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Scoping Study on Semi-Autonomous Shearing: Final Report

Prepared for Australian Wool Innovation Limited (AWI)

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1 Introduction

This report provides a final summary of the work under the Scoping Study: Semi-Autonomous Shearing project between UTS and AWI. The project's aims are to: (1) formally catalogue existing robotics algorithms and commercially available hardware with respect to technical challenges of automated shearing, and (2) identify plausible use-case scenarios of semi-autonomous shearing that will inform the focus of near-future technical development.

The technical activity of the project is organised around three work packages:

1. **Work Package 1 (WP1): Analysis of existing robotics technology.** The focus of this work package is on matching existing robotics technology with known challenges in autonomous shearing. This will be done through the investigation of robotic technology that currently exists, including both mechanisms and algorithms.
2. **Work Package 2 (WP2): Evaluation of off-the-shelf robot hardware.** The testing and validation of robotic equipment through experimental means with a focus on shearing, including manipulator arms and sensors for sheep perception.
3. **Work Package 3 (WP3): Generation of use-cases for semi-autonomous robotics in shearing.** Identifying and bridging the gap between robotic technology and the needs of the wool industry. This includes conducting a workshop session with industry stakeholders to allow for issues to be identified as well as for a full appreciation of the shearing environment and the restrictions that are present within it.

This final report marks the conclusion of the project and satisfies contractual Milestone 4. We have completed the industry workshop specified in WP3, completed the analysis required in WP1, and performed multiple live robotics demonstrations as per WP2. Our workshop was featured in AWI's podcast *The Yarn* [1], and *Beyond the Bale* magazine [2]. Recently *ABC's Landline* filmed footage at UTS and interviewed Robert Fitch about the project [3]. A recap of our efforts on emulating the blows with a robotic manipulator arm on a 3D printed sheep were featured in AWI's podcast *The Yarn* [4].

The remainder of the report is organised as follows. Section 2 describes the design, delivery, and outcomes of the industry workshop. Section 3 contains the work packages as outlined in the original scoping study contract. Finally, Sec. 4 provides recommendations on the research questions and projects that will require funding in order to achieve the use-cases generated for semi-autonomous systems.

2 Industry workshop

This section describes the workshop conducted in partial fulfilment of WP3. We present the workshop design proposal, describe the workshop delivery, and summarise outcomes.

2.1 Proposed workshop design

The workshop aims to identify and bridge the gap between robotic technology and the needs of the wool industry. This is an exciting opportunity for industry stakeholders to learn about the capabilities of modern robotic technology and how it can assist with shearing. Moreover, the floor will be open throughout the day for discussion of issues, allowing attendees to express their opinion and for researchers to identify key development areas. There will be a demonstration of two modern robotic arms and 3D sensing for attendees to experience, first-hand, today's robotic capabilities.

Location	Date	Organisers	Email
Sweven at Cattai	14 June 2018	A/Prof Robert Fitch Dr Alen Alempijevic Fred Sukkar	Robert.Fitch@uts.edu.au Alen.Alempijevic@uts.edu.au Fouad.Sukkar@uts.edu.au

2.1.1 Motivation and background

Automated shearing has a long history in Australia. The first automated shearing blows were performed over 40 years ago in 1975, and repeatable demonstrations of fully automated shearing were performed in the late 1980s. Development then stopped abruptly due to a funding crisis in the industry. This pioneering work is now memorialised in museum exhibits (Museum of Applied Arts & Sciences, Sydney).

The number of people involved in agriculture and horticulture in Australia has been in steady decline for the last four decades. The number of farmers in Australia has dropped by 40% since 1981. This decrease is due in part to the reluctance of young people to remain in family farms. Worse, nearly one quarter of farmers are at or above retirement age. Similar trends are present worldwide. Robotics has the potential to play a significant role in improving the efficiency of existing agricultural methods, and more importantly in introducing fundamentally new methods.

Other than lack of available skilled labour, motivation for automation in shearing stems from a desire to improve occupational health and safety conditions for workers. Other motivation includes the possibility of benefits in terms of performance predictability and quality control, which has been observed in other industries where robots have been successfully applied.

The aim of this workshop is to develop a comprehensive understanding of how modern robotics technology could be applied to the problem of semi-autonomous (human assisted) shearing. Robotics includes hardware components and mathematical tools that are being applied in an increasingly broad collection of activities, including broad acre agriculture, horticulture, cargo handling in ports, maintenance of infrastructure such as the Sydney Harbour Bridge, mining, defence, and commercial aviation. Many such applications were pioneered by the organisers of this workshop and their colleagues at the University of Technology Sydney and former colleagues at The University of Sydney.

2.1.2 Detailed event proposal

The workshop will be organised as a series of interconnected sessions. The objective of these sessions is to: (1) present a selection of existing robotics algorithms and hardware with respect to the technical challenges of automated shearing, (2) identify plausible use-case scenarios of semi-autonomous shearing, (3) engage with industry stakeholders to gain appreciation of the shearing environment and restrictions presented within it, and (4) understand the industry's preferences with respect to the problems that robotic solutions may address. All of these factors will inform the focus of near-future technical development.

- *Session 1:* Introduction to robotics in agriculture

A presentation on the rise of robotics in agriculture, translation of capabilities of modern robotic technology and adoption in industry, by A/Prof Robert Fitch.

- *Session 2*: Ice breaker activity

  At the session the attendees will have 2 minutes each to introduce themselves to the group. We will have a list of attendees ahead of time and will create a powerpoint slide for each name to facilitate this activity.

- *Session 3*: Interactive hands on with robots

  A demonstration of a compliant robot arm with 3D sensing capabilities will be undertaken. Attendees will have the opportunity to physically interact with the robot and experience modern compliance and perception technology first-hand.

- *Session 4*: Topics in automating the shearing process, Part 1 (outdoors)

  This will be the first main working session. We will move to an area with live sheep and discuss issues in sheep handling (sheep movement throughout the process) and workflow (cutter blows and wool handling) of a semi-autonomous process. Through guided discussion, we will attempt to identify steps in the process where automation could help. We will approach this discussion from two directions: within the current process (where could robotics be inserted?), and within a fully automated processes (where could human assistance be inserted?).

  Within the current manual process, we will aim to describe the normal workflow, including: process flow of people; blow patterns; sheep control and motion; sequential/concurrent operations; and difficult/easy tasks with respect to time, effort, skill, labour, and required experience. The scope of this discussion will include all workflow beginning from when the sheep is removed from the race and ending with wool handling. We will discuss crutching/wigging versus shearing and the timing of these operations. Within the shearing operation, we are specifically interesting in discussing the differences in how different areas (body parts) are shorn.

  Within a hypothetical automated process, we will aim to describe a semi-autonomous workflow. We will discuss how the robot can help the human, and what the robot would need to be able to do (functional requirements). One way to guide this discussion is to revisit each stage of the manual workflow and ask “could a robot help with that?”

  We will also consider alternative automated workflows. We will seed this discussion by presenting example of full automation proposed by Trevalyn [5], and look at humanising parts of this workflow.

- *Session 5*: Topics in automating the shearing process, Part 2 (indoors)

  This session will be held in the main workshop area to discuss topics specific to robot workflow, including: compliant shearing with a robot-arm, logistics for setting up a system, quality control.

  We will first recap the previous session, using post-it notes and butcher’s paper. Then we will analyse parts of the workflow that are repeated, examine the classification of difficult tasks (time/effort/skill) and which are essential. We will focus on where can human assist the robot, and vice versa.

  Specific questions to consider include:

  - Cutter. Differences between thin/thick combs? Proximity to skin, angle, force, fleece length?

