BRITE EURAM RESEARCH PROJECT

Robotic Butchery of **Carcasses for Meat Production (ROBOCAMP)**

BE 4420- BREU CT91 0484 (RZJE)

PUBLISHABLE SYNTHESIS REPORT

Partners and their role

UNIVERSITY OF BRISTOL (AMARC)
- Co-ordinator
Queen's Building
University Walk
Bristol
BS8 lTR
Tel: ++44 1179257126
Fax: ++44 1179257127

A Centre of Excellence for research in robotics: responsible for co-odination and execution of all supporting research and development including integration and testing.

BANSS MASCHINENFABRIK GmbH
Industriestrasse 4
35216 Biedenkopf
Hessen
Germany
Tel: + +49 64617050
Fax: ++49 6461705115

A leading international manufacturer of quality machinery in the meat sector: responsible for development of mechanical and low level control subsystems.

HITEC SA
Modern Technology and Computer Applications S.A.
204 Messogion Ave.
Cholargos 155.61
Athens
Greece
Tel: + +30 16548873
Fax + +30 16547740

A technological company specializing in computer applications: responsible for sensor technology development.

FRIGORIFICOS ANDALUCES DE CONSERVAS DE CARNE SA (FACCSA)
Plaza Prolongo 2
29580 Cartama Estacion
Malaga
Spain
Tel: + +34 52420050
Fax: ++34 52420115

A company specializing in pork products: the end-user in the project.

INTELLIGENT DECISION SYSTEMS (IDS)

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KEYWORDS:

Meat cutting
Robotics
Food
Modelling
Vision

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SUMMARY

Shortages of skilled labour and the increasing demand on meat processors to reduce price whilst improving quality and safety in production plants have been major issues for the food manufacturing companies. The use of robotics technology has been an important option for this sector, however, in recent years the development of such technology has been a subject for research. Under the CEC BRITE/EURAM programme a new initiative to support RTD project was initiated in the late 1980s resulting in a number of research and development projects receiving financial support to develop technologies for food production. The BE4420 (ROBOCAMP) project has been one such project dealing with robotic meat cutting in the 'hot' butchery sector. The aim was to develop the techniques and define the necessary equipment for operation in an industrial plant, automating an example set of butchery operations in the production of primal cuts. The partners in the project include a machine manufacturer BANSS, an end-user FACCSA, a technology company HITEC and a research centre AMARC at the University of Bristol. AMARC became the co-ordinator of the project after the first year of this four year project. The project has met all its research objectives demonstrating for the first time the feasibility of robotic meat cutting in an industrial environment. The research has developed new expertise and opportunities for new products to be developed by the companies involved in the project.

OBJECTIVES OF THE PROJECT

The research has aimed to advance the state-of-the-art in the field of robotics by demonstrating the industrial feasibility of automatic meat cutting. The main objectives of the research have been concerned with both technical and business issues. These include:

- Understanding automation for pork carcass cutting in a 'hot' butchery environment.
- Definition and demonstration of a system integrating sensing, cut path prediction and trajectory control; robotic cutting; manipulation; tooling and fixturing in an industrial cell for anatomical cutting of pork carcass sides into primals.
- Installation and testing of the system in a meat processing plant demonstrating benefits in: productivity, quality, higher yield, improved work conditions and increased confidence in this technology.

The project has achieved the above objectives in spite of a number of severe 'technological challenges which have been resolved.

SCIENTIFIC AND TECHNICAL APPROACH

The subject of intelligent robotics has been under extensive investigation in recent years. This project has aimed to increase understanding of the application of such technology to new and skilled tasks.

The task of meat cutting has been a focus for the research and the process of 'hot' butchery has been identified as the main example for researching robotics in meat production. Meat cutting of pork sides into primal cuts has been chosen using the current practice of butchery at FACCSA, the partner in the consortium interested in using such technology for meat processing.

The process of manual butchery involves several important steps each requiring judgement and manipulation of flexible meat and tools to achieve the desired cuts. The approach adopted by the project has been to implement a new method of sequencing the cuts such that robotics may be used. This is illustrated in Figure 1, based on the South European (or Spanish) butchery of carcass sides. The current method of removing meat from whole carcasses involves a series of cutting and pulling or handling action which were considered beyond the capabilities of robots. The new method reduces the number of cutting and handling operations which make it more suitable for automation.

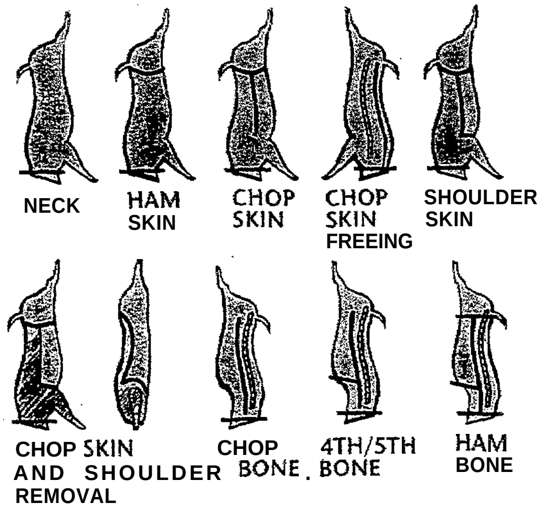


Figure 1: Cuts for Primal Separation

The project has followed a step by step progression in achieving. its targets. In addition to the definition and demonstration of the technologies it has been necessary to prove the specific processes in the new scheme of butchery defined for FACCSA. As the cuts in 'hot' butchery represent the most difficult in the production of primal cuts the experimental approach adopted has explored the high risk areas first, prior to the implementation of the specific facilities for testing the full concept,

In the new butchery scheme, developed by the project, it is necessary to perform the anatomical cuts in three stages: skin deep cuts on ham, chop and shoulder primals (see Figure 1); remove the chop skin and shoulder manually, as this step was considered beyond the scope of the research; and finally perform the through cuts in meat and bone for the chop, 4th/5th rib and the ham primals. A number of manual trials were performed to prove this scheme and the key technical issues have been addressed in the following manner:

- Measurement and cutting trials were performed to define the main important factors which effect the new process (e.g. carcass size variations).

- The technologies for achieving robotics cutting of pork were required with the view to perform a number of trials at the various stages of the research. This approach was adopted to minimise technical and financial risk.

- Initial trials were performed to demonstrate the feasibility of two of the major cuts in the scheme, the ham and chop bone/meat cuts, using a modified revolute industrial robot. The system demonstrated that it was feasible to use a set of anatomical feature co-ordinates to make these cuts. The main requirements for fixturing, path generation and sensing (including vision and forces monitoring) were achieved from these trials.

- A first demonstrator for initial trials with specific subsystems was desired. The main elements of the fixturing, robot, cell computer, path generation and vision sensing were integrated as a first attempt to prove system performance.

- A set of trials were to be performed on carcasses. This required the integration of upgraded subsystem and installation at FACCSA. Each subsystem was tested for its function in order to meet the requirements of two sets of trials. The first were to quantify the bone/meat ham and chop cuts (named RCB trials) and the second (named RCD trials) to perform the skin cuts in the scheme, described earlier, as well as the bone/meat cuts.

- The final demonstration of the system has proved that the technologies in the project cart reach the capabilities needed to perform the important cuts in the butchery of pork carcasses into primal cuts.

The overall performance of the system through the implementation and integration of the new technologies has been quantified. The ham and chop cuts may be made to within $\pm$10mm (RCB trials), which give a significant improvement on overall yield compared to the manual process. The match between the skin cuts and the bone cuts have been shown to be within O - 10mm (RCD trials), which is acceptable.

TECHNICAL PROGRESS

The concept of the project has been to prove the [ethnical feasibility of a number of subsystems integrated in a cell to perform a set of meat cutting operations (Figure 2).

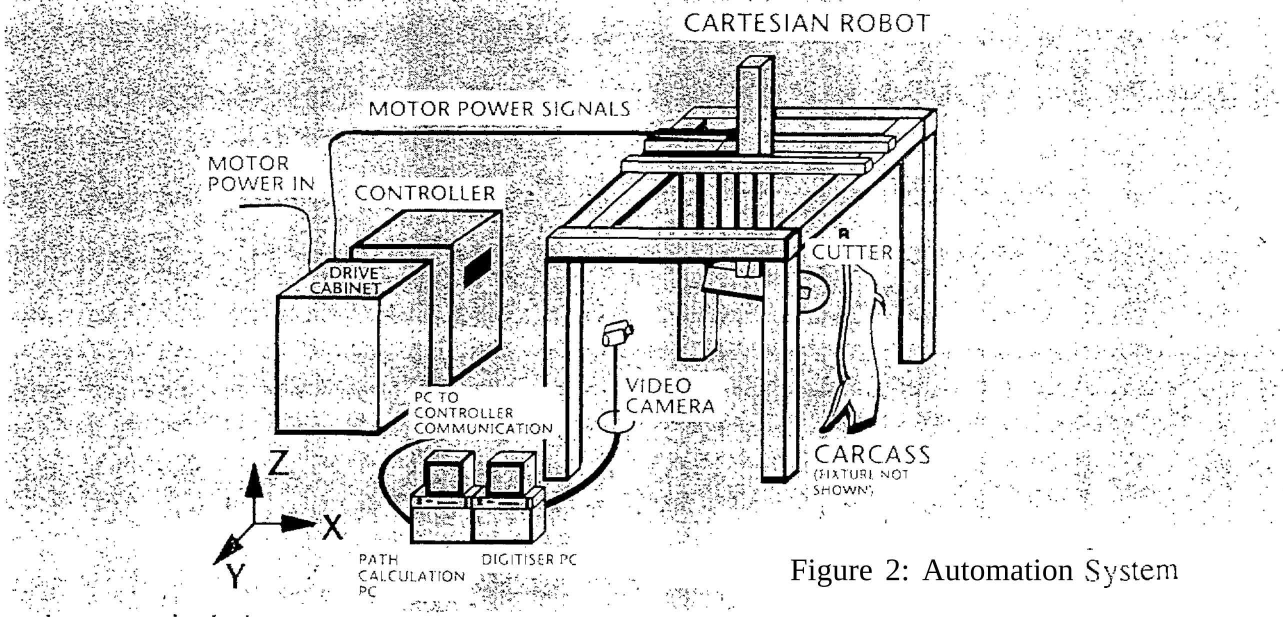


Figure 2: Automation System

The subsystems include:

- A transport system for delivering each carcass to the robotic cell.
- A fixturing system for holding the carcass and ensuring its position and orientation for sensing and cutting.
- A computer vision system designed for food application capturing the features necessary for path generation.
- A software package that utilises a
- novel method for predicting cut paths anatomically referenced using a minimum of computer vision data whilst accommodating for variations in shape, size and type of carcasses.
- A robotic manipulator capable of trajectory following which uses the path information to guide a cutter tool along the desired cut path.
- A set of rotary cutting tools with force sensing capabilities that perform the separation action to produce the specified cuts whilst monitoring the cutting process,
- An integration software module that provides the overall link between the subsystems.

