FINAL REPORT

OPEN

Feasibility research and evaluation of miniaturised snake robotics for spinal cord removal prior to splitting beef carcasses

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PREPARED BY:	**Koorosh Khodabandehloo (BMC, UK) and OC Robotics, UK**
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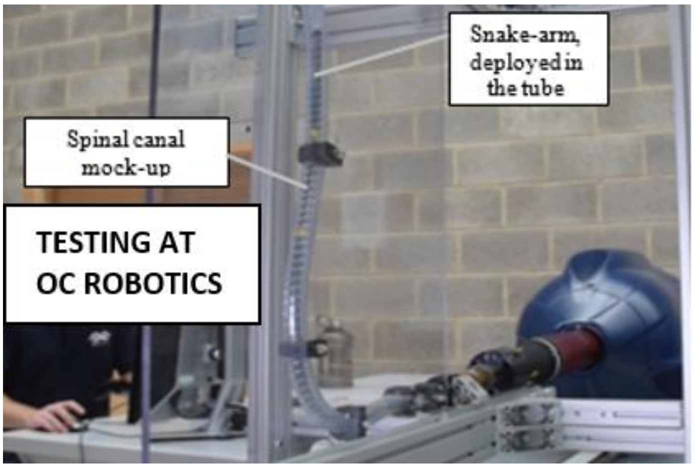
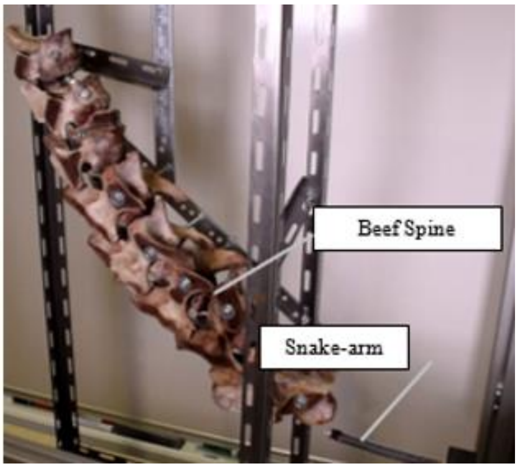
1.0 EXECUTIVE SUMMARY

A 1-meter length miniaturised Snake-arm robot, as a first step pioneering solution towards the automation of beef carcass spinal cord removal prior to splitting, has been implemented and successfully tested, with live presentation of the solution in an engineering environment.





Spinal cord removal and splitting have remained manual processes in slaughter houses around the world, due to the variability of the carcasses and the processes themselves posing significant challenges for automation. Since the beginnings of the BSE crisis, starting in the UK, BMC has been involved in the consideration and indeed evaluation of approaches for spinal cord removal in beef and lamb. Spinal cord removal is best done when the carcass is whole, which requires an “intelligent” tool to drive up the cavity, following the spine, extracting and scraping cord and nerve tissues leaving the inside of the spinal cavity free of any “risk material”. The line of the spine can also be referenced, facilitating accurate splitting by automation.

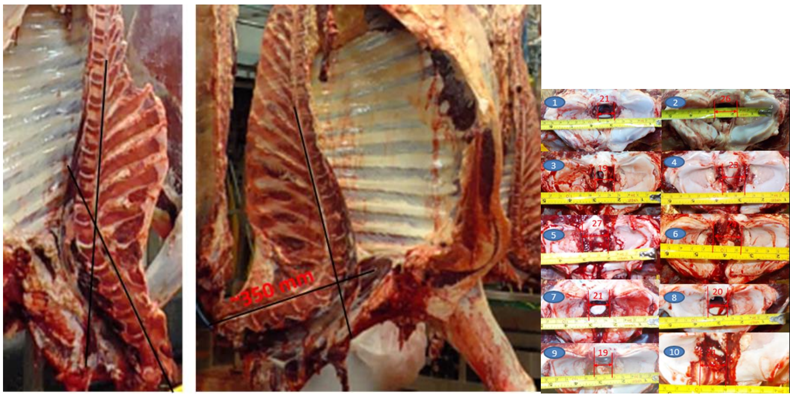
The approach for the project has been to develop an experimental miniaturised Snake-arm capable of entering the spinal cavity from the neck end of the whole carcass, with the head removed prior to splitting. It is the longer-term intent that the cord would be removed by such a robot arm, whilst providing data that could be used for a more accurate splitting, following the centreline of the spine, along the length of a whole beef carcass. This has benefits as follows:

- Improved yield avoiding soft siding by having accurate spine profile data for the calculation of line of cut for splitting,
- Increased containment of spinal cord as it would be removed prior to splitting, which is currently performed by a saw blade spreading the spinal cord tissue,
- Improved efficiency, as cord removal is a manual process as is splitting in most plants.

The operation of a Snake-arm robot needs to accommodate carcass variability and this research has quantified the following as relevant to its design:

- Carcass weights range: 120Kg to 400Kg in general,
- Carcass length, from hook attachment point to the tip of the neck: 2,000 mm to 3500 mm.
- Length of the spinal cavity as measured along the cavity: 1500 mm to 2800 mm,

- Spinal cavity cross section (best fit smallest circle): 14 mm to 25 mm (30 mm at neck entry)
- Angle of change in the spinal cavity: 15 degrees to 90 degrees at worst on a 100-mm radius.

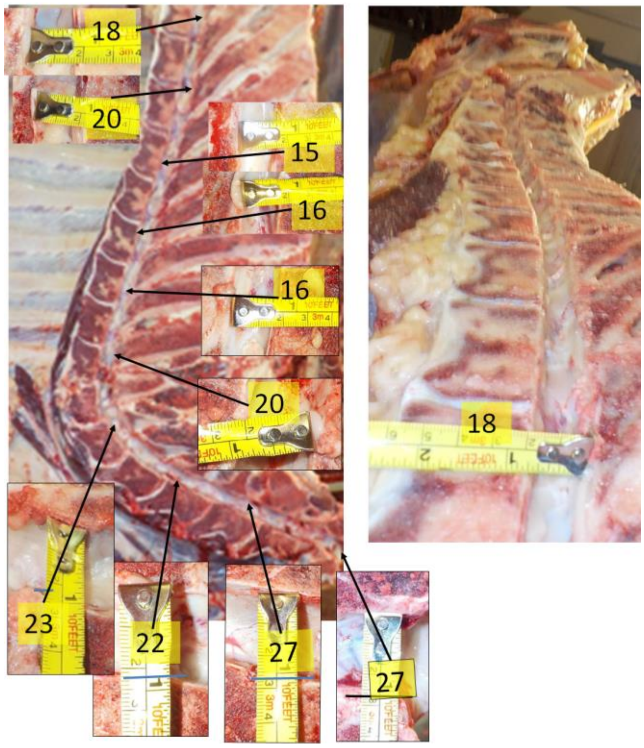


No	mm
1	21
2	26
3	19
4	23
5	27
6	24
7	21
8	20
9	19
10	21

The variability of the diameter along the length of the cavity poses the main constraint on the cross-section diameter of the Snake-arm being considered in a miniature form. A suitable design overcoming this constraint has been achieved.

The change of curvature in the spinal cavity in the neck region poses another constraint on the construction of the Snake-arm, with challenge for it to travel along the channel after a sharp bend. This has also been considered and resolved.