  - Fleece length (length of wool fibres) and integrity. Does the fleece need to remain in one piece? What is the driver for this requirement – handling and storage?
  - Skin stretching. What is the role of stretching the skin while shearing (in detail)?
  - Possible logistics of a semi-autonomous system. Who does what, who owns the process, what is the scale?
  - Setup. How would a semi-autonomous system be set up and used?
  - Evaluation. How would outcomes be measured? How would quality be assessed? What level of throughput would be acceptable?

- *Session 6*: Data as by-product of automation

  We will present user interface concepts and gauge what type of additional information and functionality the audience would be interested in having available to them. For example, 3D models of sheep, yield estimation, sensory feedback and other statistics. Led by Dr Alen Alempijevic.

- *Session 7*: Wrap up

  We will present a summary of the results of the indoor/outdoor working groups, and facilitate the identification of action items and take-aways.

Desired attendee profile

To create a sufficient cross section of stakeholders across the industry, we anticipate that participation should cover producers (farmers) and shearers. We will rely on AWI's judgement here. Between ten and fifteen attendees, plus AWI and UTS staff, seems appropriate.

Program: Thursday, 14 June 2018

Time	**Theme**	**Topic**
8:00-8:30	Arrival	
8:30-9:15	Session 1	Introduction to robotics in agriculture
9:15-9:45	Session 2	Ice breaker activity
9:45-10:15	Session 3	Interactive hands-on with robots
10:15-10:30	Coffee Break	
10:30-12:00	Session 4	Topics in automating the shearing process, Part 1 (outdoors)
12:00-13:00	Lunch	
13:00-14:00	Session 5	Topics in automating the shearing process, Part 2 (indoors)
14:00-14:30	Session 6	Data as a by-product of automation
14:30-14:45	Coffee Break	
14:45-15:30	Session 7	Wrap up
16:00	Workshop closes	Contingency time in case we run late throughout the day

2.1.3 Logistics

Task	Responsibility
Robot demo bump-in and bump-out	UTS
Attendee choice, communication, travel	AWI
Venue selection (including sheep)	AWI
A/V: projector and screen	AWI
Laptop computers for presentation	UTS
Stationary for working group activity	UTS
Morning/afternoon tea	AWI
Lunch	AWI

2.2 Delivery

The workshop took place at Sweven, a 57-hectare estate in Cattai, NSW with 11 attendees in total (plus a videographer). Attendees comprised shearers (Daniel McIntyre, Richard Leahy, Dwayne Black, Cartwright Terry), AWI staff (Jim Murray, Blake Chandler and Marius Cuming), and UTS staff/students (Robert Fitch, Alen Alempijevic, Fred Sukkar, Stefano Aldini).

- *Arrival and Setup:* UTS staff arrived at 7:30am and, with the help of AWI staff, completed setup of the two robots to be demonstrated.

- *Session 1:* Introduction to robotics in agriculture


The workshop opened with Robert Fitch delivering a presentation about robotics applications in industry with focus on UTS projects and agricultural robotics. The audience was generally surprised by the robotic applications being presented to them, even those that were implemented over a decade ago, for example robotic straddle carriers. The free flowing discussion revolved around recent advances in computing, sensing and actuators that have given rise to a tide of robotic applications in the real world.

- *Session 2:* Ice breaker activity

  During this session each person took turns introducing themselves and sharing a fun fact. Everyone seemed comfortable and excited about the day. In particular, the sheep shearers were determined to work together and find a robotic solution. This sense of cooperation was promising given the day had only just begun.

- *Session 3*: Interactive hands on with robots


  Two robots were on display. The first was an assistive robot, called ANBOT - a bespoke built assistive robotic co-worker designed to allow an operator to effortlessly position a spray nozzle tool for sand blasting. It can be thought of in layman's terms as a "robotic power steerer". Three aspects of the robot were demonstrated to the audience: self collision avoidance, singularity avoidance and relief of back force on the nozzle. For the third demonstration the audience was asked to try move the tool around while someone else applied force to the front of the nozzle. The group was pleasantly surprised by how the robot was able to cleverly separate the two forces and how easy it was to use. The shearers starting hypothesising how they may use the arm to assist with their job, for example, to relieve the force required to manipulate the sheep.

  The second robot on display was an apple seeking robot with integrated sensing and actuation (using a Sawyer robotic arm). This arm was tasked to find apples on a mock-up apple trellis. The aim was to demonstrate to the audience how robots can intelligently look around and actively perceive their environment. Further, the high resolution 3D sensing capabilities, high computational power and advanced algorithms of the robot were made evident.

- *Session 4*: Topics in automating the shearing process, Part 1 (outdoors)

  The bulk of the discussion occurred during this session. All participants went to the sheep paddock and the shearers demonstrated the shearing process on merino sheep. A walk-through of the workflow process was undertaken: moving the sheep through the race, dragging them to the shearing platform, the sequence of sheep manipulation poses and then the fleece skirting. The shearers emphasized in detail the difficult and easy tasks and provided insights on what makes a good shearer (versus a bad shearer). Jim presented

various equipment used to shear the sheep, such as the different combs, cutter blades, cutter holders, motor drives and back support. UTS staff were given the opportunity to try a few blows on a sheep in order to gauge the feel of the comb on the skin of the sheep and discern the vibration of the clippers vs the force feedback (with close assistance by the shearers).

On completion of the session UTS staff compiled the knowledge gained to fine tune the discussion to follow.

- *Session 5*: Topics in automating the shearing process, Part 2 (indoors)

  The session was designed as an ideation activity. Discussion opened with possible avenues for semi-autonomous operation. The shearers were asked to confirm UTS staff understanding of the process by writing down all the repeatable steps explicitly. The intention was to elicit discussion of tasks that are high yielding and require significant effort, mapping them to sensing/feedback/control loops of a robotic manipulator. The session evolved with the group steering the discussion, which was immensely encouraging, focusing on possibilities and values of semi-autonomous operation.

  Given the shift to semi-automation rather than full robotic shearing, the group identified that the sequence involving handling the sheep used in human shearing was incredibly complex. This need for holding was identified as a by-product of the human skeletal system and the need to exercise force by the human shearer only within the breadth of their shoulders.

  The cutter and comb mechanisms were reflected upon; the lifetime of these devices has increased significantly though higher-end devices are very expensive. The history of cutter/combs indicated resistance to change within the industry. However, any change to the cutter mechanism, e.g. a laser cutter, is possible if it makes a robot's job easier.

Thereafter, the group adopted a view of avoiding shearing the whole sheep in the immediate application of robotic shearing, and instead focusing on the higher quality wool on the top half of the sheep. This approach could follow structured practises of crutching, removing of wool from around the tail and between the rear legs of a sheep and extend it to removing wool from the head of the sheep and underbelly. A robotic shearer could remove the remaining high quality fleece without compromising value by cross contamination.

Discussion identified that the remaining fleece could be accessed with a “prone” holding method which would prevent the need to manipulate the sheep. A number of options for “prone” shearing were discussed, revisiting other existing approaches and mapping them to the effective robotic workspace. Keeping skin stretched and ease of fleece management were considered. The group identified underbelly support the best option with keeping the feet off the ground so as to disengage the sensory of touch and dissuade the sheep from escaping. Some conformation of pressure points on sheep (above its knees which can be leveraged to restrain it) and animal behaviour (sheep to go to sleep by lying it on its back and then covering eyes) were also discussed.