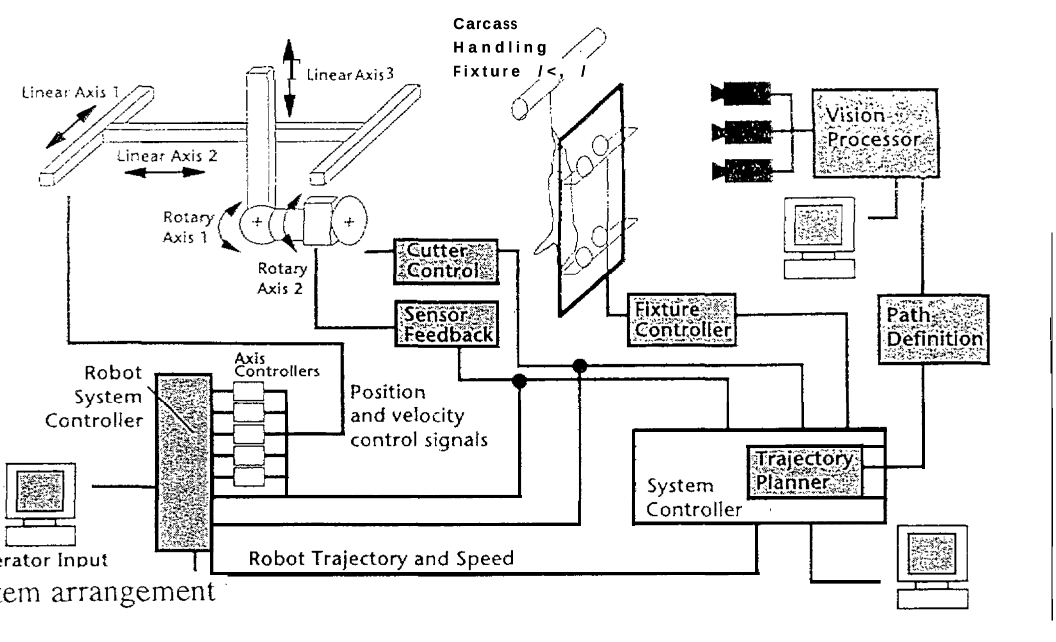


Figure 3: System arrangement

Figure 3 shows the system comprising an integrated configuration for the production of pork primal cuts. Although the work is focused on 'hot" butchery, the resulting expertise and technologies are applicable to other butchery tasks and species.

Cutting trials were carried out at FACCSA to develop the system and to meet FACCSA's accuracy requirements, especially the size and shape of the chop primal (Figure 4). The accuracy of the position of the vertical cut which separates the chop and belly primals is key to profitability of the factory and development work has concentrated on meeting the requirements of FACCSA.

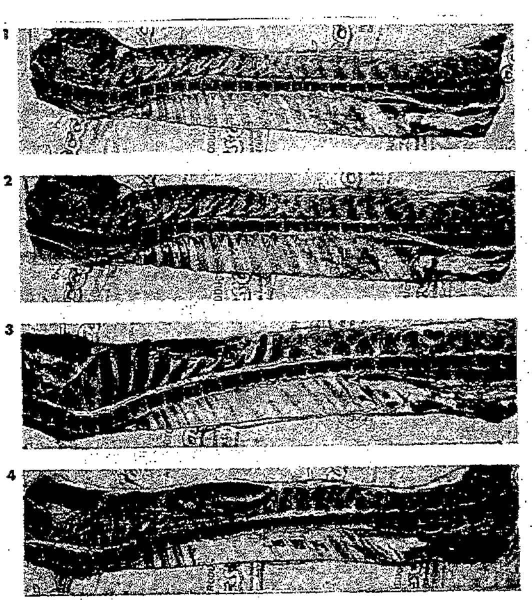
Main technical results

The project has been recognised as a success story for Europe and it has achieved the following:

- Demonstration of robotics technology for meat cutting in an industrial environment for the first time.
- Development of methodologies and techniques for implementing robotics for dealing with flexible materials such as meat.
- Practical implementation of a skilled robotic system for future use in research

It is proposed that a pig carcass side enters the system along a standard transport rail and passes a sensor which measures the overall carcass length. This data is used to configure the fixturing system so that it correctly locates the carcass side. The vision system takes an image of the carcass side and measures the position of four anatomical points: the centre of the last lumbar vertebra; the edge of the belly, the minimum of the spine curve at the neck and the centre of the 15th vertebra in 2D .

The data is passed to the cell computer which calculates the cut path to achieve the skin deep and bone/meat through cuts. The cut path data is sent to the robot controller. The cutter is started and the robot moves the cutting system through the cutting path making the cuts. Examples of the chop and ham, bone/meat through cuts are given in Figures 5 and 6.



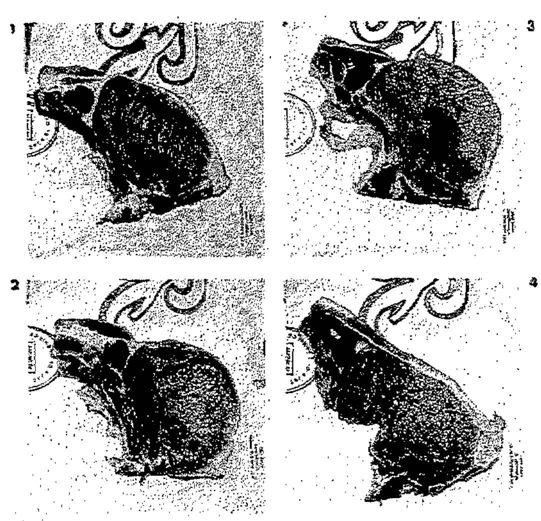


Figure 4: Example of Primals cut by Robot

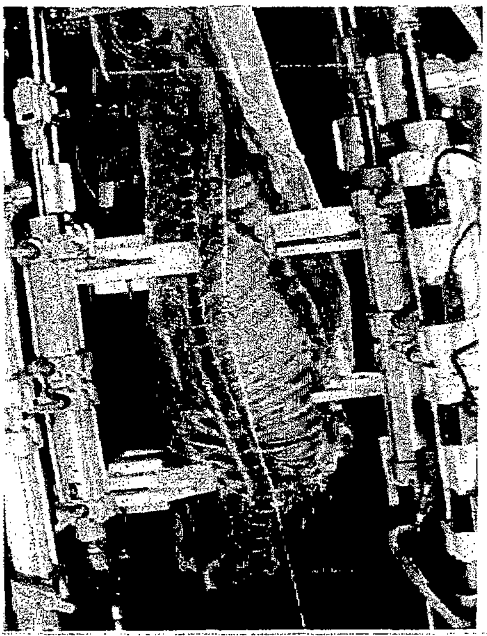


Figure 5: Planned Cut Path

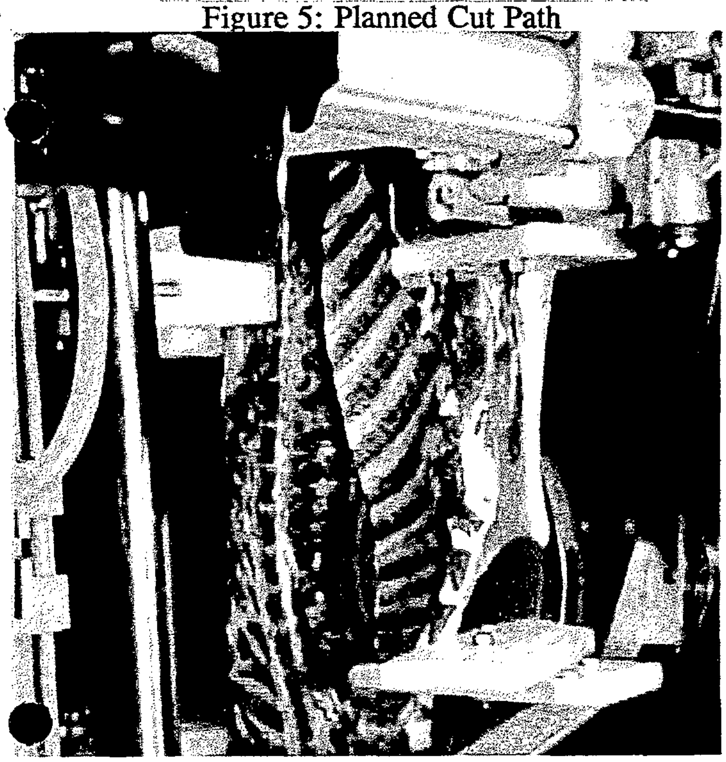


Figure 6: Robot cutting using vision system

At the end of the cut the fixturing system releases the primals and the next carcass side can enter the system. The system is operated such that a complete carcass side is fixtured and the skin cuts are performed first. Then it is released and the shoulder/skin removal is carried out manually. The carcass is then fixtured again for the bone/meat through cuts.

A major problem for an automatic vision system is identifying spine and vertebrae which are hidden by skin or fat. This can be overcome by using an idealised spine and vertebra model (Figure 7) against which the raw vision data can be compared and any missing data provided, even when certain carcass features are obscured. This is extremely important for a robust unmanned system since a full, clear carcass image cannot be guaranteed but an accurate cut must be made.