Two units of labour are generally used for splitting and two for cord removal at 60 carcasses per hour. In some plants, additional labour is used to clean the spinal channel after splitting, and prior to the cutting room. The target of two operator savings at A$ 140,000 is anticipated as a minimum in the cases of cord removal and splitting.



Soft-siding and inaccuracies resulting from splitting misalignment results in rework and loss of yield in around 1 or 2 carcasses per hundred. Saw blade thickness of 3.5 mm, generating bone dust during splitting resulting in an estimated loss of A$ 80,000 per year at 60 carcasses per hour in a single shift operation. The overall value proposition of the combined splitting and spinal cord solution is estimated at A$ 360,000 per year. Additional benefits include improved quality and shelf life (relating to bone dust), reduced spread of high risk spinal cord tissue, otherwise requiring intensive wash as well as subsequent reduction in water use.

As a first step pioneering feasibility, this project has reached the practical implementation of a fully operational 13.5 mm cross section, 1-meter long Snake-arm, bringing the possibilities of an automated beef spinal cord removal solution closer to reality. The Snake-arm has been tested in an engineering environment, showing its capability to manoeuvre a 90-degree bend having a 100mm radius of curvature.

2.0 INTRODUCTION

The project has come about from consultation with several Australian Companies. Customer specification as well as legislative measures require the removal of high risk tissues in Beef Carcasses. Assessment of procedures in the USA places McDonalds at the top of the list in respect of stringent requirements above those that need to be met by veterinarians, with zero tolerance. High penalties and automatic delisting from the supply list are measures that impose almost impossible trading constraints on processors.

Since the beginnings of the BSE crisis, BMC has been involved in the consideration and indeed evaluation of methods for spinal cord removal in beef and lamb. A main conclusion is that the removal of spinal cord is best done when the carcass is whole, which requires an “intelligent” tool to drive up the cavity, following the spine, extracting and scraping cord and nerve tissues leaving the inside of the spinal cavity free of any “risk material”. After head removal and evisceration, spinal cord removal in beef carcasses is best done when the carcass is whole (unsplit). This requires an “intelligent” tool to drive up the cavity, following the spine, extracting and scraping cord and nerve tissues leaving the inside of the spinal cavity free of any “risk material”. The line of the spine can also be referenced, facilitating accurate splitting by automation.

The approach for the project has been to develop an experimental Snake-arm capable of entering the spinal cavity from the neck end of the whole carcass, prior to splitting. Beef carcasses are split with spinal cord in the carcass and it is intended that the cord would be removed by such a robot arm, whilst providing data that could be used for more centred splitting along the vertical line of the spinal.

OC Robotics (**http://www.ocrobotics.com/**) and BMC have been the providers in this project, delivering the target Snake-arm model as functioning 1-meter long unit, with 13.5 mm cross section for the first time. The main challenge that has been overcome has been the miniaturisation of the Snake- as s first step.

The need for accurate splitting and removal of spinal cord is clear in the current beef slaughtering operations. This project has reached successful feasibility in the implementation of a trial miniaturised Snake-arm robot in an engineering environment.

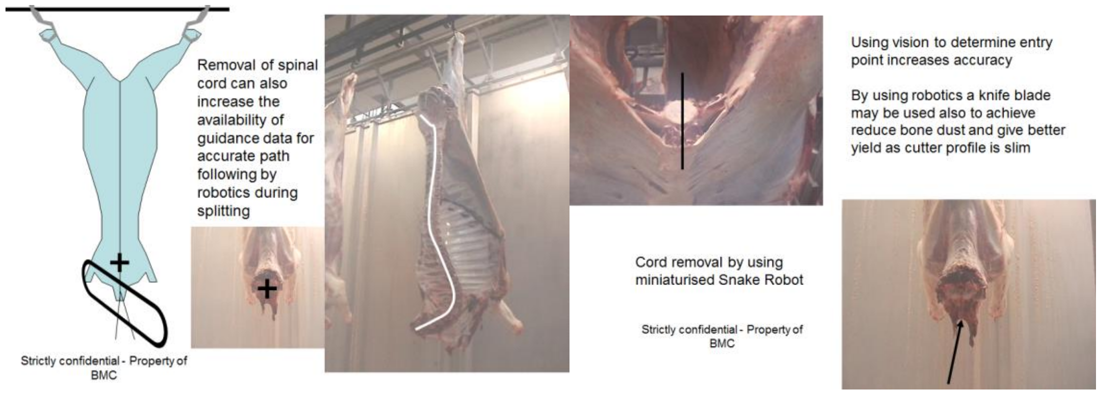
3.0 PROJECT OBJECTIVES

- Examination and documented quantification of the spinal column variability in beef, including process parameters influencing cord removal and splitting
- Evaluation of efficiency and process capability factors
- Specification of technical requirements for combined Snake-arm robot tools and splitting technology to achieve automation, with cord removal before splitting
- Quantify Snake-arm miniaturisation parameters
- Define manufacturing constraints including Snake-arm link prototyping
- Construct experimental miniaturised Snake-arm and test with spinal section of beef carcasses (small and large.
- Report on findings

4.0 METHODOLOGY

- Measure carcass variability
- Define range and constraints in technical specification
- Observe and quantify limitation of current practice including losses in efficiency and yield due to soft-siding
- Review existing developments, including medical arms for endoscopy in medical applications
- Define Snake-arm parameters and technical specification of the mechanical arm (no controls, but limited electrical drives)
- Construct and test mechanical arm (no electrics)
- Add simple electrical drive and test with sections of beef spine
- Produce video and written report

The following figures illustrate the long-term concept:



5.0 PROJECT OUTCOMES

The project has successfully reached the following outcomes in accordance with the timeline of the project.

- Quantification of variabilities in respect of spinal cord removal,
- Documenting current practice and key performance drivers for the processors,
- Definition of combine cord removal prior to splitting and automated splitting, based on practical information in existing operations,
- Specification and implementation of a miniaturised Snake-arm of 1 meter in length, tested with a section of a representative beef spine section.

The project has demonstrated the feasibility for the implementation of a miniaturised Snake-arm robot, capable of travelling into the spinal cavity of a whole beef carcass through the neck after head removal. The project has specified and fully constructed a 1 meter long, 13.5 mm diameter cross section model of the Snake-arm. The operation of the miniaturised Snake-arm with a skeletal section of a beef front section was formally demonstrated on 9th August 2017.

The following sections of this final report on the stage 1 of this project describes the outcome.

5.1 Quantification of Beef spinal column variability

The variability of beef carcasses ranging 120Kg-400Kg has been reviewed. The measurements that quantify the variability have focussed on those relevant to the scope of the feasibility, whilst highlighting the challenges that must be overcome in a full development.

Figure 5.1.1 shows the intended process, which is to remove the spinal cord in a beef carcass immediately before splitting. The challenge will be to engage the robot for travel along a channel with variability of 15 mm to 27 mm in diameter of cross section, whilst cleaning out the spinal tissue in full, before splitting.