- *Session 6*: Data as by-product of automation (replaced by prone sheep holding platform test)

The originally planned session on data usage is automation was not carried out. Instead, the decision was to test the sheep holding method suggested in Session 5. The group moved back to the sheep paddock and the shearers improvised a mock-up of what they had in mind to hold the sheep. The mock-up consisted of two half logs held up by four panels. The sheep sat comfortably on the logs while the shearers determined a suitable sequence of blows to shear the sheep. They successfully sheared the top half of the sheep using one hand emulating the blows of a robotic arm, without needing to manipulate the sheep.

- *Session 7*: Wrap up

  The day ended at approximately 5:30. The group as a whole was pleased at what had been achieved over the day. Marius conducted an interview with Robert for *The Yarn* podcast summarising the day's achievements. Finally, UTS staff, again with the help of AWI, packed away all the robots and left the property.

2.3 Outcomes

The industry participants responded well to the opening presentation of robotics in agriculture and the ability to interact with state of the art robotic systems, developing an understanding of the advances in automation and having been primed for digital revolution upon the industry. A transition to hands-on shearer-led activities mid-afternoon allowed researchers to gauge the complexity of shearing and handling the sheep simultaneously. The planning and execution of the sessions allowed synergy of the group (industry participants + researchers), steering discussion as it suited, which was immensely encouraging and fostered creation of ideas on possibilities and values of semi-autonomous sheep shearing.

Given the shift to semi-automation rather than full robotic shearing, the group confirmed that the sequence involving handling the sheep used in human shearing was incredibly complex. This sequence was a product of a multitude of competing requirements, primarily driven by need for smooth and consistent blows when shearing. To achieve this need, sheep need to be comfortable yet firmly restrained so they do not attempt to escape the hold. The use of elbows, knees and hand not carrying the shears creates a plethora of pressure points to aid in stretching the skin (to avoid cuts) and simultaneous fleece handling. While having incredible dexterity, a human's effective manipulation area to perform blows is squarely limited to shoulder width. Full blows over the entire body are therefore not possible by a human shearer, whereas a robotic arm's effective reach could span more than 2m.

A view of avoiding shearing the whole sheep in the immediate application of robotic shearing, instead focusing on the higher quality fleece, was formed. A two-stage approach was developed that could follow practises of crutching. The first stage would consider human shearer removal of wool from around the tail, between the legs and extend from the head of sheep and underbelly. Thereafter a robotic shearer could remove the remaining high quality fleece without compromising value by cross contamination.

A method for holding sheep in shearing that can leverage the wider ambidextrous operational area of a robot arm would still need to perform smooth and consistent blows aiding fleece handling, and ensuring the animal is compliant, completely unharmed and at ease during the process. Discussion identified that the remaining fleece could be accessed with a "prone" holding method which would prevent the need to manipulate the sheep. A number of options for "prone" shearing were discussed, revisiting other existing approaches and mapping them to the effective robotic workspace. Keeping skin stretched and ease of fleece management were considered. The group identified underbelly support the best option with keeping the feet of the ground as to disengage the sensory of touch an dissuade the sheep from escaping. The practicalities of this method, evaluating the reach of robot and skin smoothness achieved are to be evaluated in WP2.

2.3.1 Media

The outcomes of the workshop are also covered in media releases by AWI.

- *The Yarn*, Episode 69, "3D printing - could this lead to robotic shearing?", 02 November 2018 (podcast)
- *The Yarn*, Episode 47, "Robotic shearing: can it become a reality?", 29 June 2018 (podcast)
- *Beyond the Bale*, Issue 76, "Robotic shearing revisited in the digital age", September 2018.

3 Outcomes relative to initial objectives

This section contains the work packages as outlined in the original scoping study contract.

3.1 Work Package 1: Analysis of existing robotics technology

The objective of this work package is to produce a survey of modern robotics technology relevant to sheep shearing, including both hardware and algorithms. Although multiple decades have passed since its publication, the now-classic text *Shear Magic* by James Trevelyan and his team is still the primary work in the area of automating sheep shearing [5]. Trevelyan's work will be regularly referred and compared to throughout this survey.

3.1.1 Alternative Technologies

One view is that there is an alarming lack of change and innovation in the sheep industry. This is supported by Australian Wool Growers Association's Robert McBride who explained during an ABC Landline episode [3] that sheep are still being shorn the same way as they were in the eighteenth century.

Other alternative technologies have arisen, such as *ShearEzy* [6] and *BioClip* [7], however they have not been widely accepted and often abandoned by farmers mainly due to high cost, lower-than-promised productivity and logistical issues. In the case of BioClip, farmers reported issues such as unsatisfactory animal losses, the need for easier to use fitting nets and that the process was too labour intensive [8].

3.1.2 Robot Manipulator Arm Mechanisms

Robot arm technology has undergone two generations of evolution since the 1980s. At the time when the majority of the work in autonomous shearing was performed, the best viable arms were actuated via hydraulics, as is still common in heavy duty agriculture and construction machinery. The first major technology leap was the development of highly precise, digitally controlled arms actuated by electric motors. This class of arms is extremely precise and repeatable, and can be extremely strong (can lift 100-1000kg). However, because of their strength and lack of safety sensing, these arms can be potentially fatal to humans and so their operation requires humans to stay out of their reach. The second major advance was to implement safety measures that allow arms to work alongside humans, including series-elastic actuators (motors with springs that absorb contact forces). These collaborative arms have only become widely available in the past five years after considerable investment that targets manufacturing industries.

There exists several commercially available collaborative arm models with varying capabilities and price points. Typically, price increases with level of accuracy, sensing availability and maximum payload. For example Rethink Robotic's Sawyer arm [9] is a relatively low cost arm at $40,000 USD with a 4kg maximum payload compared to the $70, 000 USD Kuka LBR iiwa [10] which has 3.5 times higher maximum payload. Further, the Kuka arm has better force sensing capabilities and a higher control loop frequency, allowing for more robust force control. The Universal Robots UR10 [11] is modestly priced at $45,000 USD and has a payload of 10 kg. The UR10 is a six degree of freedom (DOF) arm compared to the former two which have seven DOF. This difference in number of DOF can be important depending on the end application. It should be noted that these prices can change dramatically depending on where they are procured. A detailed comparison sheet of collaborative robots can be found on Robotiq's website [12].

As mentioned above, certain parameters of a robot arm can have significant implications on the capabilities of the arm when performing tasks. Many studies have been carried out to optimise these parameters [13]–[19], including the number of DOF, joint types and link lengths. These studies typically use general metrics such as workspace reachability and manipulability, a measure of how much freedom the arm has to move in a particular position, to quantify performance. Recently, Sukkar [20] carried out experiments that consider practical implications directly, such as the effect on planning performance.

Typically six DOF or higher robot arms are used for dexterous tasks [21]. While six DOF allows for any arbitrary position and orientation in 3D space, also called a 6D pose, higher DOF allow greater flexibility in how the arm achieves such a pose. This can be beneficial for performance depending on the task, in particular for environments with difficult obstacles and constrained tasks as shown in [20]. Constrained tasks are where the robot's end effector is restricted to move in a reduced configuration space. In the context of sheep shearing, the robot arm's end effector will most likely need to perform constrained motions when shearing the sheep. An example of a constrained motion is to always ensure the end effector tool is normal to the surface of the sheep as it performs a blow.

3.1.3 Planning and Control for Robot Manipulators

Although the Trevelyan-era robots represent a tremendous engineering milestone, the systems were never adopted commercially. One issue was that the system was heavily over-engineered to overcome the algorithmic, sensing, and computing limitations of that time. In particular, manipulator motion planning and control was still very premature. As such, the robot arm was designed with many redundant degrees of freedom (DOF) in order to avoid singularities, points in the workspace where the robot loses the ability to move in particular directions. However, with clever motion planning, these singularities can be avoided and the same blows can be achieved with a more compact, easier to transport and simpler robot arm.