One aim of the trajectory planner is to use a minimum of *sensory data* to correctly predict the position of the edge of the eye muscle for each carcass side. From this prediction the additional length of rib to the chop cut position can be added by the processor to meet the requirements of the customer while maximizing yield. This distance can easily be modified to suit prevailing market conditions or to include other factors such as carcass

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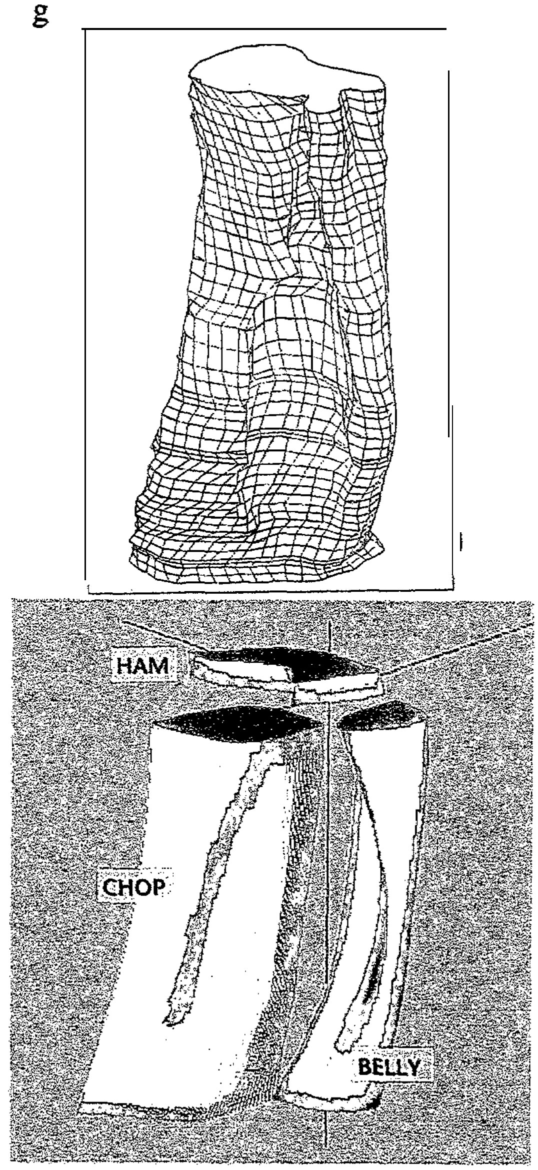


Figure 7: Carcass data: Primals surface model generated cut path algorithms

To develop a method for predicting the position of the 1 lth vertebra (half-way along the chop primal), a database with measurements of 200 carcasses has been made.

Using this database many potential methods for predicting the position of the eye muscle have been tested and the most accurate chosen.

The method only uses the position of four anatomical features from the vision system to predict the position of the edge of the eye muscle to a proven accuracy of ± 10mm for 80% of carcasses and ± 15mm for 95 %.

A new cutting blade has been supplied by BANSS which is capable of cutting through meat and bone without producing unacceptable bone dust. The cut quality of this blade is extremely good when operating within its design range. An experimental system has been used to establish the optimum blade rotational speed and power to meet the required robot cutting speed while maintaining good cut quality. The parameters which limit the speed and quality of the cut have been specified and the requirements of a cutting system defined.

During each cut the forces and cutter speed are measured in real time by sensors attached to the cutting system. Potential failures or problems, such as blunting or fracturing of the blade, can be detected automatically from this data and the cutting stopped before any further carcasses are cut.

The current system can make the vertical chop cut in approximately three seconds at a speed of $0.32 mm/sec^{-1}$ but the power of the cutting saw is limiting the speed of the horizontal cut through the centre of the last lumbar vertebra. This is because the carcass cutting saws, currently available on the market are designed for manual butchery and are limited in their power. The robot needs a more powerful cutter to increase the speed of cuts while maintaining acceptable cut quality.

*Transport and **Fixturing** Concept*

In the development of the robotic cell it has been necessary to implement the relevant devices and automatic mechanism for transporting and fixturing each carcass. It should be noted that carcasses vary in shape and size and structural flexibility. The variations need to be accommodated. The main requirements are to locate the split plane of each carcass in a desired position relative to the vision and robot systems. This is to ensure that orientation and attitude of the carcass remains within defined tolerances for the data from the vision system to be accurate and the cuts to be made to the required quality.

The second most appropriate fixturing solution used a series of clamps to locate the carcass side (Figure 8). A novel fixturing system was designed and built by AMARC (Figure 9) for a series of initial cutting trials performed from the bone side of the carcass. Although not suitable for use in a commercial butchery room, this design proved the method of carcass location and several features were incorporated in the final fixturing system designed jointly by AMARC and BANSS.

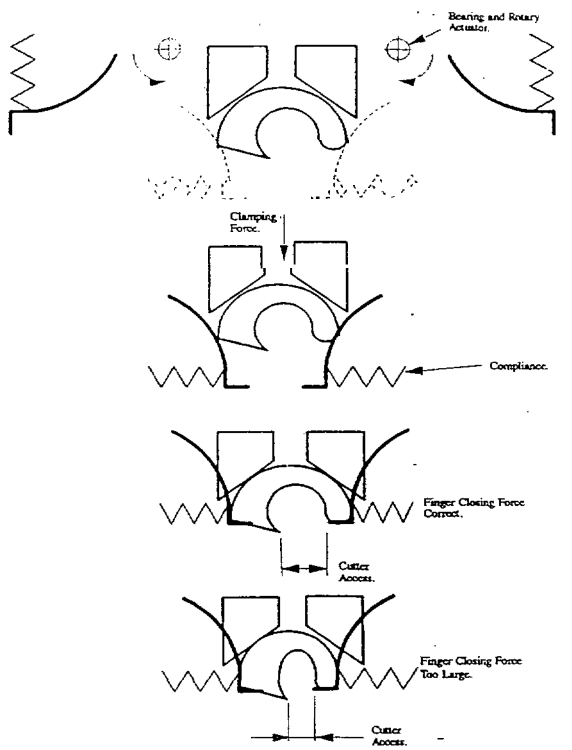


Figure 8: Fixturing concept with clamps

Vision system and sensing

Automation of butchery tasks is impractical without sensory information about the size and shape of carcasses. Vision sensing can provide this information in a non-contact and therefore hygienic way. An important goal is the location of anatomical features. These can be used directly or used as the input to a carcass model in order to determine the positions of features which cannot easily be located. The main objective of the vision system is to provide automatically specific points on the carcass that are used at the next stage in order to calculate the path to be followed by the robot that makes the cuts.

The vision system consists of a computer, two colour video cameras and a framestore which digitises images from the camera and makes them available to the computer as an array of values representing the intensity at every point in the image. The computer attempts to locate the features of interest in this image and, because distances in the image can be related to real distances, the actual positions of the features can be found.

The specific vision system used for this project incorporates an array of INMOS transputers for parallel processing. The general configuration is shown in Figure 9 below:

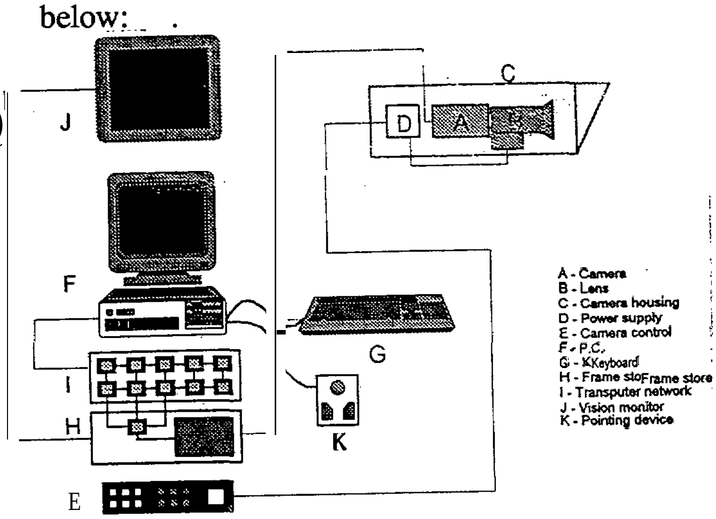


Figure 9: The Architecture of the Vision System

The vision system has been developed to fit into an automatic system. It has the following features:

- It employs parallel processing for scaleable performance.
- It can be calibrated to give red-world co-ordinates.
- It can receive control signals and return feature co-ordinates via an RS232 link to another computer.
- It is set up using a simple menu system which can be easily customised.
- Cameras can be positioned up to 25 m away from the vision system and controlled remotely.
- Cameras and/or complete systems can be housed in IP65 enclosures.

In the butchery of half-carcasses the spine is an important feature. Many cuts are made through the cartilage separating the vertebrae. In addition, the overall shape, length and position of the spine gives useful information about the carcass as a whole.

Standard image analysis techniques can be used to locate the spine and inter vertebral cartilage on split carcasses under ideal conditions. In the course of normal production, however, it is likely that parts of the spine will be obscured by fat or fixturing elements or be unrecognizable due to bad splitting. In addition, the indications of joints between vertebrae may be 'noisy', ie there may be indications where there are no joints or some joints may be faint or obscured and therefore give no indication.

Model-based techniques have been developed which solve both of these problems. The techniques have a filtering effect on the joint indications by deciding which ones correspond to viable joint positions. They also facilitate interpolation or extrapolation in order to reconstruct the spine in areas where it has not been detected successfully.

The image is searched in two windows, one either side of the central clamp of the fixture in order to locate the general line of the spine. A search is performed along this line to find the inter-vertebral joints.

A model is fitted to the pattern of joints and angles along the line.

This model represents the spine in terms of vertebra lengths and angles and it allows parts of the spine that are not directly visible in the image to be predicted. The size of the model can be altered by multiplying all of the lengths by a scaling factor and rotation is achieved by adding the rotation angle to all of the model angles. Multiplying the angles by a constant causes the model to become more or less curved. The scale of the model must be correct to better than 0.5 per cent for the joint positions to match.

The joint positions can be then marked off along the spine line to give the actual vertebra positions.

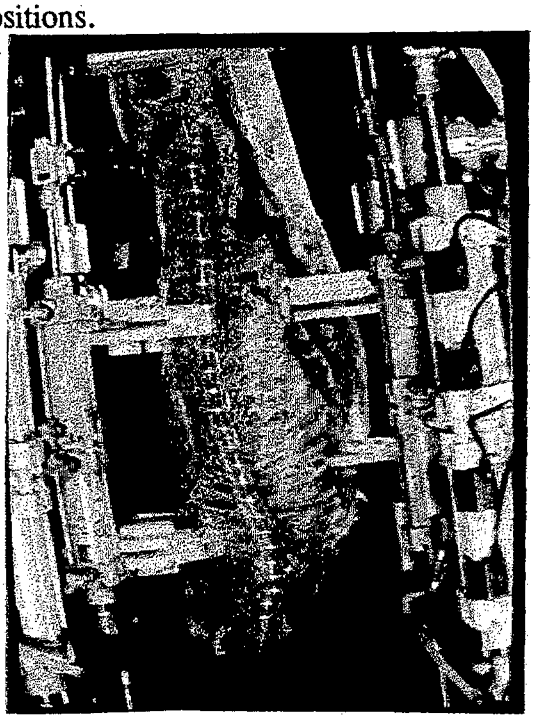


Figure 10: The model (the red and yellow line) fitting to a typical carcass and the intervertebral joints marked with white crosses.

The vision system used for this work can be calibrated to provide data in the co-ordinate systems of other equipment. In trials with a butchery robot, vision information was used for cut path planning. The robot produced accurate cuts along these paths (Figure 10).

The model works well in locking onto noisy or incomplete data. When a successful fit is achieved, currently in 75% of cases, the centre of the spine is generally located transversally to $\pm$ 2 pixels in the middle of the carcass increasing to +1, -5 pixels at the extremities (where the ventral direction is positive) and the inter vertebral joints are generally located longitudinally within $\pm$ 2 pixels.

