comments thus far, has been demonstrated in Chapter 2.

The survey is currently in need of further expansion. It covers robotic systems in Arctic environments, though pays little attention to artificial neural networks, immune systems or fuzzy logic. Given the aims and objectives, stated in Chapter 1, these need further attention. Further, although not specifically related to robotic systems in Arctic, polar regions, much of the work towards planetary robotics may be highly relevant and so needs further consideration. Examples of such include automated science target identification in order to improve science gain for rovers on Mars (Pugh and Barnes, 2007; Barnes et al., 2009).

3.3 Action Plan for Future Work

3.3.1 May 2011 - December 2011

A continuing aim will be towards completing the literature survey. Emphasis will be on the incorporation of artificial neural networks, the immune system, fuzzy logic control and planetary robotics; areas relevant to the research, but which, as yet, have not been addressed in the current literature survey of robotic systems in Arctic, polar regions such as Greenland.

This survey will continue during the period identified, whilst additional work outlined below is also conducted. Of note is the lack of any existing survey papers relating to Arctic robots. Currently, the possibility of a survey paper is being investigated.

3.3.2 May 2011

Scenarios relating to the potential situations the robotic systems will be likely to experience will be produced. These will include a diverse range of potential operations robotic systems must perform including straight-line surveying missions, navigation, obstacle avoidance, sample acquisition, science target identification, etc. They will further include the potential hazards including numerous possibilities such as crevasses and obstacles, falling ice, loss of communication, hardware failure, sensor failure, power failure, etc. These scenarios will be analysed to identify the underlying principles that we, as humans, consider important when evaluating risks; why is one activity considered safe whilst another is not? What is it about one activity that means we are prepared to sacrifice a robot, or specific sensor, compared with another where we are not? Are there general classes of hazards and scientific missions and, if so, what groups them together? This type of analysis will significantly help towards identifying the strategies we use to trade-off the risks involved when performing, or allowing robotic systems to perform, science missions. Having this knowledge will then help towards the development of a control system and strategies that allow robotic systems to make similar decisions autonomously.

Various possible solutions will be evaluated including the potential for neural networks, fuzzy logic systems, rule-based methods and knowledge-based approaches. It may be that various approaches will be needed for the differing scenarios identified.

3.3.3 June 2011

Data from the box sent to Greenland will become available. This data includes laser range values, camera images and IMU base-line data. These data need analysis to better understand the conditions affecting sensor data in Arctic environments. The analysis of this data will be highly useful for developing new methods of detecting obstacles, and potentially crevasses, evaluating the potential for the use of visual navigation techniques in Arctic environments and identifying the effects of the Earth's magnetic field direction on the use of magnetometers for yaw readings.

3.3.4 July 2011

More work will be required on the robotic platform, as a result of the data gathered and analysed from Greenland, in order to be ready for deployment in Greenland. In particular, work is needed on the low-level control system towards autonomous obstacle detection and avoidance, navigation techniques to achieve slow arcing turns for towing ground penetrating radar arrays and grid-based survey patterns for the use of the snow penetrometer.

As this work progresses, control system tests will be conducted with the Argo ensuring slow arcing turns are possible at sustained speeds of 10 km h^{-1}, as well as GPS navigation trials in order to facilitate the towing of ground penetrating radar and the grid-based surveying of snow.

3.3.5 August - October 2011

Experiments will be designed to test the scenarios identified. We will evaluate the different control methods in terms of their efficiency and appropriateness for each scenario. This will likely include the measuring of the quantity of science data gathered and the perceived importance of the data, the time required to collect such data, the route taken in terms of efficiency, the obstacles and hazards that were avoided and those which were not, the success rate of the robots at returning to their final way-point, etc. These experiments will be designed to replicate each of the scenarios previously identified, some of which will relate to the operations of the Argo in Greenland as a primary case-study, though will include the potential uses of other robotic systems such as Minty the boat for scanning at the calving-fronts of glaciers, Idris for surveying archaeological sites and Mars based rovers performing autonomous science.

These experiments will be conducted in Aberystwyth and the surrounding area, in a number of different environments, from small beaches where there may be the potential for a rover to dig itself into a hole, rough terrain where there are small hills that the robotic system must be able to overcome whilst avoiding obstacles such as wind turbines, to the relatively flat, forgiving fields on campus.

3.3.6 November 2011 - December 2011

Based on the results from the initial experiments a conference paper is planned detailing the design of the robotic system, the experiments to be conducted in Greenland and the results of testing in Aberystwyth prior to deployment.

3.3.7 January 2012

Experiments may be modified and developed further as a result of the initial work.

3.3.8 February 2012 - April 2012

The Argo will be shipped to Greenland and then used for real-world ground penetrating radar and snow penetrometer data collection. This data will be used by Geographers and Glaciologists at Aberystwyth University.

As a result of performing science gathering tasks, the Argo will experience many of the situations detailed in the scenarios. The various control architectures developed will be tested in order to evaluate the robot's performance in terms of performing science operations whilst trading-off against the various dangers and hazards in a similar fashion to that in Aberystwyth.

This period will constitute the primary experiment and testing phase of the PhD. The data collected will make the primary contribution to the analysis of the various strategies for trading-off scientific goal achievement over robotic survivability.

3.3.9 May 2012

Significant analysis will be performed on the results from the experiments in Greenland and Aberystwyth. These will be linked back to the scenarios and first principles identified in order to evaluate the various strategies and define a more generalised frame work for trading-off the accomplishment of science missions whilst avoiding, or taking appropriately calculated, risks and hazards. A journal paper will expand on the conference paper, including details of the trip to Greenland and a discussion of the analysis. The planned journal is the Journal of Field Robotics.

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