A common problem in autonomous systems is determining how a robot should move from a start state to a target state in a given environment. Motion planning is the process of determining this movement, often by breaking it down into a sequence of discrete motions so that when executed moves the robot from its current configuration to a goal configuration without colliding into obstacles. Further to avoiding obstacles, another objective of motion planners can be to optimise trajectory costs, such as energy consumption, execution time and even uncertainty. The textbooks by Choset et al. [22] and LaValle [23] provide a rich overview of fundamental motion planning algorithms.

The problem of moving a manipulator from a start to goal state is a relatively simple problem if obstacle collisions are not a concern. Once obstacles are introduced, the problem is no longer trivial and motion planning is needed. In fact it is well known that a complete motion planning algorithm for this problem is proven to be PSPACE-Hard [24] [25]. A complete planner here means for any planning problem instance, the algorithm will either find a solution or will correctly report that no solution exists. PSPACE is the set of problems that can be solved given unlimited time but only using a polynomial amount of space in memory. PSPACE-hard means that the problem is at least as hard as any problem in PSPACE. Another example of a PSPACE-Hard problem is the game GO [26].

Motion planning for robot manipulators has a rich literature and remains a highly relevant research topic. As such there have been great advancements in these algorithms and today there is a large list of different planning categories, each suited to different applications. These include: grid-based search algorithms [27]–[30], sampling based planners [31]–[33], any-time planners [34]–[40] and trajectory optimisers [41]–[44].

Grid-based search algorithms are generally not suitable for manipulator motion planning because their computational complexity grows exponentially with the number of DOF. Sampling based planners overcome this issue by avoiding explicit construction of obstacles in the state space, rather configurations are probabilistically sampled and kept if collision free. Any-time planners allow for fast naive solutions which can be improved over time. Trajectory optimisers are similar to any-time planners, however they continuously improve an initial seed trajectory over time rather than produce completely new solutions.

While generating planned motions for robot manipulators within a few hundred milliseconds is now possible with standalone planners, achieving efficient solutions reliably and in complex environments is difficult and can take up to several minutes [21]. An industrial bin picking robot [45] and weed killing robot [46] motivated the need for reliable near real-time motion planning. They were able to achieve this through a new framework which computed trajectories offline and then adapted them online to a given task. Sukkar [20] expanded on this idea and developed a framework called Fast Reliable and Efficient Database Search Motion Planner (FREDS-MP) which achieved significantly better computation times, execution times and success rates, making it feasible to plan trajectories in complex environments in real-time.

FREDS-MP is able to achieve this through clever combination of the different planning types mentioned earlier. Sampling based planners and any-time planners can produce fast solutions however they tend to be sub-optimal and produce jerky motions. Trajectory optimisers can produce smooth trajectories quickly, however they are susceptible to local minima which can lead to high failure rates depending on the environment. FREDS-MP utilises grid-based search and sampling based planners to compute offline paths and then adapts these prior solutions online using trajectory optimisers.

Motion planning for constrained tasks is more complicated. The problem of planning manipulator motions on constrained manifolds has been well studied and there exists general purpose, high performing algorithms such as Constrained Bi-directional Rapidly-exploring Random Trees (CBiRRT) [47] and Task-Relevant Roadmaps (TRM) [48]. FREDS-MP additionally allows for offline computation and online adapting of constrained motions, significantly improving performance over the standalone state of the art constraint planning algorithms.

In the context of robotic sheep shearing, the need for fast, reliable and efficient planning is critical in order to be cost effective. In the offline computation phase for FREDS-MP a wide range of sheep models can be used as problem instances. The offline computed motions can then be adapted online by matching any given sheep to the closest stored offline model which acts as an accurate prior.

3.1.4 Compliant Control of Cutter

In addition to motion planning there exists force-based control methods for robot arms such as impedance control [49]. This control mode allows the robot arm to be compliant to external force such that a given relationship is maintained between the applied force and displacement. In other words, in the case of shearing we want the position of the robot's end effector, the cutter, to follow a surface, the sheep's body.

This idea was also considered by Trevelyan, however, it was deemed too difficult due to high variability in the compliance, or stiffness, of the sheep's body. Instead they developed a compliant controller using a combination of capacitive and resistance sensing. Since, there has been significant research into this issue and force tracking impedance control methods have proliferated [50], [51]. These methods are designed to handle variable target stiffness without having to explicitly model the stiffness and position of the environment, in this case the sheep's body. These methods were motivated by surgical robots performing insertion and extraction of needles, needing to penetrate through different layers of tissue of varying stiffness.

Modelling and responding to constrained interaction, also known as constrained object manipulation (COM), in the presence of uncertainty still remains a challenge. This is important to consider because there will be uncertainty in estimating the sheep's surface or even the slightest movement by the sheep can perturb the cutter resulting in imprecise contact dynamics. Recently, researchers proposed combining constraint planning and impedance control into a unified framework [52]. They attempt to solve this by learning a task manifold offline that encodes task constraints, devising an online adaption strategy using Gaussian process regression and then integrating the manifold with an impedance controller that offers a task-consistent adaptation during online execution. Interestingly, this work learns the control parameters from human demonstration and can capture the different levels of impedance required for the varying stiffness along the sheep's body. It may be possible to explore such a method for handling COM uncertainty for sheep shearing.

An alternative to actively controlling the arm's end-effector is to utilise a passively compliant mechanism. Passively compliant mechanisms alter their orientation or shape in reaction to applied forces during operation. These mechanical mechanisms are used in many industries for self-alignment, self-stabilization, and passive actuation. The mechanical nature of these mechanisms, though not re-programmable, reduces electrical requirements of a system and achieves repeatable performance.

Consider a single blow as following a contour around a 2D slice of a sheep. The orientation plane of the cutter along this contour is tangent to the curve. This plane can be consistently approximated with 3 or more points of contact near the cutting interface. Provided the contour path can be achieved from a moving arm with 2 or more degrees-of-freedom, then a spring-damper system with two rotational degrees of freedom and 3 or more points of contact on the sheep skin can achieve the desired cutter orientation at anywhere along the blow.

3.1.5 Perception for Cutter Control

Excellent work was performed by Trevelyan's team for perceiving the distance between the cutter and the body of the sheep, and also for detecting when the cutter began to cut flesh as opposed to wool. The sensing hardware to support this capability was custom built. We now have commonly available capacitance sensors, for example, that are routinely used in factory automation.

Further, at the time of Trevelyan's work, force sensors did not have the level of sensitivity and robustness of today's sensors [53]. Force-based control could now be a promising method to pursue in this project. Force-based control could be advantageous in that there would be no need to pass an electric current through the sheep nor place an electrode on its mouth, as was necessary with the shear magic robot. Further, problems with resistance and capacitive sensing, such as conductive wool, water/ urine in the wool and variability in conductivity between different sheep can be avoided.

Another interesting sensing modality to explore is tactile sensing. Any device which senses information such as shape, texture, softness, temperature, vibration or shear and normal forces, by physical contact or touch, can be termed a tactile sensor [54]. A motivation for using tactile sensing is that vision systems are not suitable for cutter control given that the sheep's body is covered by a thick layer of wool.