One difficulty remaining is that carcasses can have different numbers of vertebrae between the last lumbar vertebra and the neck. Because the lumbar area may be covered by fat from the splitting process, there is currently no means of telling how many vertebrae the carcass has. The implications of not knowing is that approximately 50% of the carcasses to which the model fits will still have an error on the ham cut of 1 vertebra (i.e. 36mm approx.). Alternatively, all of them could have an error of half a vertebra.

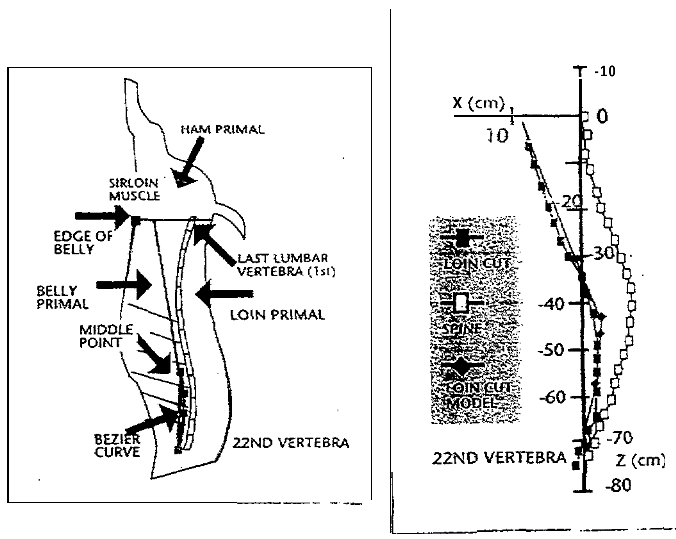


Figure 11: Path Prediction

Cut path prediction requirements

Path planning is needed to guide automatic cutting systems to perform the cuts in the process of butchery at FACCSA. The prediction of cut paths for bone/meat through cuts as well as skin deep cuts has been necessary and achieved by AMARC. This involves the 3D prediction of specific butchery cuts and more general surface modelling. Yield benefits are achieved by the implementation of path algorithms.

A study of the pork butchery process has been undertaken and adapted for automation. Significant improvements in yield from the automatic cuts have been achieved. Expertise has been provided in the following areas:

- Process analysis and definition suitable for robotics
- Selecting anatomical points for use in cut path models
- Modelling of cut paths and type of model chosen
- Developments of databases for testing algorithms
- Implementation of cut algorithms (Figure 11)

A database of carcasses selected from a production line has been developed. The carcasses were measured using a sonic digitiser. The measurements included salient anatomical features and cut paths. Models

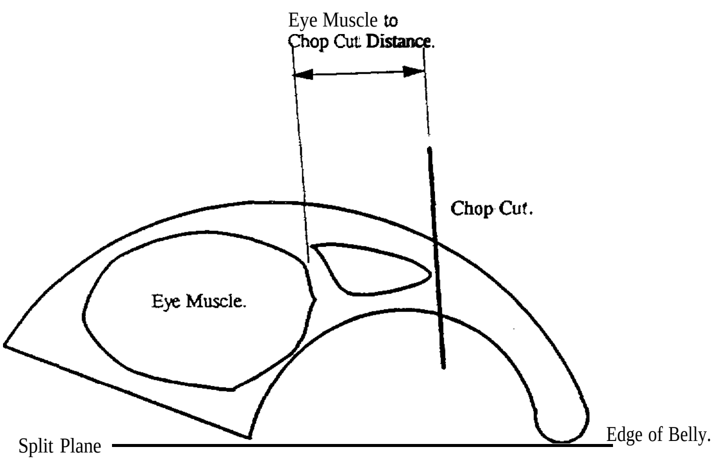


Figure 12: Measurement of Chop Cut Position

were developed for predicting the cut paths on the carcasses and tested on the carcasses in the database using software written for the purpose. The most suitable algorithms were then refined and improved further.

The requirement of the path of the chop cut is to produce a straight chop primal with the edge of the cut a set distance from the edge of the eye muscle (Figure 12). The start and end points of the cut are defined anatomically therefore the path between these points must be provided by the path prediction algorithm.

The skin cuts of the cutting scheme require the skin side of the carcass side to be modelled. The carcass database of 200 carcass sides included the data to allow various methods of modelling the line of the cuts to be analysed and their accuracies assessed. This procedure allowed the optimum modelling method to be chosen and implemented on the robotic butchery system.

Mathematical Approach and Modelling

Using the database of 200 carcass sides several methods of modelling the 3-dimensional shape of carcass sides using a minimum of initial data were developed and their accuracy documented. The cuts divided into two groups the path of the chop cut and the paths of the skin cuts.

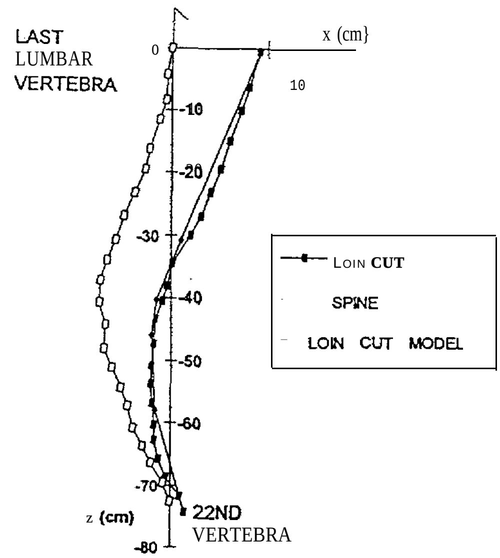


Figure 13: Loin Cut Model and Data (right hand carcass)

Chop Cut.

The method adopted for modelling this cut was to define the start and end points of the cut and provide a path between these points which cuts, the ribs at a set distance from the edge of the eye muscle while providing a straight edge to the final chop primal. Observation of the method adopted by butchers when making the cut suggested that from the start point (which is a fixed proportion of the distance between the centre of the last lumbar vertebra and the edge of belly) the butcher aims for a point on the spine of the carcass and then forms a smooth curve to meet the end point (which is a fixed distance form the edge of the cervical vertebrae). The data used for developing the model was the position of the individual spine vertebrae, the chop cut path, as defined by FACCSA, and the edge of belly.

The cut was modelled in two ways:-

(i) the X/Z co-ordinates of the cut were determined (Figure 13).

(ii) the depth of the cut, Y axis, was modelled.

To analyse the cut path data from the measured carcasses the orientation of the Cartesian axes for each carcass was standardized so that the spine axis (from the last lumbar vertebra to the last cervical vertebra) was the Z axis and a line form the last lumbar vertebra to the edge of the belly was the X axis (Figure 14) The plots were then viewed from the angle that the butcher would see them, from the split plane looking into the rib cage cavity. A correct chop primal is defined as one that produces a chop to the specified length at the level of the 1 1th vertebra. From the carcass data it was apparent that the ideal chop length is produced by a line from the start point to the centre of the 15th vertebra from the last lumbar vertebra. A second line is then defined from the original line at the level of the 1 1th vertebra to the edge of the 22nd vertebra, the cut end point. These' two lines are used as the basis for the cut path and a smooth curve fitted using a Bezier function between 4 control points which are calculated from these lines. This method predicts the specified chop primal length at the 1 lth vertebra to an accuracy of ± 10 mm for 80% of carcasses and ± 15 mm for 95% using only four 2-dimensional vision points. These are the centre of the last lumbar vertebra, the edge of belly at the level of the centre of the last lumbar vertebra, the centre of the 15th vertebra and the edge of the 22nd vertebra (the minima of the spine curve at the neck).

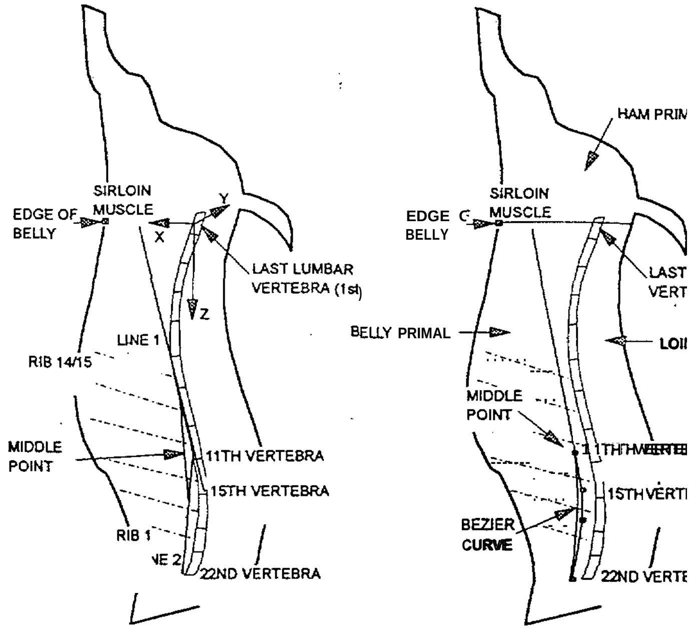


Figure 14: Loin Cut Model

The depth of the cut was constructed by assuming the rib cage is circular about the cut axis. The depth of cut (Y co-ordinate) is then equal to the x distance from the cut axis (a straight line in the XZ plane from the cut start to the cut end) to the spine. The shape of the spine is unknown but approximates to the shape of the chop cut plus a linearly diminishing distance from the cut start, where it is from the cut start to the last lumbar vertebra, to the cut end, where it is zero. The approximation is shown in Figure 15.

This algorithm was implemented in the cell computer and the robot driven through the X,Y, Z positions defined by the algorithms. The chop primals produced by the path were then compared to the ideal chop primal required by FACCSA to calculate the yields.

Skin Cuts.

The skin cut paths in the YZ plane are known since they lie on the chop cut path defined previously or are horizontal at a fixed height defined by an anatomical feature such as the centre of the last lumbar vertebra. Consequently the depth of the cuts must be modelled and added to these paths.

The models used for the skin cuts were built up using Bezier curves to fit the X co-ordinate data at the particular YZ paths. Again the amount of 2-dimensional vision data necessary to produce the cut paths was minimised.

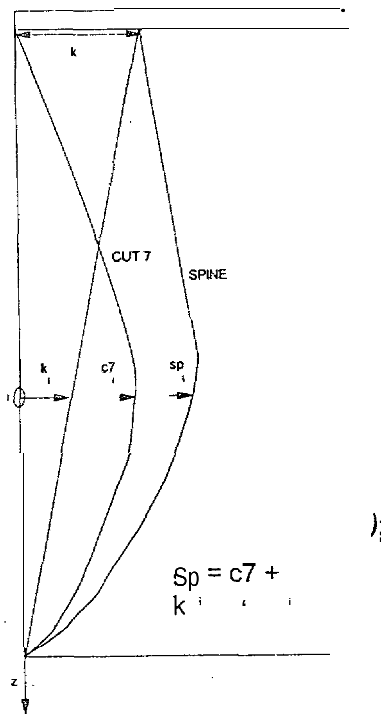


Figure 15: Spine depth approximation

Figure 16 shows the database used for modelling and the variation which must be accommodated. The method adopted for modelling each of these skin cuts will be described in turn.