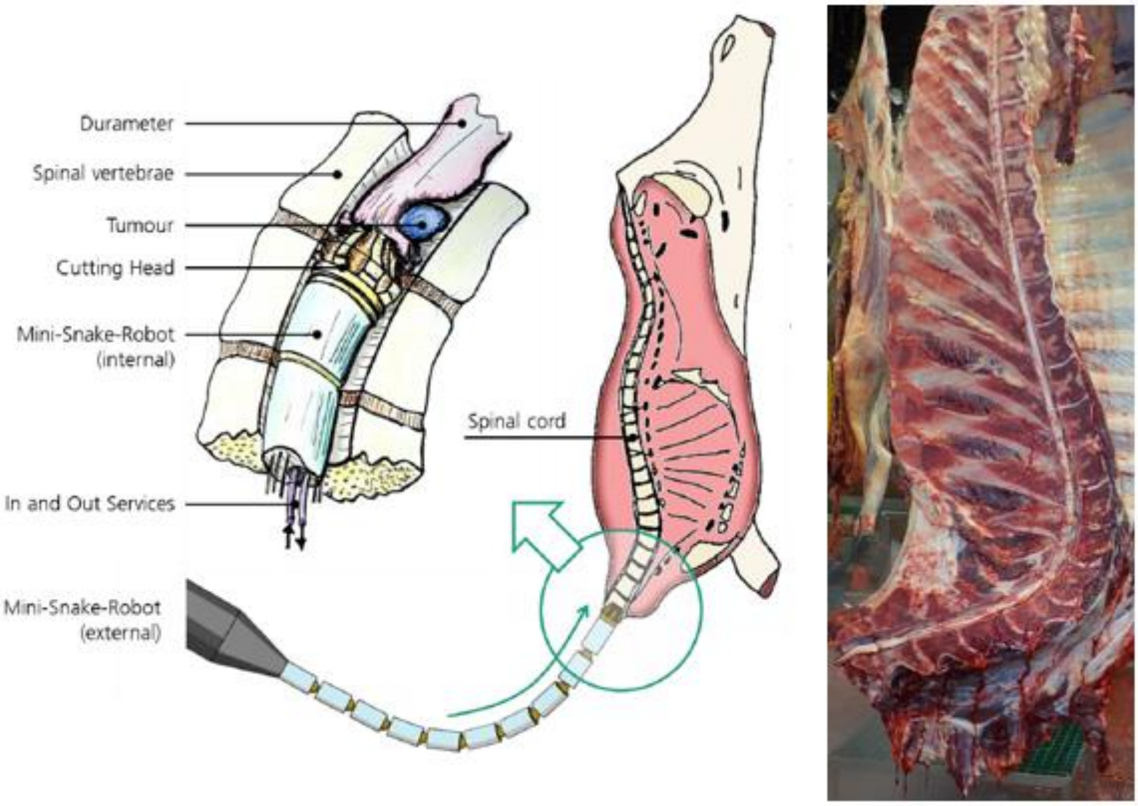


Figure 5.1.1: Target cord removal

It is anticipated that the Snake-arm would provide data that can be used to perform splitting by following the centre line of the spinal column for a more accurate vertical separation that may be achieved manually. This will complement a parallel R&D activity to achieve automatic splitting as an integrated process.

It is considered that a Snake-arm of 1 meter would show the feasibility process, especially with respect to positioning, penetration and following the channel passed the point of maximum curvature (see Figure 5.1.2).

Figure 5.1.2: Change of angle of spinal cavity along the length of the spine.

5.1.1 Size variability

The range of beef carcasses have been measured as follows:

- Weight range, which is an indication of magnitude of variability is measured to be 120Kg to 400Kg.
- Carcass length measure from the hook attachment point holding the carcass to the lowest point of the carcass with carcass hanging (which is the tip of the lower part of the neck) is measures in the range 2500 mm to 3300. See Figure 5.1.3.
- Of relevance is the length of the spinal cavity along the body of the carcass as measured along the spinal channel, which is 1500 mm for the smallest carcass and 2100 mm for the largest observed.

Figure 5.1.3: Size variation.

5.1.2 Variability at spinal cavity entry at neck

An important feature in the intended Snake-arm solution for spinal cord removal will be the location of the spinal entry point at the neck of the carcass with the head separation, prior to splitting. The main variable will be the physical location of the positioning of the neck entry point in 3D space, which may be sensed using conventional laser imaging systems. As the carcass travels along the rail, the measurement along the chain would require a vertical scan covering the range of carcass lengths. It is necessary to locate the neck entry as in Figure 5.1.4, with the resolution that allows placement of the tip of the Snake-arm for automatic entry into the spinal cavity. The variability of relevance is the diameter of the opening at the neck entry, which is quantified in the range 19 mm to 27 mm as presented in Figure 5.1.4.

The extent of the challenge would be as follows:

- Measure carcass neck spinal cavity entry point in the 3D space to better than ±10 mm, where the carcass length can vary after head removal in the vertical space of 1 meter.
- Locate by focused measurement using vision the location of the spinal cavity entry point at the neck centre to ± 1 mm within the minimum 19 mm diameter circle, but in a search window, that covers the diameter of 27 mm in the expanded window by a minimum of 20 mm around the area of interest. Thus, the imaging window would need to be 50 mm by 50 mm minimum with pixel resolution that provides the entry point to better than ±1 mm.

No	mm
1	21
2	26
3	19
4	23
5	27
6	24
7	21
8	20
9	19
10	21

Figure 5.1.4: Neck entry point variability.

It is important to highlight that the speculated definition of sensing capability to measure the neck entry point, based on the relevant variability as described, may be augmented by additional operational considerations, such as carcass movement and speed of the line. The data; however, for the carcasses available for measurement at the time of observation present the scope and range of variability for the purposes of the feasibility, which is to define the Snake-arm specification and intended capability, over the period of the project. Further evaluation of the variables and the carcass variation that could influence the definition of a full-size Snake-arm for commercial implementation may be necessary, prior to such future undertakings.

5.1.3 Variability along the channel

Once the Snake-arm has entered the spinal cavity, the channel variability becomes relevant. Figure 5.1.5, presents the variability of the channel diameter in the larger and the smaller carcasses observed at the time of data collection and measurement.

Figure 5.1.5 left presents the cavity diameter at 100 mm intervals along the channel and to the right is the same for the smallest of the carcass sides observed. The measurements considered relevant to the scope of the feasibility, which is to test a short length (1 meter) Snake-arm, that is to extend a distance beyond the point of the spine maximum curvature (see image bottom left of Figure 5.1.5).

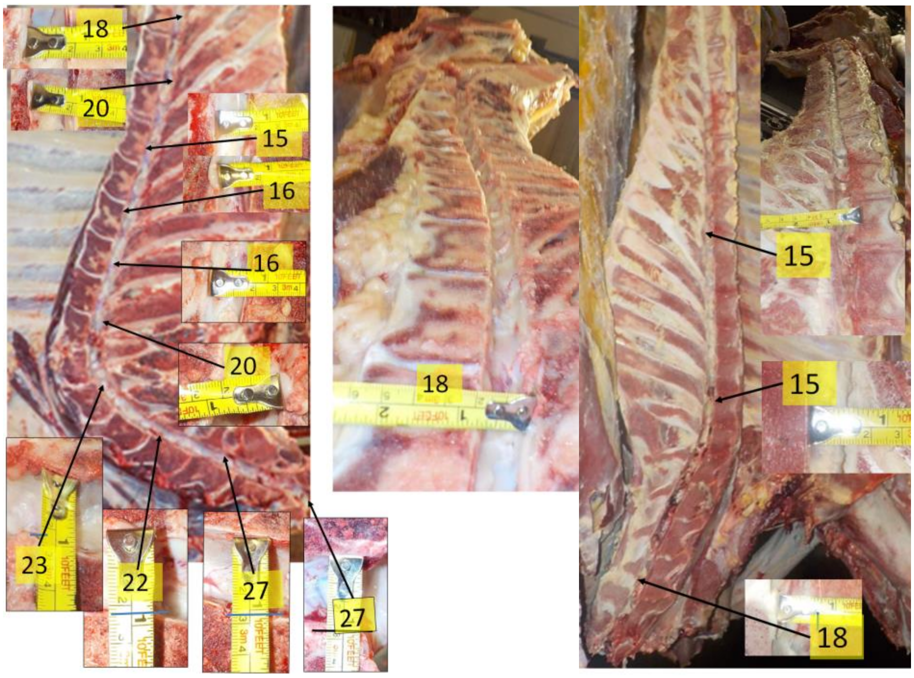


Figure 5.1.5: Spinal cavity channel variability.