The importance of tactile sensing was realised in the 1980s [55], however high manufacturing costs and low computational processing power was a major hurdle for research into advancing the technology. Since, there has been major breakthroughs in the ability for computers to process large amounts of data and material manufacturing, particularly flexible electronics and nanotechnology. Today wearable tactile sensors have become possible [56]. It may be possible to line the comb with these tactile sensors and estimate the local geometry of the sheep's surface.

3.1.6 Geometric Representation of Sheep

Trevelyan used a series of parallel and equally spaced one-dimensional spline curves to model the surface of the sheep. This was unnecessarily restrictive and required awkward interpolating between curves to ensure coverage and smooth motions. Today there exists several surface representation methods that are capable of handling 3D surfaces [57], each with their own advantage and disadvantage depending on the application. Criteria general revolves around required smoothness, scalability, accuracy and post processing such as computing intersections.

There has been significant research and progress in mesh-based representations. In particular for reconstructing surfaces from raw sensor data [58]. Reconstruction methods have become robust to artifacts such as non-uniform sampling, noise, outliers, misalignment and missing data.

Mathematics to represent and estimate uncertainty is a cornerstone of modern robotics, across all of its component areas. One advance in the past ten years has been the adoption of statistical tools such as Gaussian process regression (known as Kriging in geostatistics) that represent a variety of phenomena along with a quantitative measure of uncertainty. Gaussian processes can be used to represent surfaces, for example, from a number of sample observations, as we have shown in our previous work for fruit detection [59]–[61]. These methods were not well developed in robotics at the time of the original work in shearing, which used geometric methods to represent the surface of the sheep to be shorn.

3.1.7 Perception for Estimating Sheep Geometry

A vital component of the Shear Magic robot was the machine vision system, which attempted to locate the position of the sheep and infer its geometric model under a roughly 100mm-thick fleece. This required significant manual thresholding and, in some cases, manual intervention if certain events occurred. For example, if the sheep moved after trying to measure the height of a shorn patch, the operator would need to manually measure it instead.

At the time, 3D sensing was in its infancy. Trevelyan's team used, for example, light stripping. Since then, there have been significant advances in computer vision algorithms, computing power and sensing technology. Significant work on face shape modelling in 3D from shading or 3D data has examined the idea of creating generic models [62] that are then updated to match that of an observation of a new face. This is achieved via blending between models. Advances in 3D sensing have also resulted in dense 3D models [63], [64].

Capabilities of depth sensing (3D sensing) have transformed modern robotic perception. Acquiring spatially dense and temporally consistent 3D data of a scene is now possible with commodity hardware. This in turn allows for dealing with uncertainty by actively positioning sensors, parameterisation of surfaces and dealing with deformable objects such as moving livestock, as we have done in our previous work [65].

3.1.8 Perception for Quality Control

In the original work on autonomous shearing, robot perception had not advanced to the point where it could support adequate quality control. Final inspection of the shorn sheep was done by a human, who would also perform any necessary clean up. The advert of high frame rate 3D sensing allows to reconstruct scene geometry to produce increasingly denoised, detailed, and complete reconstructions where each measurement is fused into an updated model in real time [66], [67]. Therefore, it would now be possible to use sensors to examine the shorn sheep and look for unshorn patches, both during shearing and afterwards. 3D sensors are integrated with RGB sesonrs, which could allow for other types of inspection during shearing, such as contaminents or black wool.

3.1.9 Sheep Holding and Manipulation

The key to Shear Magic's effective shearing was manipulating the sheep into a convenient position for each part to be shorn. In effect, each position stretches out the skin in a way that creates a convex surface and exposes hard-to-reach wool. The manipulation mechanism was large in size and complicated with many actuators. It also required a human to physically lift a sheep onto the holder and restrain it.

The sheep holding and manipulation seems even more difficult now than before the project. After observing shearers it is evident that there are on the order of thousands of manipulations. This would be extremely difficult to produce on a fully autonomous system. For example, there would need to be difficult measurements carried out and separate perception problems would need to be addressed for each part of the sheep being shorn. Every manipulation pose may be an individual research project. Moreover, we found that implementing this dominates the complexity and hence the cost of the system relative to the added value.

The relaxed requirement (discussed at the workshop) of not having to shear the entire sheep means that it is possible to place the sheep into a prone position, where the more valuable body wool can be harvested without further manipulation. This significantly reduces the complexity and manual labour required by the sheep holder. In the prone position, gravity lets the skin sag down in the direction of the cutter blows and the sheep's entire body surface is convex.

Alternatively, there is a body of work in robotic control that allows physical human-robot interaction, such as methods developed for assisted grit-blasting in infrastructure maintenance [68]. The idea is that the robot can alleviate the load of the grid-blaster and in a sense provide "robotic power steering" to the operator. Such technology could be adapted to sheep shearing, where one or multiple robot arms could be used by the shearer for example to manipulate and restrain the sheep.

3.1.10 Wool Handling

The Shear Magic robot used a combination of the robot arm pushing the wool out of the way after it was shorn, gravity and the use of a conveyor belt to move the accumulated shorn wool away from the sheep to avoid second cuts. The idea of using a vacuum suction machine was devised and experimented with at the time by the Melbourne University Sheep Handling Engineering Experimental Project (Musheep) laboratory. However, it was found to be ineffective due to the difficulty of separating shorn wool from unshorn wool. When the shorn wool separated it did so in clumps and immediately blocked the vacuum. A double conveyor system was used to assist with gradually pulling the wool away however it required height adjustment for different lengths of wool and hence was not considered practical.

The devised prone position solves the issue of wool handling due to gravity, since the wool will automatically fall off the sheep if an appropriate sequence of blows is programmed. Afterwards, moving the wool is a material handling problem which is a well studied problem and any factory automation technique could be applied. Hence, this can be seen as an engineering problem and not a research one.

3.1.11 Final Remarks and Conclusion

Other factors to consider as to why Trevelyan's Shear Magic robot was not adopted commercially include the large degree of human supervision and intervention required to operate the machine. After replacing the comb and cutter, there was a need for re-adjustment by the operator. The machine itself seems difficult to use by the average person and had many moving parts that likely would have made it difficult to maintain.

From a functional point of view, many movements were pre-programmed sequences. One example is re-positioning the arm to move wool out of the way. They were performed in an open loop-fashion, and hence there was no feedback to acknowledge whether the move succeeded. Rather, the action would be tried again and, if it failed, repeated until a maximum number of attempts was reached.

Trevelyan proposed that placing the comb as flat and close as possible on the skin of the sheep allowed the cutter to glide easily without accumulating significant drag force. Interestingly, our workshop revealed that close shearing may not be desirable. Rather, the attendees argued that there is an optimal length of wool that should be left unshorn, and close shearing has no benefit over the life of the sheep. It may be desirable to design a system that can allow for easy adjustment of the length of wool left over by the cutter.

Lastly, the robot was slow when compared to a human shearer. This could be attributed to the sheep manipulation time, limitation on computing power and confidence in the machine. This time could increase significantly if there was human intervention required.

In terms of future work identified by Trevelyan, there is the question of scalability and adaptability. The trials carried out used average sized merino sheep that were in good condition. Sheep can vary in size, proportionality, wool thickness, skin properties and physical condition. When considering the design of the robotic system, ensuring the robot can detect and deal with these variations will be critical.

In conclusion, algorithmic and sensing capabilities have matured far beyond those in the 1980s due to several decades of research and development. Equipped with this technology, there are multiple avenues that can be taken to produce an effective solution to autonomous and semi-autonomous shearing.

3.2 Work Package 2: Evaluation of off-the-shelf robot hardware

The objective of WP2 was to perform preliminary experimental validation of easily accessible robot hardware. We provided a live demonstration at the workshop of the basic capabilities of manipulators and 3D sensors. Recently, we performed a live demonstration at UTS of two robot arms performing "imaginary" blows over a life-scale 3D printed sheep.