The ham skin is a horizontal cut at the level centre of the last lumbar vertebra. The algorithm developed uses four input po

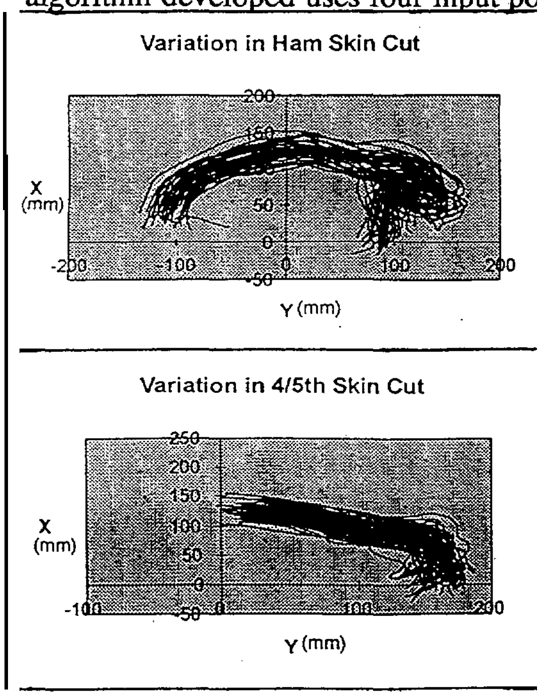
These are the edge of the back at the level of the centre of the last lumbar vertebra, the centre of the last lumbar vertebra, the edge of belly at the centre of the last lumbar vertebra and the ham cut path already calculated

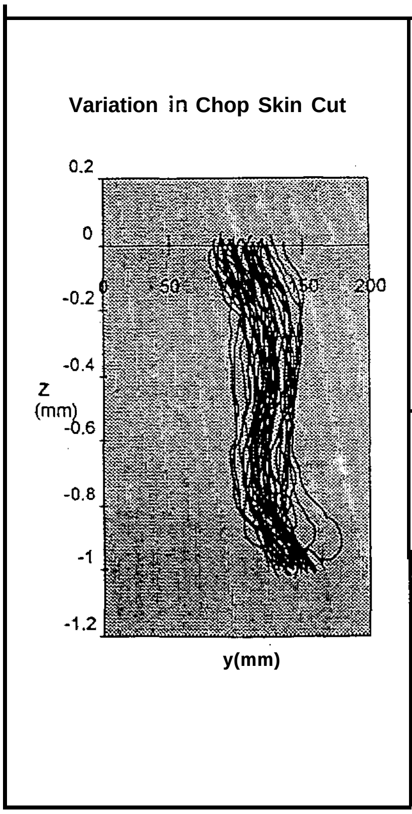
From this data the four control points are calculated and a Bezier curve produced. Figure 17 shows the modelled Bezier curve for the ham skin cut.

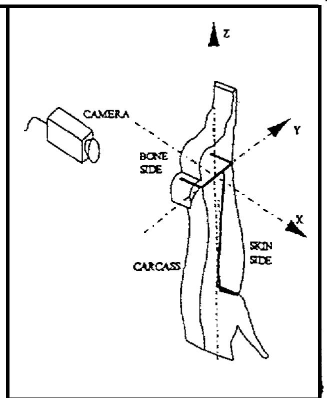
The shoulder cut is the most difficult to model and uses a 5 point Bezier curve to achieve an adequate fit. The input data used is the position of the back at the level of the 4/5 th rib gap, edge of belly at the 4/5th rib gap, edge of 22nd vertebra and the path of the chop cut. From this data the five control points are calculated which produce the path shown in Figure 18.

Chop skin cut lies at the same YZ co-ordinates as the chop cut path and therefore uses the YZ path calculated for the chop cut, the position of the back at the 1 1th vertebra and the height of the 4/5th rib gap. The cut is modelled using a four point Bezier curve to produce the curve shown in Figure 19.

The models described defined the skin cut paths to sufficient accuracy to allow a compliant cutter to make the cuts.







'igure 16:

Variation of ham skin cuts

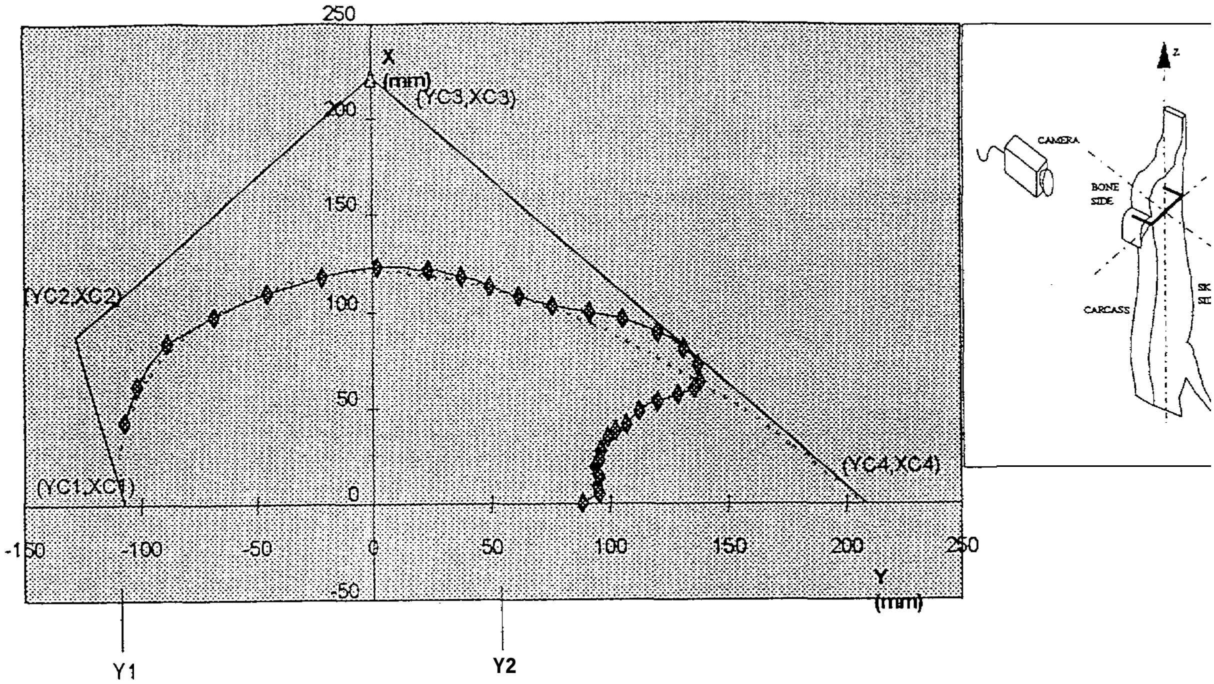


Figure 17: Average cut path for ham skin cut

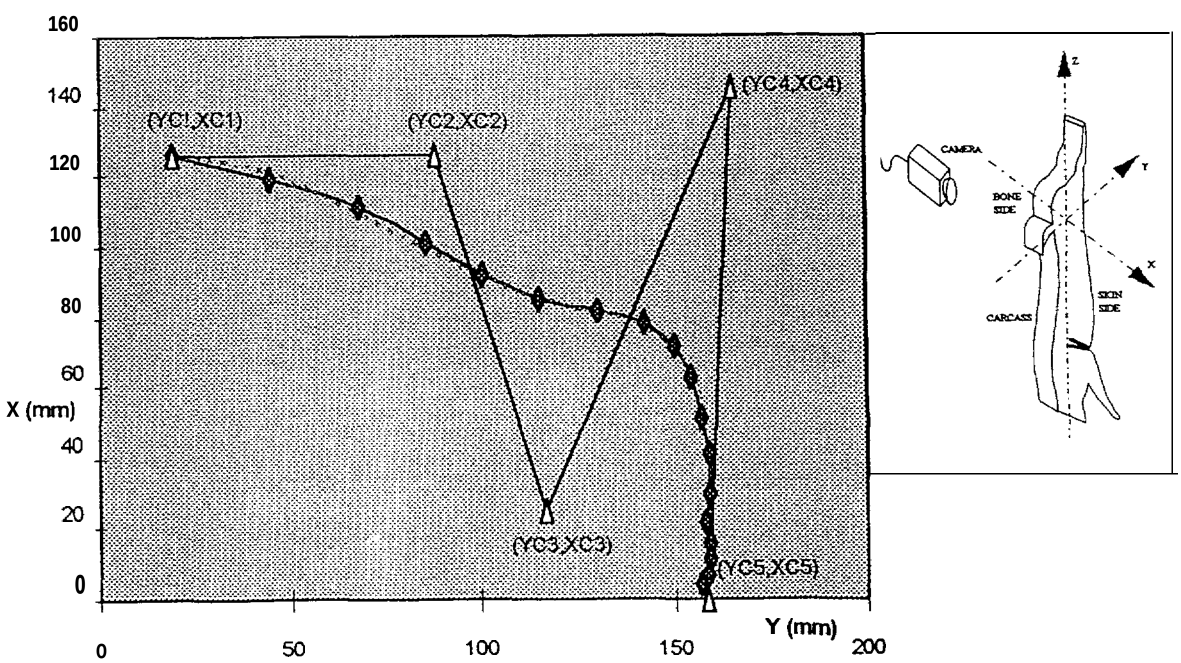
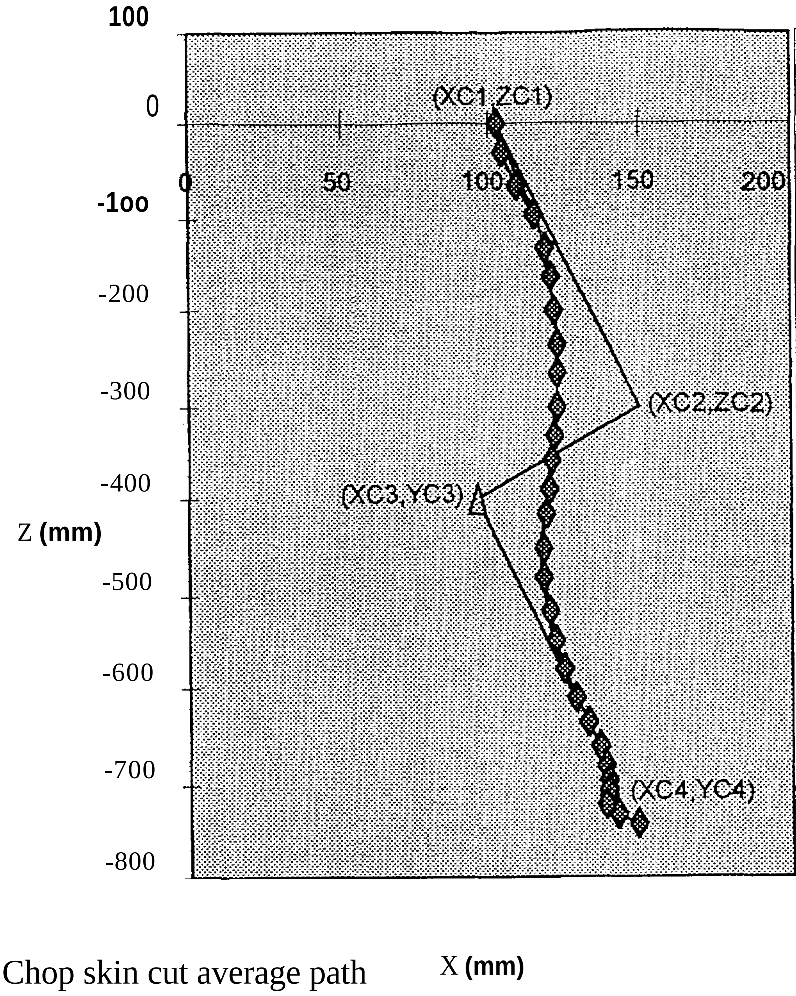