The smallest diameter along the channel cavity observed is 15 mm and the largest observed is 23 mm after the entry point. The Snake-arm diameter of 13.5 mm is thus considered appropriate in this feasibility study. The process; however, needs to accommodate for a tool tip that can free and evacuate the channel across the full spinal cavity cross section removing cord along the spine accommodating for the variability of the channel diameter, ranging 15 mm to 27 mm.

5.1.4 Variability maximum curvature at turning point along the cavity

The Snake arm needs to navigate along the spine following the bends as shown in Figure 5.1.2 with spine angle changes that can be close to 90 degrees. The flexibility in the linkages need to allow for a worst-case curvature, which is estimated at 100mm (Figure 5.1.6).

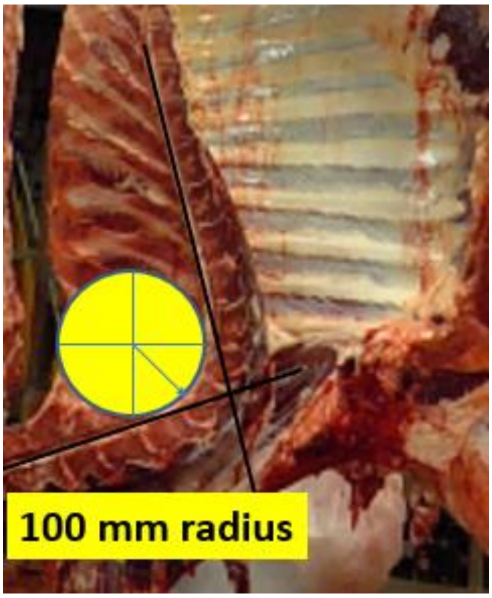


Figure 5.1.6: Curvature in the spinal cavity along the spine in the neck region.

5.1.5 Other observations

Observations were made highlight practical considerations relevant to the project beyond this feasibility. Breakage of the back, half way up the carcass, as in Figure 5.1.7, and the narrowing of the channel at the tail as in Figure 5.1.8 pose additional challenges for the Snake-arm to be implemented for practical use.

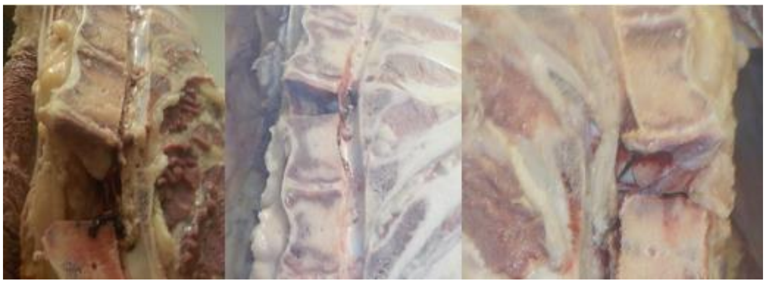


Figure 5.1.7: Spinal break points.

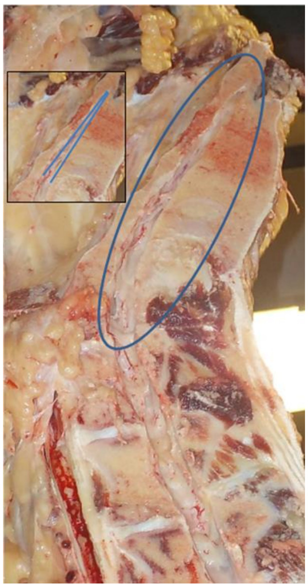


Figure 5.1.8: Narrowing of the channel in the tail end of the spine.

The strategy for the broken spine would be to follow one the unseparated wall of the cavity or follow the channel straight to relocate the cavity after the breakage, whilst evacuating spinal tissue. The practical test s with the 1-meter long Snake-arm suggests that bridging of such gaps would not pose a risk to the Snake-arm travelling along the spinal channel, as such break points are not observed at the turning points of high curvature around the neck region.

The considerations of the narrowing of the tail cavity is outside of the scope of this feasibility; however, a future approach would be to have an extending insert that has much smaller diameter to protrude into the narrow section once the Snake-arm-trip reaches the point where its diameter prevents further travel of 13.5 mm tip of the Snake-arm tip along the channel.

5.2 Evaluation of efficiency and process capability

The current practices of splitting and spinal cord removal in meat companies slaughtering cattle have been observed. Examples from USA, Europe and Australia have been included, where process capability has been observed. In total, the assessments have been based on seven locations, one in Europe, one in USA and 5 in Australia. It is considered that automatic cord removal would need to be compatible in speed to splitting, the rate being compatible to the rate of separation during the splitting action, resulting in a cycle match. The manually performed spinal cord removal for two carcass sides, after current manual splitting, in the present process is on average 20 seconds. This is verified by observation and video recordings of current practice. Documented results estimate 10 seconds per split side to be the duration of cord removal using a hand tool (20 seconds for the two sides). The cord removal duration by the Snake-arm robot is recommended at 20 seconds mapping approximately the average splitting duration. Wash and sanitisation cycle of splitting tool requires an average 10 seconds. Adding manual handling actions between carcasses on the overall cycle for both is estimated at 50-60 seconds. In general, two units of labour are used one for splitting and two for cord removal at 60 carcasses per hour, depending on carcass sizes. In some plants, additional labour is used to clean the spinal channel after splitting, two before the end of the slaughter line and one prior to the cutting room. The target of two operator savings at A$ 140,000 is anticipated as a minimum for both splitting and cord removal operations in an average single shift 60 carcass per hour plant.

Soft-siding and inaccuracies resulting from splitting misalignment results in rework and loss of yield in around 1 or 2 carcasses per hundred. Splitting saw blade thickness of 3.5 mm results in a loss of A$ 80,000, totalling the value proposition for an automatic splitting solution at A$ 220,000 per year. This is in addition to other benefits from improved quality and shelf life (relating to bone dust), reduced spread of high risk spinal cord tissue, otherwise requiring intensive wash, with subsequent reduction in water use. Labour savings for splitting and cord removal and their re-deployment to safer and less physically intense operations will result in better work for staff in such tasks.

The penetration process as a requirement is targeting 50 mm/s. The process would replace the current process where a person uses a small diameter, powered trimming tool with a vacuum attachment as shown in Figure 5.2.1.

Figure 5.2.1: Bettcher vacuum process: a hand tool trimmer evacuating spinal cord.

The manual process occurs after splitting, which uses a saw cutter and exposes the rest of the carcass to high risk spinal cord tissue during the separation process. See Figure 5.2.2. The saw blade is generally 3.5 mm in thickness. It is envisaged that a knife blade would be used once the centreline is capable of being sensed with the Snake-arm. The Snake-arm, having followed the spinal column cavity, would be able to register the path of the cut that needs to be followed. This information would provide a path for standard splitting robot, but with a knife-blade to carry out the process.