Figure 5: Photos from Sweven property showcasing 3D scanning process.

Originally, our plan was to use rough mock-ups of a sheep torso to demonstrate the kinematic capability of modern manipulators. We have since decided to expand the scope of this work package slightly in order to provide more compelling results.

Emphasis during the evaluation of possible semi-autonomous shearing was placed on the holding pattern for sheep, which is primarily driven by need of smooth and consistent blows. To achieve this, sheep need to be comfortable yet firmly restrained so they do not attempt to escape. The physical size of a sheep, within some constraints, bares no relevance to the shearing pattern. A prone stance for holding sheep was proposed and needed to be evaluated, which should not require further manipulation of the sheep given the requirement that only the top half of the sheep will be shorn. Therefore approval to sheer sheep in the prone stance was provided by AWI and UTS staff obtained 3D scans of live sheep, before and after shearing.

From the scans we have built 3D models and printed a full-scale 3D model using UTS's in-house facility, ProtoSpace. These models may be the world's first biologically accurate 3D printed sheep. Using the 3D prints, we demonstrated plausible blow patterns using a robot arm where a proxy compliant end-effector maintained contact with the surface of the model sheep.

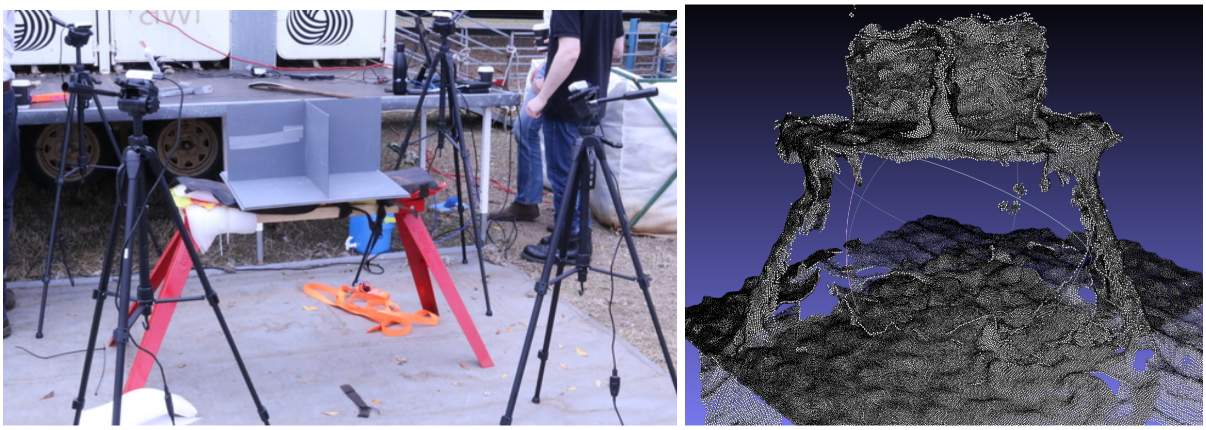

Figure 6: Calibration tool (left) and fused 3D point cloud (right).

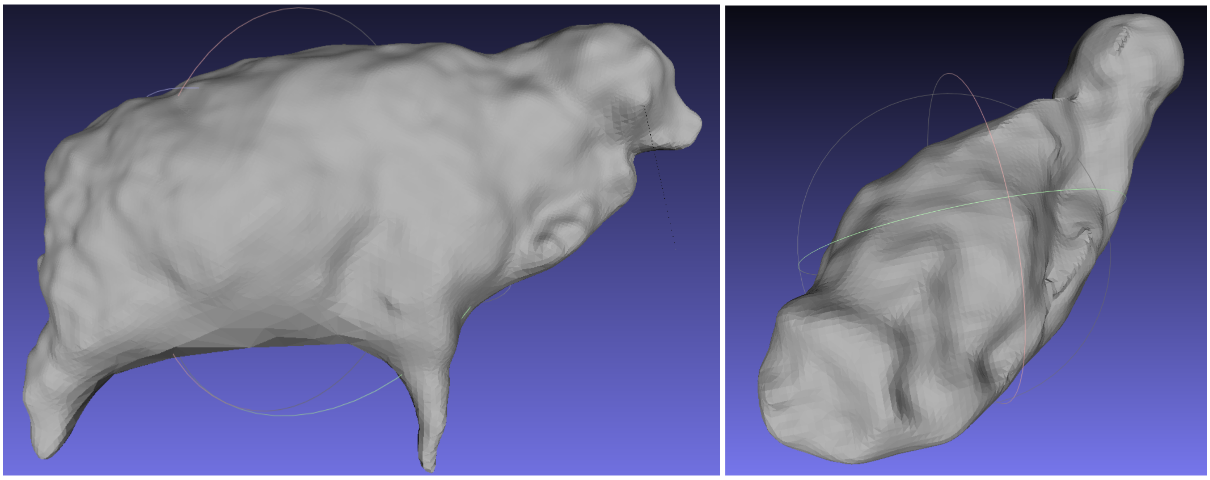

Figure 7: Unshorn sheep (left) and shorn sheep (right) meshes.

3.2.1 3D sheep scans

On the 3rd of October, 2018 we carried out 3D scanning of three sheep on the Sweven property with the assistance of AWI. Photos from the day can be seen in Fig. 5. To scan the sheep four Intel Realsense D435 cameras were placed in opposite corners around the sheep, which sat on a bench fixture in the prone position as established during the workshop. The following scans were taken of the sheep: unshorn, after the first blow, half shorn and fully shorn.

To calibrate the relative position and orientation of the four cameras with respect to each other, necessary to align the 3D scans, a three plane calibration tool was used, see Fig. 6. As can be seen the resulting fused point cloud is wavy and noisy. This is due to high exposure of sunlight regardless of the large overhead tarp used. In ideal conditions, the D435 camera fuses infrared (IR) with stereo vision to produce detailed 3D data and rectify the noise typically suffered by stereo vision. When the IR illumination of the D435 cameras is saturated, as was the case on the day, only the stereo camera depth data is used.

This prompts the need for either (a) setting the work area to shaded or completely indoor (wool shed) or (b) investigation into sensors that will provide more reliable and robust 3D depth information in outdoor settings. The D435 cameras are still considered promising since it is possible to apply more advanced filtering in the future. Further, they are small form factor, low cost, low power, allow overlapping field of views for multiple cameras and have relatively high depth resolution if necessary.