Figure 18: Average for shoulder skin cut path



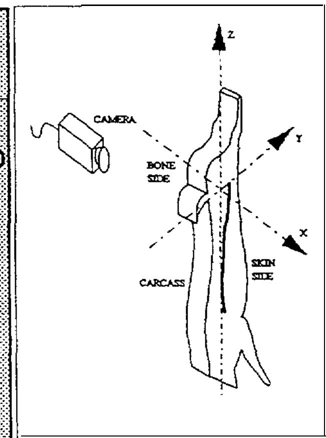


Figure 19: Chop skin cut average path

Robotic system requirements

The main requirement has been to achieve a design that meets with the load, accuracy, speed and work volume requirements of the application. In addition the robot must meet with the trajectory requirements and its structure must withstand the conditions generally imposed by the industry.

A gantry robot concept was chosen and based on an agreed specification a new robot has been implemented which is the first of its kind for meat cutting application.

The specification determined at that time was the following:

Work Volume

X-axis	1.250 mm
Y-axis	750 mm
z-axis	300 mm

***Rotary* axes**

Al, A2	$\pm$ 300 degrees

Positional accuracy

Linear axes	$\pm$ 2 mm
Rotary axes	$\pm$ 1 degree

Path accuracy

+ 5mm of demand path at cutting velocity 0.5ms-’

Speeds

X-axis	1 m/s
Y-axis	1 m/s
Z-axis	1 m/s
Rotary axes Al, A2 .	I.

Cycle *Times*

10 seconds per half carcass

Previous investigations on the market proved that no industrial robots were available to meet these specifications and the additional demands concerning material (stainless steel) and the hygienic aspects.

The development of the robot was made by BANSS in a gantry with 5 axes. In view of the short cycle times (10 seconds per carcass half) and the accuracy required during the positioning, electric servomotors have been provided for all drives.

The basic design of the robot is shown in Figure 20. The drive of the three linear moving axes has been effected by means of toothed belts, both rotational axes have been driven directly by the servomotors via cyclogears.

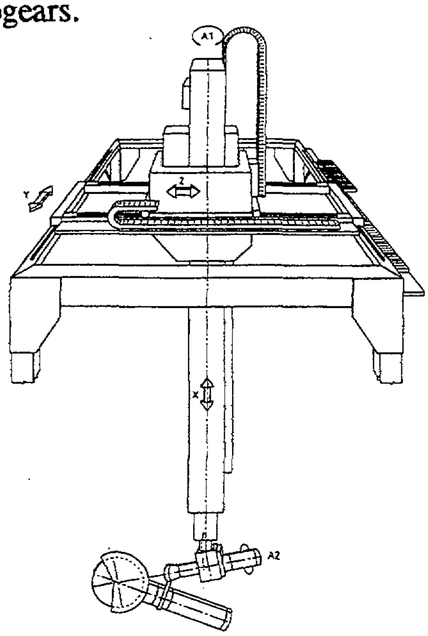


Figure 20: Basic design of the robot

Cutter tool desire

The meat processing industry has a need for adaptable machines capable of task currently performed by skilled butchers. To automate the process appropriate cutters must be developed. Equipment has been constructed and used to test pork cutter tools. The equipment is designed to measure cutting forces and drive power under controlled conditions of blade speed and feed speed. Blade-drive-torque or feed-force can also be controlled.

There are several requirements for knowledge of the separation process (Figures 21(a) and 21(b)). The optimum cutter blade speed and power is needed to design a cutter which can perform cuts at the speed and quality. The FACCSA cuts required the implementation of a skin cutting tool and a combined bone cutter, which have been developed. The forces generated by separation must be delivered by the manipulator and resisted by the handling system. Examination of these forces is needed to permit economic design. Methods of error detection are needed to allow safe, reliable operation without the need for human supervision. Potential error modes include blunting or fracture of the blade.

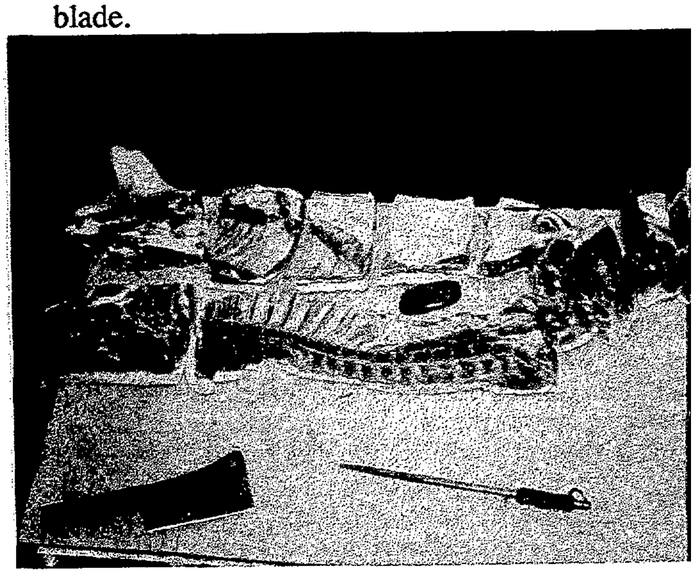


Figure 21(a): Location of test samples on pork carcass

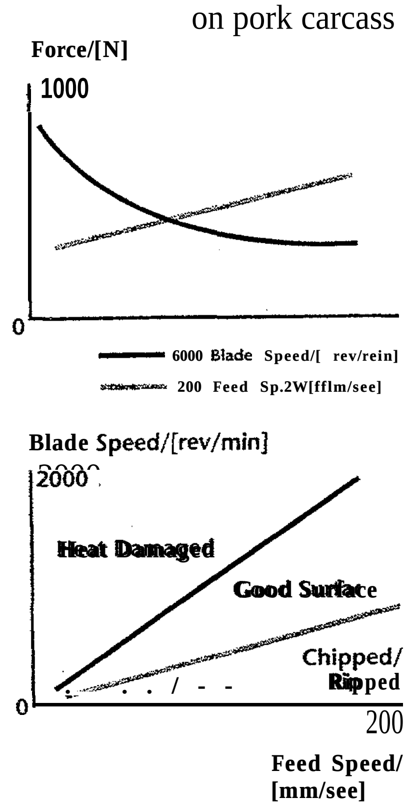


Figure 21(b): Test results for chop/belly cut

The test equipment has been used to establish optimum blade rotational speeds and to ensure that the cutter has sufficient drive power for the main cuts in an automatic pork separation system.

Force, blade drive and torque and vibration levels have been used to monitor cutting systems Use is made of the forces measured during a chop/belly cut and the corresponding signal analysis. Computer interpretation of this information can be used to monitor cut quality and cutting system condition (Figures 22(a) and (b)).

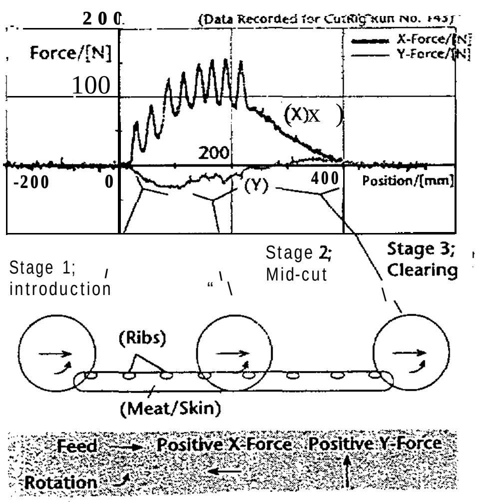


Figure 22a: Output from fast-fourier transform signaling processing and X-Force data

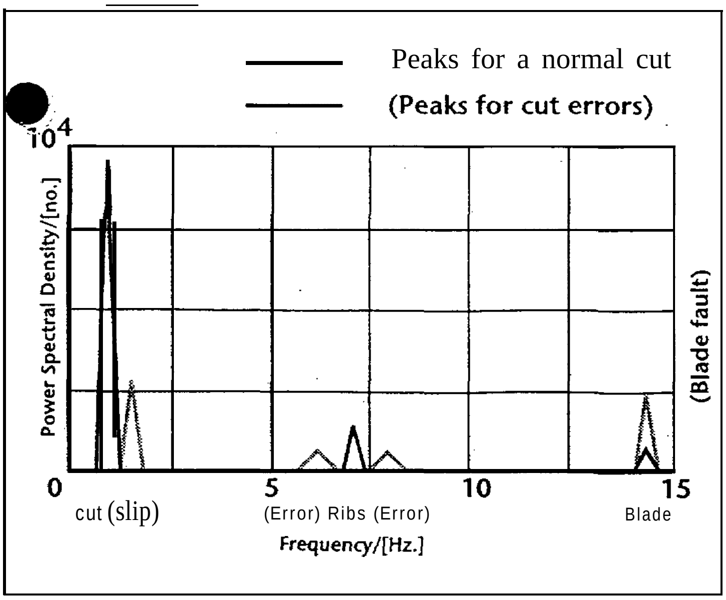


Figure 22(b): Typical Force Plot Characteristics

Cutter tool drive

Two cutting systems were developed for the project, one to perform skin only cuts and one to perform meat and bone cuts. Significant development work **was performed by** AMARC to define the optimum cutting conditions for the meat and bone cutting blade which was developed specifically for the project. Using the results of this work a standard industrial cutter was modified to fit onto the end of the robotic manipulator and perform the cuts. A force transducer was designed to mount between the robot tool attachment point and the cutting device to measure the forces generated during the cuts,

A series of manual trials were performed by AMARC to assess the requirements of a skin cutter and blade. From these trials it was decided to use a plain blade with a double bevel edge and a Kentmaster SC-550 Scribing Saw to drive it. A compliant mechanism was designed and manufactured to accommodate the inaccuracies associated with the path planning algorithms developed for the skin Cuts.