On average 3 mm of bone and meat at the centre of carcass may be left behind if a knife blade as in Figure 5.2.3 is used. It is estimated that this is a minimum of 2Kg per carcass at A$20/Kg. At 60 carcasses per hour, in an 8-hour shift, the saving would be A$ 80,000 per year.

Figure 5.2.2: Saw splitting: spreading spinal cord tissue.

Figure 5.2.3: Knife blade replacing saw blade for splitting.

Manual splitting has been benchmarked using data from 7 plants including one in Europe and another in the USA. Figure 5.2.4 shows the results placing the splitting duration using a saw blade at 19 seconds on average. The total cycle; however, is 50-60 seconds, which includes the wash process and the time to reposition the cutter for cutting the next carcass.

Snake Arm and splitting			Mar-17
Splitting cycle and efficiencies			
Location	Splitting	Speed	Splitting
Code	Duration	mm/sec	Length mm
1. HV	20	125	2,500
2. MP	23	87	2,000
3. SY	20	100	2,000
4. FP	18	139	2,500
5. NL	19	105	2,000
6. TF	16	125	2,000
7. RO	17	118	2,000
Average	**19**	**114**	**2,143**

Figure 5.2.4: Observed splitting duration.

In a cyclic operation, it is envisaged that the cord removal process would start with the Snake-arm entering the spine cavity from the neck. After cord removal, at the point when the Snake-arm is about to retract, the splitting process would start from the tail down as the Snake-arm withdraws. The Snake-arm would be automatically wash and sterilise during every retract cycle.

The process steps would be as follows:

- Snake-arm to engage a carcass entering at the neck end of the carcass to remove spinal cord on the move,
- Snake-reaches the end of its travel along the full length of the spinal column cavity,
- Data on the centreline is transferred to a splitting robot with knife blade,
- Splitting starts, whilst Snake-arm starts retracting (at higher speed) whilst washing itself to engage the next carcass for cord removal.
- Snake-arm engages the next carcass and starts removing the cord,
- The splitting robot completes the wash cycle for the splitting tool and engages the next carcass as soon as cord removal process for that carcass is complete, with the Snake-arm retracting,

5.3 Specification of combined Snake-arm robot and splitting technology

The specification requirement for the combined spinal cord removal and splitting, referred to as the CordSplit Process has been documented by the project. The automated system for carrying out the process (the CordSplit robotic system) combines the capabilities of a Snake-arm robot, with appropriate tooling and controls to enter a whole beef carcass from the neck opening after head separation at the end of a slaughter line, after evisceration and before splitting, to remove spinal cord tissue from the spinal cavity.

The Snake-arm needs to have appropriate sensory elements that would provide guidance to a robot, equipped with a splitting tool as well as complementing sensory devices to achieve carcass splitting in a more precise manner than achievable manually using the spinal centre line, determined from the path followed by the Snake-arm during cord removal.

Figure 5.3.1 presents the combined system elements as a visual specification in a conceptual manner. The system components need to include:

1. Snake arm with associated controls, sensing subsystems and drive system that allows the Snake-arm to be extended (Figure 5.3.1A) from the point of entry, guided by sensors (Figure 5.3.1B) and mechanisms that support and drive the Snake-arm (Figure 5.3.1C).

2. A splitting system (Figure 5.3.1D) that places the cutting tool accurately at the start of the splitting line as shown, driving it down, with the blade cutting along the centre line of the beef carcass.

3. Sensing capability on the Snake-arm that allows the cutting blade to follow the path defined during cord removal.

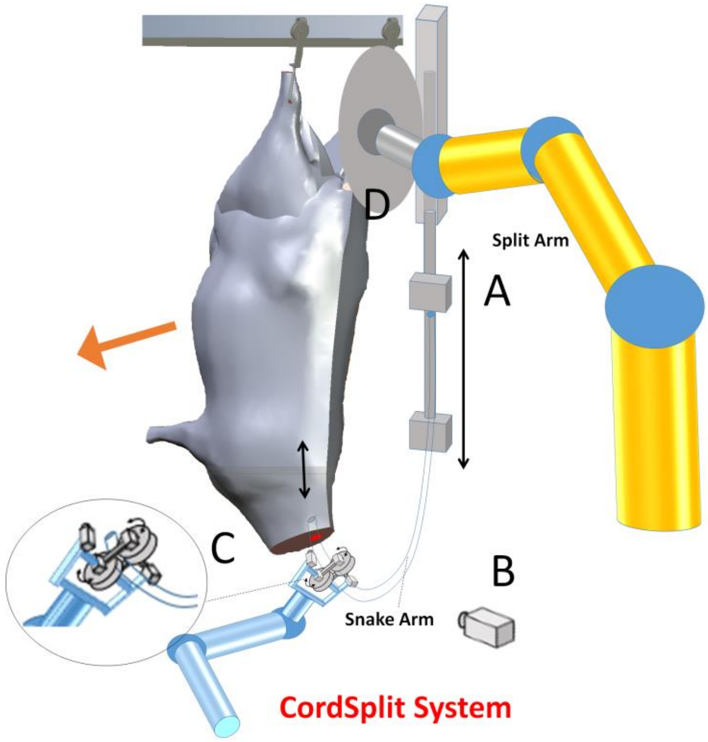


Figure 5.3.1: Visualisation of CordSplit - combining Snake-arm robot and splitting technology.

The specification of the overall system is summarised, with reference to Figure 5.3.2, as follows:

± 2 mm positioning of the head of the Snake-arm relative to the neck entry centre point.
± 2 mm positioning of the tip of the blade at the point of the entry on the tail vertebra centre
± 2 mm line deviation for splitting robot blade along the splitting line path.

The Snake-arm is to follow the internal channel along the spinal column staying within the boundary of the spinal cavity.

5.3.1 Combined Snake-arm – Splitting Technology specification

Figure 5.3.2 defines the specification of the CordSplit system with the required capability of the process and the system.

The equipment in its final form must accommodate for the variability of carcasses presented earlier. The Snake-arm, when at the end of its travel in the spinal cavity, can be made to define a position in the carcass that can be referenced relative to the tail vertebrae centre point (see Figure 5.3.2). This will set up a vector (V) that would define the entry alignment for the splitting blade. In the case of a circular cutter, the body of the blade after entry into the spinal column, would fix the line of split and act as a fixture restraining the movement of the carcass side-to-side. The alignment and centring of the blade would maintain the line of separation along the splitting path. If a saw blade is used, it is possible that the path of the cut would require correction along the splitting path, hence updating can be made using the Snake-arm transmitting electronic reference of its position along the separation path as it travels up, and withdraws out of, the carcass spinal cavity.