After manual adjustment and repairing of the 3D data, a Poisson reconstruction process was used to produce meshes, necessary for 3D printing. The sheep that was scanned initially

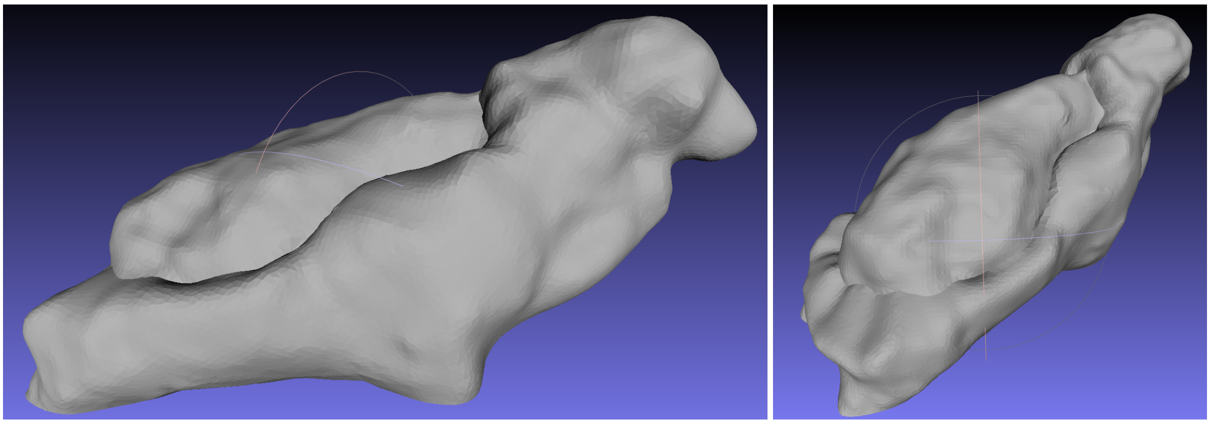

Figure 8: Merged shorn and unshorn sheep into single mesh.

produced the best results and can be visualised in Fig. 7. For a more pleasing visual appearance the unshorn and shorn meshes were combined and further repaired through a manual process using Autodesk MeshMixer software. The final resulting mesh that was used for 3D printing can be seen in Fig. 8.

3.2.2 Additive Manufacturing (3D printing)

Additive manufacturing enables rapid and adjustable design iteration and testing at every stage of a design process. The 3D mesh was sent directly to the fabrication machine for construction. The machine deposits material to create the final product automatically. The build took approximately 5 days to complete. The final model is made from a high speed biopolymer blended filament and weighs approximately 11kg. The BigRep machine, used to build the model, has a workspace of $1m^3$ which can accommodate life size sheep reproductions. Snapshots of the fabrication process are visualised in Fig. 9. Once fully constructed a worker removes the build from the platform and removes support material from overhanging features. A significant amount of path planning and experimentation can be developed using this and similarly fabricated pieces. Such animal-free testing will reduce experimental risks to animal subjects during development and accelerate the design process.

3.2.3 Hardware setup and design

For the live demonstration we placed two robot arms on each side of the 3D printed sheep, Fig. 10. They then performed “imaginary” blows over the sheep, closely following the contours. A soft ball was mounted onto the robot arm’s end effector which maintained physical contact with the surface of the sheep. The blow patterns were “taught” to the robot by a human demonstrator who followed the blue tape guides seen in Fig. 10.

The main purpose of the demonstration was to validate that the arm is mechanically capable of performing the blow motions and covering the entire surface of the life sized sheep. Furthermore, using two arms proves that the operation speed can be scaled up with multiple robots. The cost of the hardware used in this experiment provides an estimated upper bound on the cost of the end system.

Early design concepts for restraining the sheep include a net design and a roller-based lifter Fig. 11. In both designs, a sheep is guided onto a platform. Then the lifting apparatus rises from beneath the sheep. In the net design, the sheep’s legs pass through the holes in the net. The sheep is then suspended by the net and supports its weight from the belly, chest, and rear. Once shorn, the net lowers giving purchase to the sheep’s feet on the platform again. The roller

Figure 9: 3D material extrusion process.

lifter emerges from beneath the sheep and between its front and rear legs. The rollers then roll along the belly and expand toward both sets of legs. The sheep is lifted by the padded rollers located at the armpits and hip crease. The legs are clipped in to prevent folding onto the rollers and pushing off the system.

3.3 Work Package 3: Generation of use-case for semi-autonomous robotics in shearing

Based on the industry workshop, we have identified a range of use cases starting from low to high level of robot involvement, see Table 1. The proposed use cases are all semi-autonomous solutions. Any further level of autonomy is considered approaching full autonomy territory which will require significant re-design and re-evaluation of the problem.

We believe Level 1 is a relatively low risk option since we have demonstrated from the workshop that the sheep is comfortable in the prone position and that we can shear the sheep without further manipulation. Uncertainty remains in the difficulty of designing a simple compliant cutter mechanism, in contrast to that designed by Trevelyan's team. However, we believe

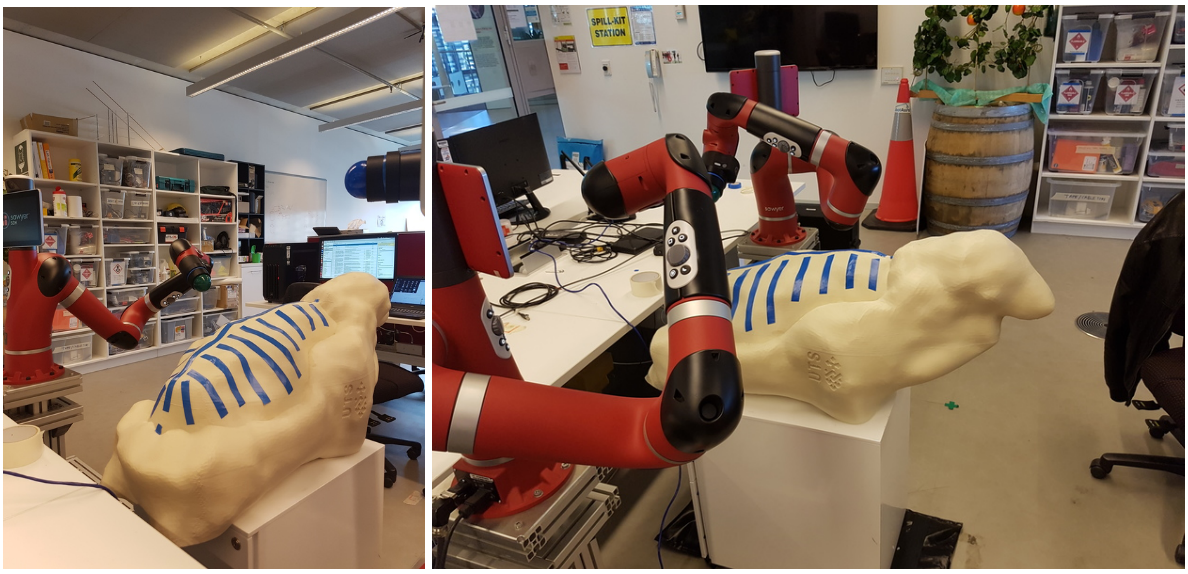

Figure 10: Live demonstration setup: dual robot arms with mounted soft ball end effectors and life-scale 3D printed sheep with indication of blow pattern.

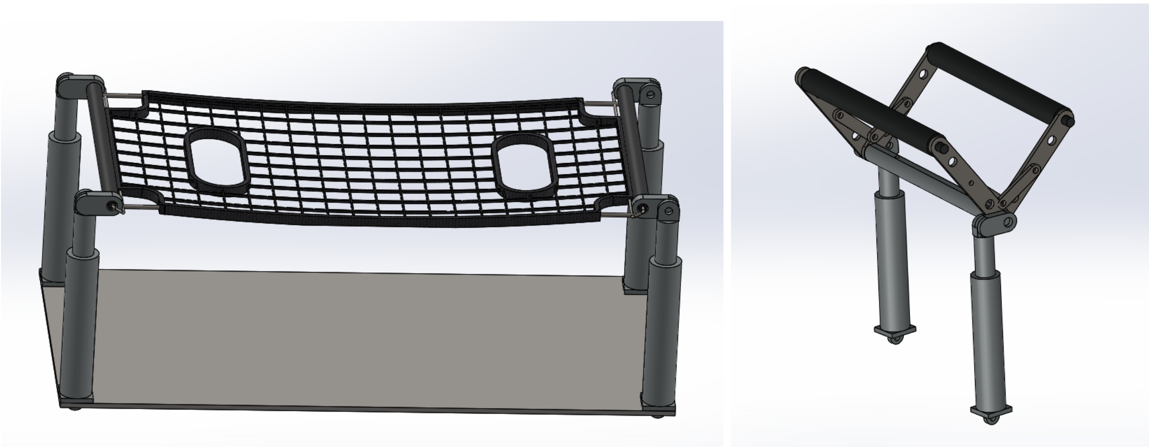

Figure 11: Early sheep restraint concepts

this is a research question that could be answered within a short period of time. Once the question of a compliant cutter is answered a prototype can be built with existing knowledge and expertise.