The work performed on the two cutting systems is described separately.

Bone Cutter Development

The main requirements placed on the bone cutting system were to cut through meat and bone at up to 0.5 m/see. A new design of cutter blade was supplied by BANSS and manual trials were performed at FACCSA to assess the cut quality and suitability. These trials were encouraging and further cutting trials were performed by AMARC using a modified industrial revolute robot, a modified industrial cutter and the force transducer to measure the cutting forces which occur at the proposed cutting speeds.

Cutter blade for bone/meat cuts

Currently the warm butchery of pig carcasses is almost exclusively performed with manual operated, mostly pneumatic or electric saws.

The total weight of the saw is taken up by means of a balancer. With the saw only ham, chop and 4/5 rib cuts are performed bone deep.

In co-operation with a German manufacturer of cutter blades, a blade, actually a circular blade, has been developed, provided with a cylindrical grinding at its outside. The cylindrical grinding in its run is provided with radial notches to increase cutting efficiency.

From a series of tests with the new stainless steel blade it was found that cutting forces increased with feed speed, the relationship is approximately linear and it agrees with data from the test-rig and the demonstrator system. Cutting forces did not change with blade rotational speed over the range tested but at low speeds (below 1000 rev/rein) rib bones were damaged and at high speeds (above 2000 rev/rein) sawdust was increased and the cut surface was discolored by heat. The limits of blade speed are dependent on the feed speed. The minimum blade speed needed to prevent bone-chipping increases with feed speed, approximately 700 rev/rein at 200 mm/sec and 850 rev/rein at 400 mm/see. maximum blade speed, above which the heat effects were noticed, was found to be approximately 1500 rev/rein at 50 mm/see and 2000 rev/rein at 200 mm/see.

Tests to compare the alternative blades showed that the conventional toothed Made produced the highest cutting forces, followed by the new design, the stainless steel blade and the coated blade, which gave the lowest cutting forces. There was a significant difference in cut quality, the conventional blade produced a large amount of sawdust but did not cause heat effects. All the new blade designs gave similar cut quality, a small amount of sawdust was produced and there were some heat effects at low feed speeds.

The feasibility of monitoring the cutting system was assessed. It appears possible to monitor cut progress from analysis of cutting-force data or blade drive-torque data. Blade speed data is of limited use in the case of the electric motor drive used in the test rig, but data from the demonstrator pneumatic mo drive should be of use. Further work required to develop a method of detecting Made fracture.

The requirements for a cutting system were defined from the cutting trials performed during the project, however, a cutting system capable of meeting these strict requirements could not be located commercially and so the original Kentmaster cutter was used throughout the project life. This reduced the cutting speeds which could be attained since the cutter did not have sufficient power or rotational speed. to perform bone cuts at 0.5 m/s therefore the feed rate had to be reduced to suit the cutting system. Force measurements were made of all of the cutting trials performed at FACCSA. A typical force plot is shown in Figure 23, pointing to the fact that further research in this area would be beneficial.

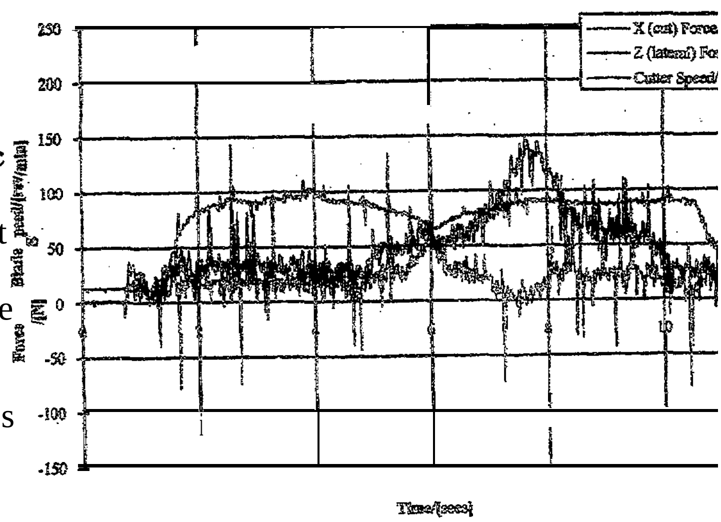


Figure 23: Data collected for RCB trial run chop cut

Skin Cutter

The manual trials performed by AMARC defined the requirements of a skin cutter and recommended a plain double bevel blade driven by a Kentmaster SC 550 cutter. The plain blade would not cut into ribs or other bones provided the cutting force supplied allowed the blade to run over the bones. To meet this requirement a compliant mechanism was designed onto which the cutting system was mounted (Figures 24(a) and 24(b)). This mechanism provided a constant force, which could be varied to suit the cutter, while providing 50 mm of compliant motion.

This system could not follow the skin contours at velocities above approximately 100 mm/see during the skin cutting trials. To improve the cutting velocity the method of controlling the compliant motion has to be improved and further developed.

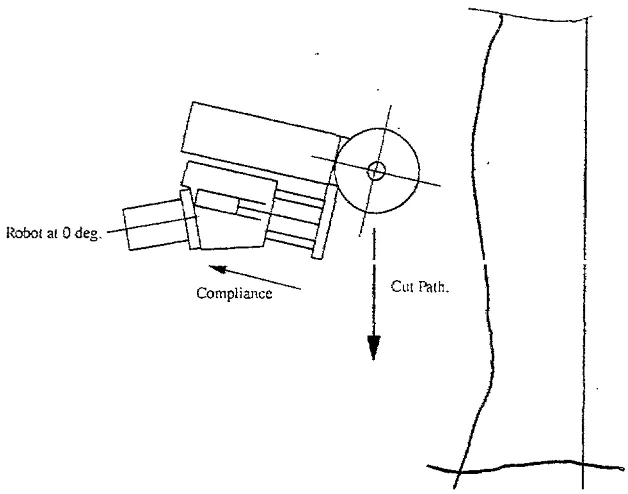


Figure 24(a): Schematic of chop skin cut

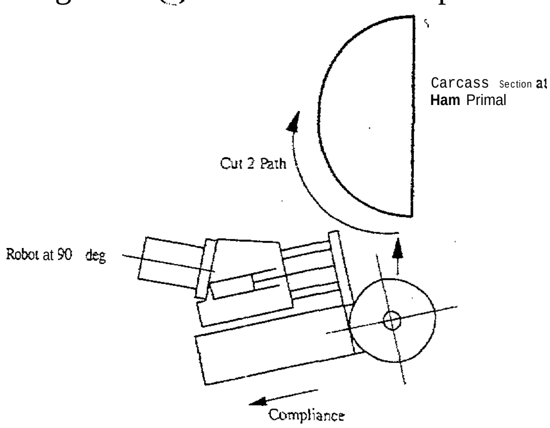


Figure 24(b): Schematic of Ham Skin Cut

System integration/overview

The integration aspects of the work have been concerned with the implementation of the communication channels and software for transfer of relevant data from one subsystem to the other, the physical link between the various computer control devices and implementation of the man-machine interfaces and safety units for the operation of the robot.

Man-Machine Interface issues

It is a requirement from the user to achieve a Man-Machine Interface standard providing:

- Safety features to prevent injuries or darnage during operation and maintenance.
- Ease of use in start up, operation and maintenance.
- Easy access to software modules that determine production parameters such as speed and yield.
- Ease of maintenance and upgrading of the subsystem hardware or software.
- Availability of useful messages indicating status of the full system and its subsystem.
- Availability of production data for analysis and control.

This aspect of the project has been restricted to the definition and implementation of the interfaces that provide operational capabilities only to complete the project as an industrial research tool. The MMI requirements for operators, supervisors and maintenance personnel have been agreed with the end-user and these have been documented.

Svstems installations and tests

The integrated system has been installed at FACCSA as the, first research demonstrator for meat cutting in industry (Figure 25). The system has been used for tests taking four major cuts in the total scheme described earlier. These are:

ham cut (skin)
loin cut (skin)
ham cut (bone)