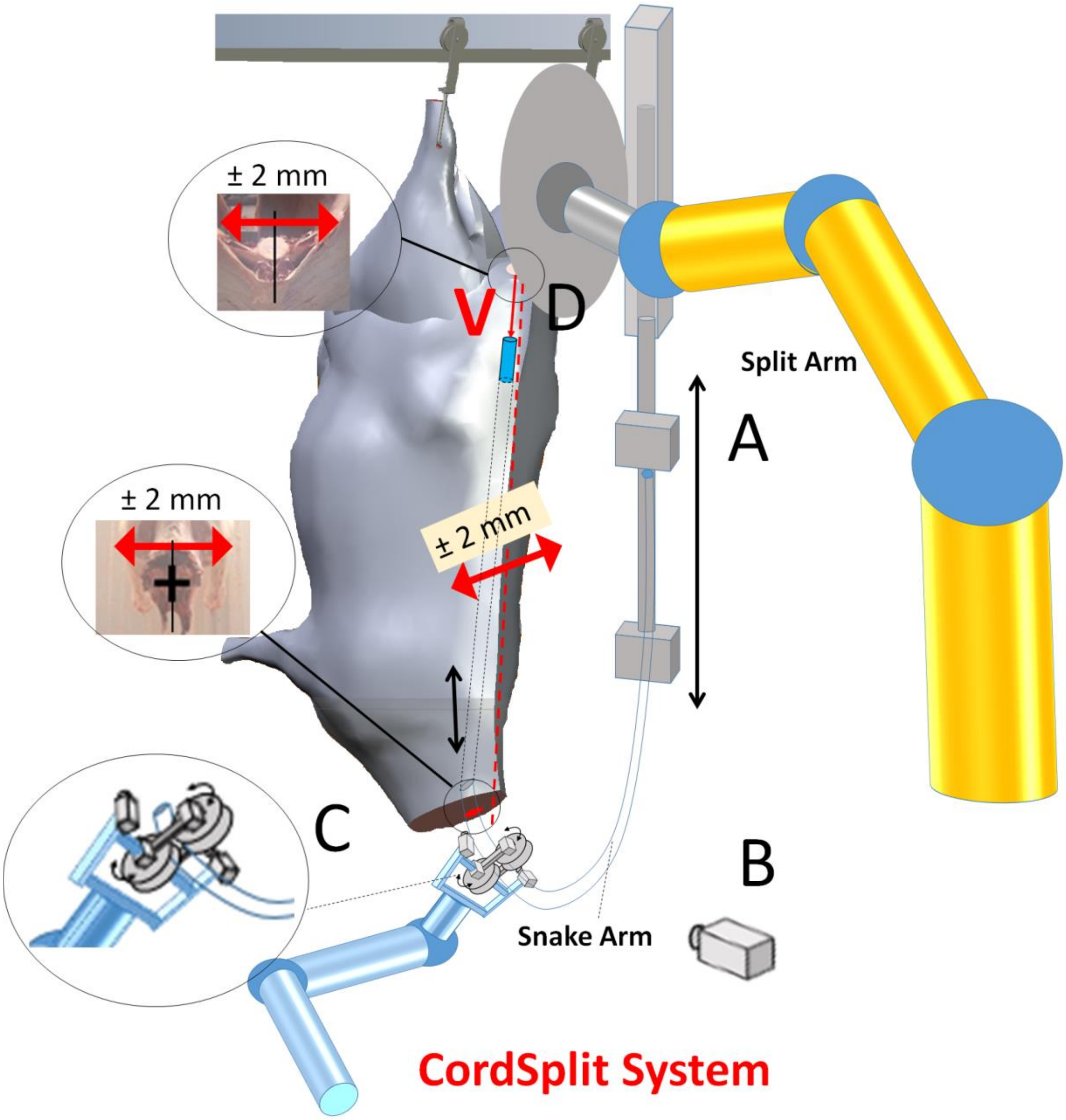


Figure 5.3.2: Accuracy and splitting control with Snake-arm transmitting position reference.

5.3.2 Mini-Snake -arm

The Snake-arm design is based on over 2 decades of OC Robotics experience of building such systems for practical use in the mining, nuclear and petrochemical industries. The schematic design of the miniaturized Snake-arm system, including its main components, is presented in Figure 5.3.3.

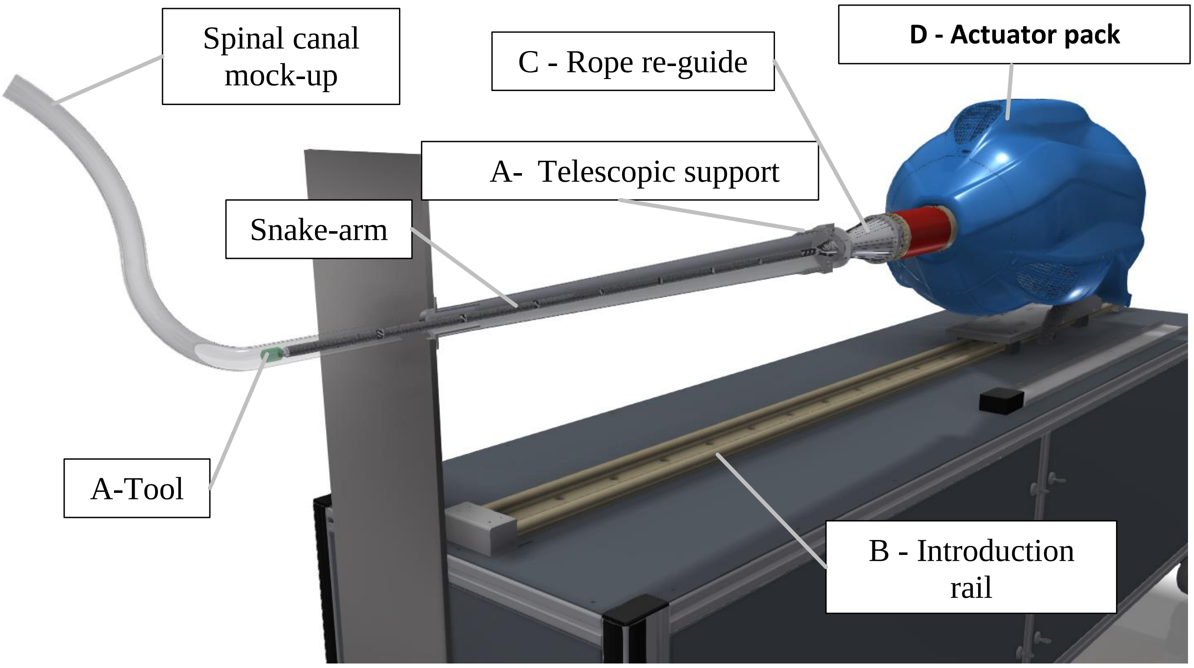


Figure 5.3.3: Experimental Snake-arm.

Specific tools and sensors may be mounted on the end of the Snake-arm for removing the spinal tissue and for providing tracking information for use in the splitting process.

The Snake-arm includes several continuously flexible segments, which are constrained serially (Figure 5.3.4). The shape of each segment is controlled by 3 wire ropes that are pulled differentially. By controlling the amount and direction of each segment's bend, the Snake-arm can be steered along a complex path as desired. The Snake-arm has a protective skin that may be cleaned or removed and disposed of.