Above Level 1, most of the problems are engineering related not fundamental research problems, aside from the requirement of the robot performing the first blow on the sheep. This is due to the necessity of estimating the sheep's body geometry from observing wool only. We are confident this is achievable however it will likely require research work.

4 Recommendations

This section provides recommendations on the research questions and projects that will require funding in order to achieve the five levels of semi-autonomy described in Sec. 3.3.

Level 1	Single station. Sheep enters from race and lifted or placed by human onto a fixture and secured in position. Human performs single blow down the back along the spine and then one or multiple robots shear the sides. Wool falls to the ground and another human collects it. Sheep exits and next one enters. Human shears rest of the sheep including legs, belly, head and crutch. This last step may not need to be done immediately and can be aided possibly by a fixture.
Level 2	Same as Level 1 except now there are multiple stations. Stations could possibly be placed on a rotary platform where a human performs the single blow and then places the sheep onto a vacant station. The idea is that the multiple stations act as a buffer since the human will only take a few seconds to perform the single blow where as the robot arms will take longer. Wool falls onto a conveyor or similar mechanism.
Level 3	Same as Level 2 except the robot performs the first blow.
Level 4	Same as Level 3 except the fixture holding the sheep will rise from the ground under the sheep and latch onto the legs. Human restrains the head.
Level 5	Same as Level 4 except the robot restrains the head.

Table 1: Use-cases for semi-autonomous shearing with varying levels of manual intervention.

4.1 Compliant Cutter

Optimal cutter design in semi-autonomous shearing depends on both (1) maintaining the cutting plane orthogonal to the direction of wool fibres (approximately parallel to the sheep skin) and (2) the interface of the cutting tool and wool fibres. Orienting the end-effector parallel to a sheep's skin could be achieved through active sensing and manipulation, passively compliant mechanism design, or a combination. This task represents a moderate design development and iteration effort for a robust solution in the shearing environment.

In addition, this design must integrate with path planning of the blow pattern and geometric estimation of the sheep body. A primary consideration of the integrated blow pattern and cutter mechanism is avoidance of "kinks" along the body. For example, the overlap of the thigh and belly represents a potential sharp change in surface topography. The blow path(s) around this region must be both compliant to follow the body contours, but also avoid a damaging collision of the comb with sheep skin in an adjoining body part.

The comb requirements for such a moving cutter would necessitate a design like the current safety combs. For each blow, a comb must have at least 4 degrees of freedom: 2 linear and 2 rotational. The two linear motions allow the comb to follow path as a two-dimensional contour around the sheep. The two rotational degrees of freedom allow the cutter to stay in the preferred cutting orientation at every point along the path. Multiple cutters are also expected in order to accelerate shearing without the need for fast robotic motions. The arrangement of these sets of cutters must integrate with the blow pattern to avoid collisions in surface "kinks".

Robotic arms do not tire or fatigue, thus selection and design of a comb/cutter combination for the automated arm requires reconsideration in the new context. The constraints on the automated process involve more assurance of safety for the animal and less restriction on the weight of the device and resistance to pushing through the wool. The cutting tool interface may be improved by materials and tribological research for loose fibrous materials (wool).

The latest investigation into cutter/comb materials was published by Mair and Berndt in 1992 [69]. Advances in composites, surface coatings, and simulation methods since the early 1990s prompts an opportunity to improve cutter design for reduced maintenance. In addition, advances in tool wear monitoring and prediction from high volume manufacturing may be adapted to this application and integrated into the system.

4.2 Estimating Body Geometry in Unshorn Sheep

Segmenting and identifying consistently meaningful correspondence between sheep will allow for improved estimation of body geometry and extraction of information for automated shearing. The process of finding correspondence of 3D data, referred to as shape registration and shape matching, has been used for applications such as rigid and non-rigid transformation, morphism, and deformation transfer. Complex approaches to shape correspondence have been developed in the computer graphics community, in particular for animation of characters. Indeed, as non-rigid deformation and morphism are required, a simple matching that only considers the distance between points of 3D acquired sheep is not sufficient. Commonly the problem of shape correspondence is formulated as an optimization where both the similarity of the points association and continuity of the shape correspondence are maximized.

Recent work that using traditional shape matching methods often leverages functional maps as a framework to maximize the similarity between the point distances, while maximizing the consistency over the surface. A recent example of such approach is Kernel Matching [70], where the distance between points is computed by solving a problem with constraints of heat propagation over the surface. While the Kernel Matching can be used out-of-the-box on any 3D mesh and present an overall good performance, the optimization can converge to a local minimum due to the random initializations. Particularly when the surface presents symmetries, such as a sheep, it is prone to inverting parts of the surface or exhibiting localized outliers present on the surface. As a result, the shape correspondence lacks robustness, and is prone to significant error in particular for methods requiring precise surface area or volume.

Therefore, we have considered jointly formulating the problem of surface correspondence and shape morphing. Our proposed method would solve these problems simultaneously in two steps: (a) poses of each sheep are aligned using non-rigid deformation (b) local search solves the surface correspondence Given the surface correspondence, the shape morphing is solved with a non-rigid deformation. Considering that each sheep is shorn in a relatively similar pose, i.e., prone position, this information is used as a strong prior to simplify the pose alignment. Further, if a CT scan of a sheep were obtained in ”prone” position, it would enable having a detailed prior of musculoskeletal system that could be exploited for shape correspondence.

4.3 Systems Engineering

This will largely involve standard system engineering practices including writing up of conceptual designs, requirements documents, software design documents and risk analysis. Throughout the implementation cycle a systems engineer will be required to manage and ensure that the system adheres to the project requirements and that any modifications to the scope are dealt with appropriately. The systems engineer will have sound knowledge on all aspects of the project and have an intimate understanding of the inter dependencies between various components of the system. The system engineer will also assist in coordinating teams and validating the system through appropriate testing routines.

4.4 High Throughput Systems

While relevant to Level 1, the complexity of the work flow may increase dramatically with Level 2 and above where there are multiple stations running in parallel. There are many factory and warehouse automation techniques available today that deal with optimising throughput such as scheduling and routing. It is likely that existing methods will be applicable, however adapting such a method to sheep shearing will require design and thought. Further, analysing the large catalogue of existing methods and determining which one is most suitable will require effort. Prototyping and testing of each subsystem (station) and integration of those operations will also require effort.

5 Conclusion

We feel that this project has successfully achieved its milestones and satisfied its aims. Our recommendations are provided within a proposed taxonomy for semi-autonomous shearing with increasing levels of autonomy. This taxonomy could be useful as a way to target future research funding and measure progress.

We are pleased that we were able to move beyond the original scope of the project. The 3D print represents tangible evidence of current technical capacity in capturing 3D geometry of live animals, and also is an indication of the capability of modern manufacturing methods.

One of the highlights of the project for us was our interaction with the shearers at the workshop. As a group, they showed their absolute mastery over their processes, which allowed us together to arrive at the general approach presented in this report.

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