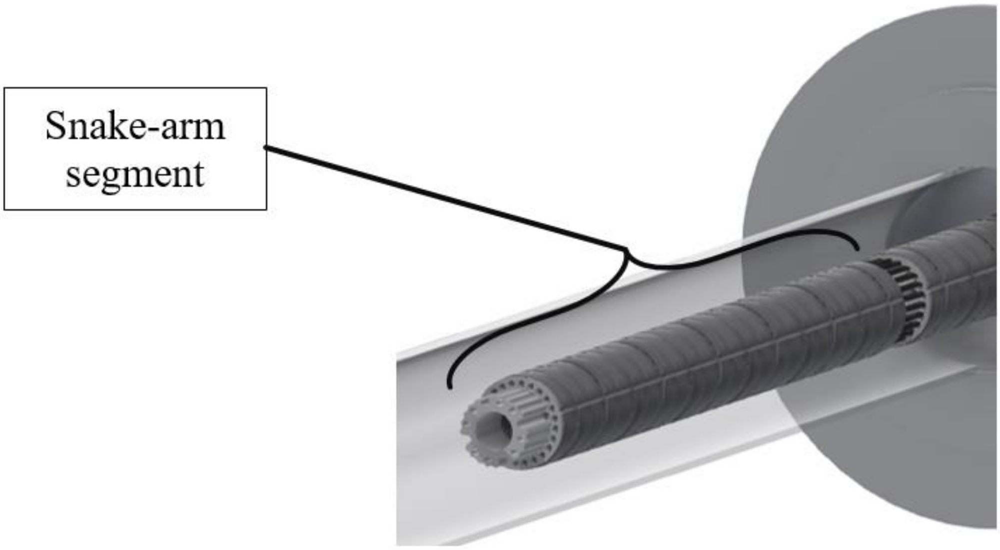


Figure 5.3.4: Close-up view of a continuously flexible Snake-arm segment.

The Snake-arm is very slender (long relative to its diameter) requiring a telescopic support (Figure 5.3.3-A) for when the arm is fully retracted. This is to be constrained between the base of the Snake-arm and the front of the introduction rail (5.3.3-B) platform, and is stowed automatically as the Snake-arm is deployed.

The rope re-guide (Figure 5.3.3-C) provides the interface between the base of the Snake-arm and the Actuator pack (Figure 5.3.3-D). This component allows for services that run along the centre of the Snake-arm to be routed between the wire ropes to avoid them running through the Actuator pack.

The Actuator pack contains all of the actuator components required to pull the Snake-arm control ropes, along with their control and communication electronics.

The Snake-arm is deployed into the working environment (in this case along the spinal cavity) by means of an introduction rail. For practical experimental tests, this will comprise a table-mounted linear rail and carriage system is used.

5.3.3 Scheme design specifications

Table 5.3 provides a summary of the system scheme design specifications.

Parameter	Specification
Snake-arm diameter	12.5mm (with no skin) 13.5 mm (with skin)
Snake-arm flexible length	1032mm
Number of independently controlled segments	8
Snake-arm minimum bend radius	100mm

Table 5.3: Scheme design specifications summary.

5.3.4 Tool development

Methods of incorporating tissue removal tool onto a Snake-arm device may be based on existing technology. To be considered, beyond this feasibility, are: method of transferring power to the tool for cutting/grinding; knife designs for cutting ganglia; tool variations depending on size of vacuum tube. Maximising the diameter of the vacuum tube may simplify the tool design and give the best tissue removal rates; however, this is considered difficult to incorporate in the existing Snake-arm design.

It is anticipated that particular technical challenges with the tool will include: 'locking on' to the cut end of the spinal cord where the head has been removed; ensuring that the tool sucks in the entire cut end of the spinal cord including the Dura Mater; continuing to capture the entire spinal cord into the end of the tool whilst inserting the tool - and avoiding rupturing the Dura Mater; avoiding the tool becoming clogged with stringy tissue and/or detecting that this has happened and providing a method for unclogging.

5.4 Construction of experimental miniaturised Snake-arm and testing

The work presented in this section establishes the basis for a practical solution, where subsequent designs extending the feasibility, would achieve suitable solutions for the industrial application environment.

The construction, implementation and testing, using a simulated set up has been reached and tested with a section of beef spine.

The project has reached full feasibility status as targeted, including:

- As a first pioneering task, the development of a 1-meter long miniaturised Snake-arm, assembled fully with an existing power pack, a protective skin added and the drive control electronics implemented for its operation.
- Integration and software modules for guiding the Snake-arm along a narrow tube testing the Snake Arm.
- Fully implemented integration with the Actuator Pack and control software for testing with a section of beef spine and reaching the conclusion of this feasibility project.

5.4.1 Integrated Snake-arm system

The Snake-arm assembly with the actuator pack is shown in Figure 5.4.1. Each section of the Snake-arm is connected to a drive actuation system using a bundle of high strength ropes. The ropes were tensioned to provide the motion control using the actuation of each rope by varying the tension. The assembly was also integrated with a telescopic support. Because the Snake-arm is very slender (long relative to its diameter), the telescopic support is required to support the arm during deployment. The telescopic support is physically integrated between the base of the snake-arm and the front of the introduction rail platform, stowing automatically as the Snake-arm extends or retracts along the path of travel, in this case the spinal channel. The Snake-arm was also sleeved with a protective skin that could be cleaned, or removed and disposed.

To control the Snake-arm with the existing actuator pack, several software components were written. These included a control module for the continuously flexible Snake-arm links and the configuration computer files for the existing hardware.

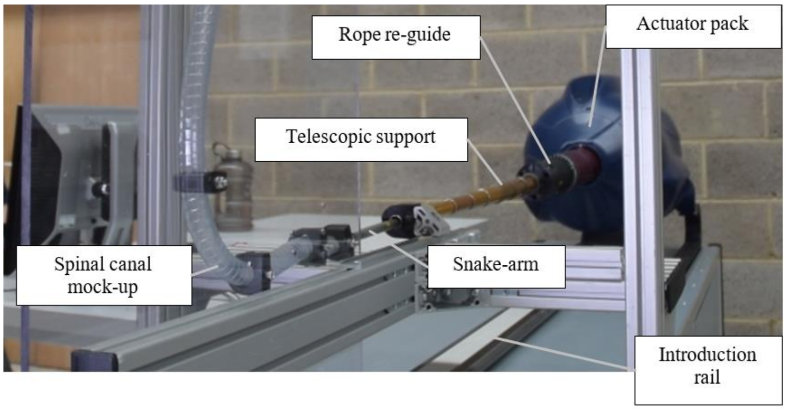


Figure 5.4.1: System setup.

5.4.2 Testing

The Snake-arm system was first deployed in a mock-up of a spinal canal. A 20mm diameter plastic tube was shaped to represent the beef spine and the Snake-arm successfully steered along its length (Figure 5.4.2).

The testing was repeated and the performance confirmed without interruptions or faults over the testing period.

The trial in the mock-up demonstrated feasibility and robustness under test conditions.

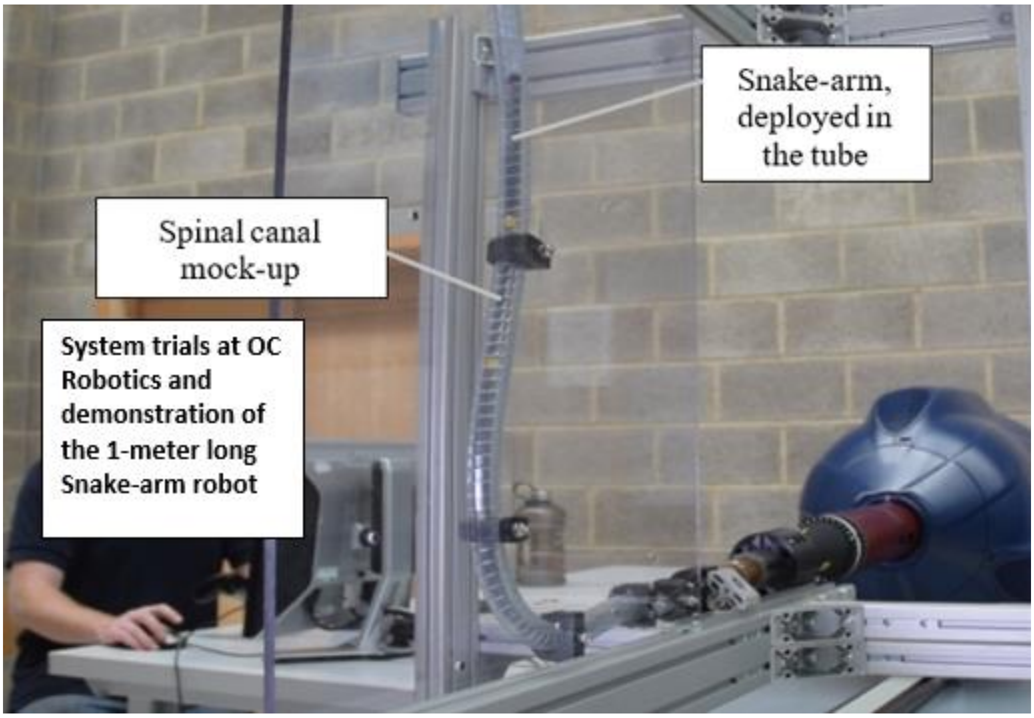


Figure 5.4.2: System testing in the mock-up using a plastic pipe, (note 90 degree, 100 mm radius bend).

The final stage of testing was to deploy the Snake-arm in the skeletal structure of an actual beef spine section. The geometry of the spinal model was made to represent the curvature of the spinal cavity in a front half of a beef carcass. The arm was successfully and repeatedly deployed through the spinal section (Figure 5.4.3).

The testing has successfully proven the feasibility of deploying a Snake-arm robot through the geometry of a beef spine, with a spinal curvature of 100mm radius, following a 90-degree bend – meeting the project's overall objectives, proving feasibility.

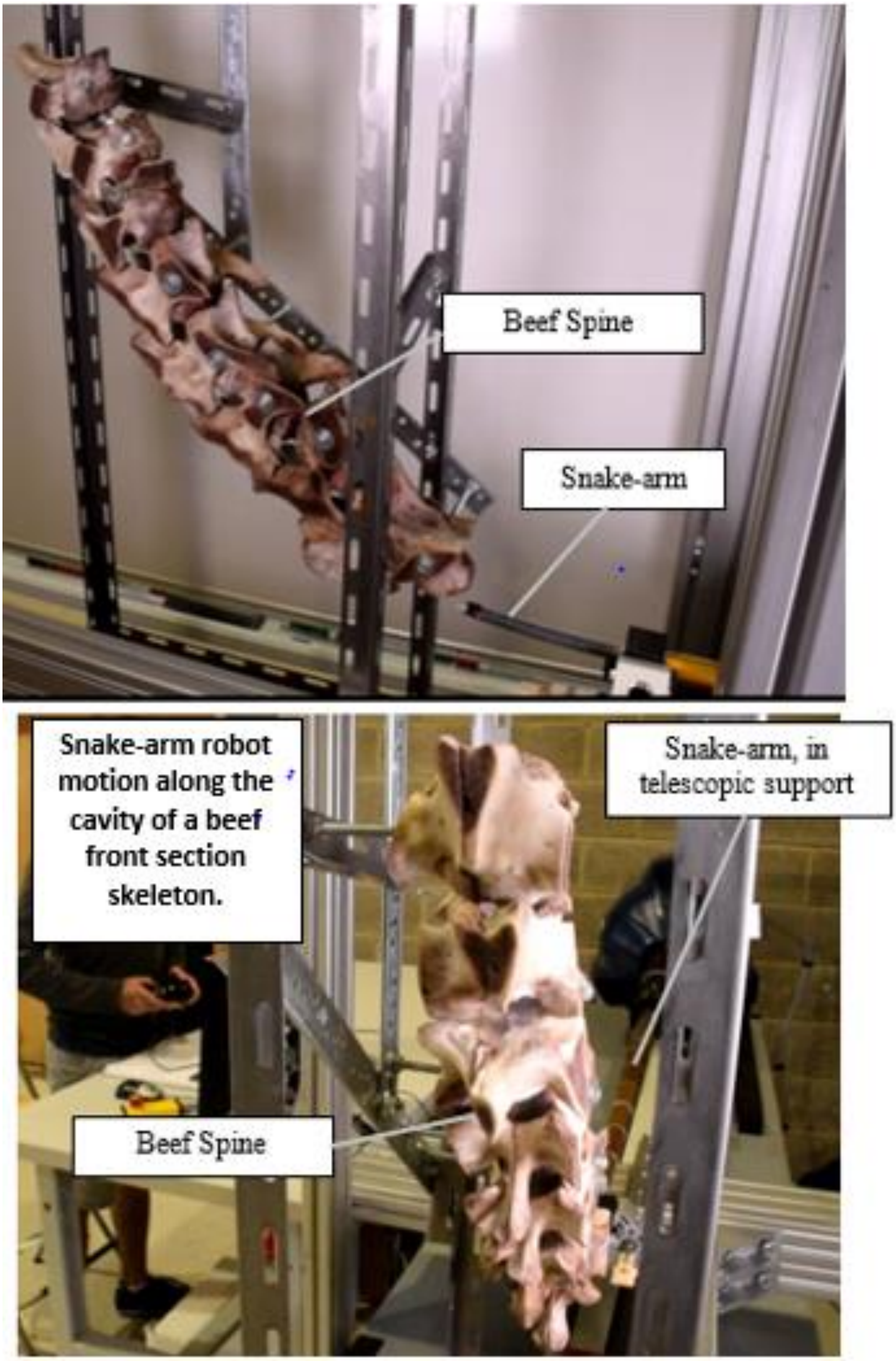


Figure 5.4.3: System testing in the beef spine section.

6.0 CONCLUSIONS/RECOMMENDATIONS

A full 1-meter length miniaturised Snake-arm as a miniaturised unit, as a first step pioneering solution targeting beef carcass spinal cord removal prior to splitting, has been implemented and successfully tested as pioneering first step by this project.

The testing has been performed using a transparent flexible plastic pipe, fixed in an assembly, representing the front section of beef spinal cavity.

The Snake-arm has been tested and the feasibility of motion along the channel of a beef spine section demonstrated.

Beyond this project, the next overall step for this technology would be to consider the integration of the miniaturised Snake-arm robot with a tool to remove spinal matter and provide tracking information for use in subsequent carcass splitting processes.

The achievement of the project to produce a miniature Snake-arm is a pioneering step of international standing and has been made possible by this project and demonstrated practically. The steps to reach the next development to use the Snake-arm for spinal cord removal as above will make an important ground-breaking contribution to the meat industry.

The overall value proposition of the combined splitting and spinal cord solution is estimated at A$ 360,000 per year. Additional benefits include improved quality and shelf life (relating to bone dust), reduced spread of high risk spinal cord tissue, otherwise requiring intensive wash as well as subsequent reduction in water use.

The funding for this feasibility under the AMPC Research is gratefully acknowledged as is the contributions for Australian Meat Industry.

Special thanks are due to the team working on the project to reach ground-breaking results in the field of robotics, especially the miniaturisation of a Snake-arm, which has been practically developed and tested.

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