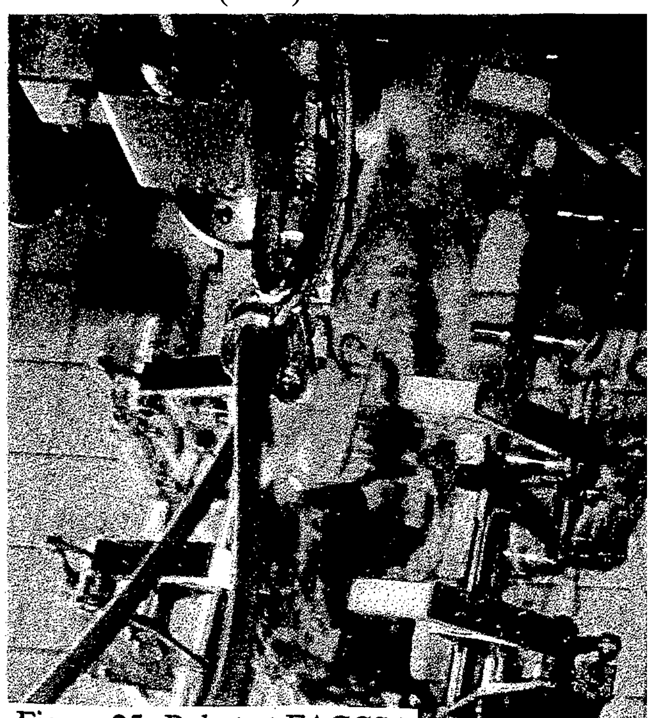


Figure 25: Robot at FACCSA

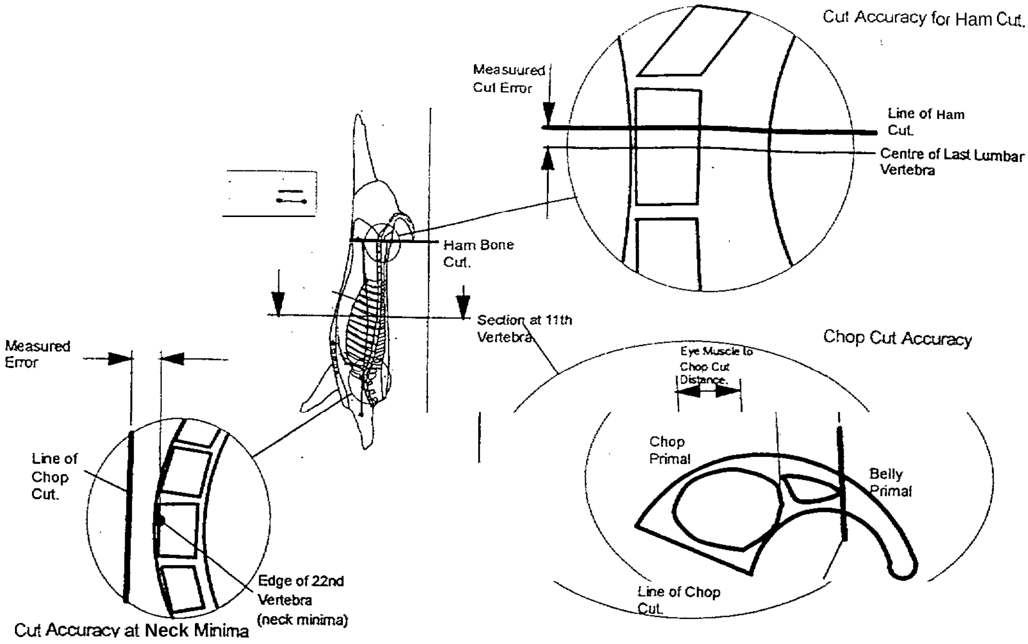


Figure 26: Measurement of Chop Cut Position

Cutting trials

Three sets of cutting trials were developed and performed to test the cutting accuracy of the robotic butchery system, each of these trials is described separately in this section. The first cutting trials performed were termed the RCB trials and comprised making bone cuts, chop and ham cuts on a statistically representative sample of right hand carcass sides. In fact a total of 38 carcass sides were cut and the results recorded. The second trials were termed RCD trials and involved making skin cuts (ham skin cut and chop skin cut on a sample of right hand carcass sides. Finally a total of 14 right hand carcass sides had ham skin and chop skin cuts performed, the chop skin and shoulder primal were then manually removed and chop bone and chop bone and ham bone cuts performed. This trial was intended to prove the viability of the butchery process defined in the initial stages of the project.

The algorithm which defines the path of chop bone cut attempts to predict the position of the edge of the eye muscle at the 1 lth vertebra. An additional length is added to this prediction to define the actual cut path. Obviously there is an error associated with this prediction and this error was assessed by taking sections from the chop primal at five positions along it and measuring the distance from the edge of the eye muscle to the actual chop cut path (Figure 26). This measurement included all of the system cutting errors and the path prediction error.

Figures 27(a) and (b) show the resulting distances from the carcasses cut during the trials.

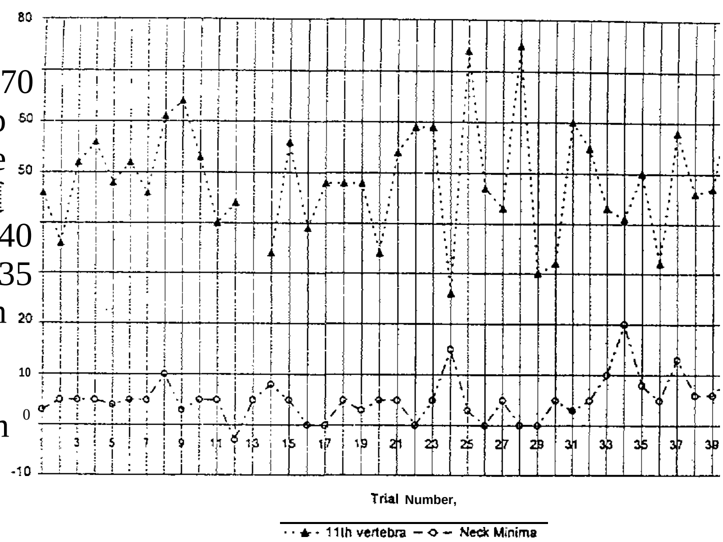


Figure 27(a): “Vertical cut” (eye muscle to chop cut position).

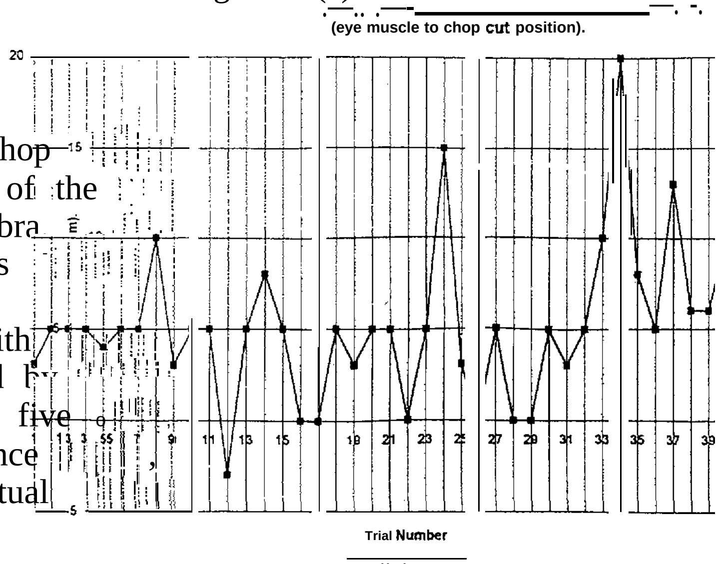


Figure 27(b): Chop cut

When performing the ham bone cut the horizontal path must be through the centre of the last lumbar vertebra and just below the pin bone. To achieve the second requirement the final rotational axis was fixed at an angle of 10° to the XY plane. Figure 28 shows the accuracy to which the pin bone was cut (+ve is too high and -ve is too low). As can be seen for most carcasses, approximate y 60% of carcasses, the position was correct to within ± 5 mm, however the remainder were significantly too high and so cut into the pin bone. This is unacceptable to FACCSA and represents a major problem when cutting through the carcass side since the position of . the pin bone must be inferred. The angle of 10° is correct for the majority of carcass sides and so cannot be altered to suit the minority of sides which are incorrectly cut.

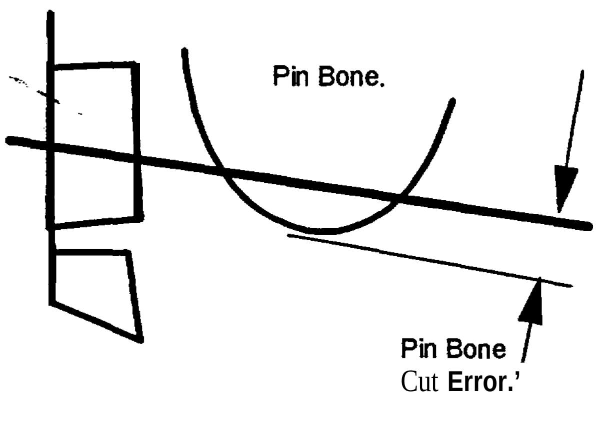


Figure 28(a): Ham cut at pin bone

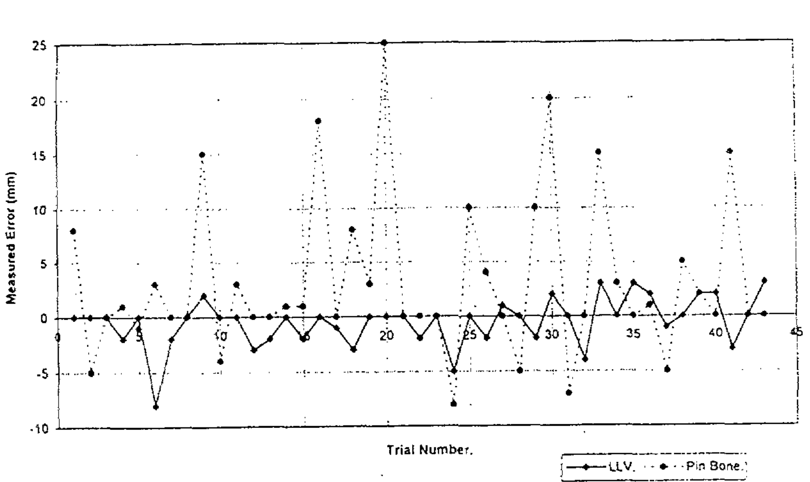


Figure 28(b): Ham cut

During development of the bone cutting system and during the RCB trials the forces generated by the cutter and the rotational speed of the cutter were monitored. This data together with observations of the cut quality was used to determine the cutting speed programmed for chop bone and ham bone cuts. Figure 29 shows typical force plots. The speed of chop bone cut was limited to 0.320 mm/see-' by the quality of the cut since at higher feed speeds the rib bones were broken rather than cut which is unacceptable to the end user. Ham bone cut speed was limited by the power of the cutter since at higher speeds the cutter stalled when cutting through the last lumbar vertebra and the cutting force increased unacceptably. The cutting trials performed by AMARC show that with a more powerful cutting system both of these limiting factors can be overcome and the cuts can be made at higher speeds.

Skirt Cuts

The RCD cutting trials were performed using basically the same robotic system as for the RCB trials but with a completely new cutting system. The cutting system incorporated a circular cutter with a plain blade for cutting through skin with compliance so that the cutter could follow the surfaces of the skin taking up errors in the prediction of the cut depth. The software was extensively modified to use more vision points and new path planning algorithms whilst taking account of the different design of cutting system.

The skin cuts were performed and assessed for cut depth, the cut path should be the same as for chop bone and ham bone cuts.

Skin Cut Depth.

The depth of both ham skin and chop skin cuts was noted along the length of the cut. This depth figure represents the accuracy of the path modelling algorithms developed by AMARC for modelling the 3D skin surface of the carcass side from 2D vision data. A programmed depth of 30 mm was used during these trials, this means that if the model was a perfect match to the carcass side being cut the depth of cut would be a constant 30 mm. The compliance in the end-effecter should help to maintain this depth, however if the model is not sufficiently accurate either all of the compliance will be used up (this did not occur) or the blade will not cut the skin (which did occur). The programmed depth was not increased because this would reduce the amount of compliance available.

For ham skin cut the depth is taken in equal intervals from the start postion on the split plane of the carcass side to the end of the cut. For chop skin cut the first point is the depth at the intersection of ham skin and chop skin cuts and the remaining points are equispaced along the cut until the end at the 4/5 rib gap.

Figures 30(a) and (b) show the variation of cut depth with measurement point. For the ham cut, the initial depth is consistent at between 25 and 40 mm but at points 4, 5 and 6 the depth is reduced to zero for some carcass sides. This is because a hollow exists in this area of the carcass below the ham primal and the surface model does not adequately allow for this feature. Consequently the cut depth is not always sufficient.

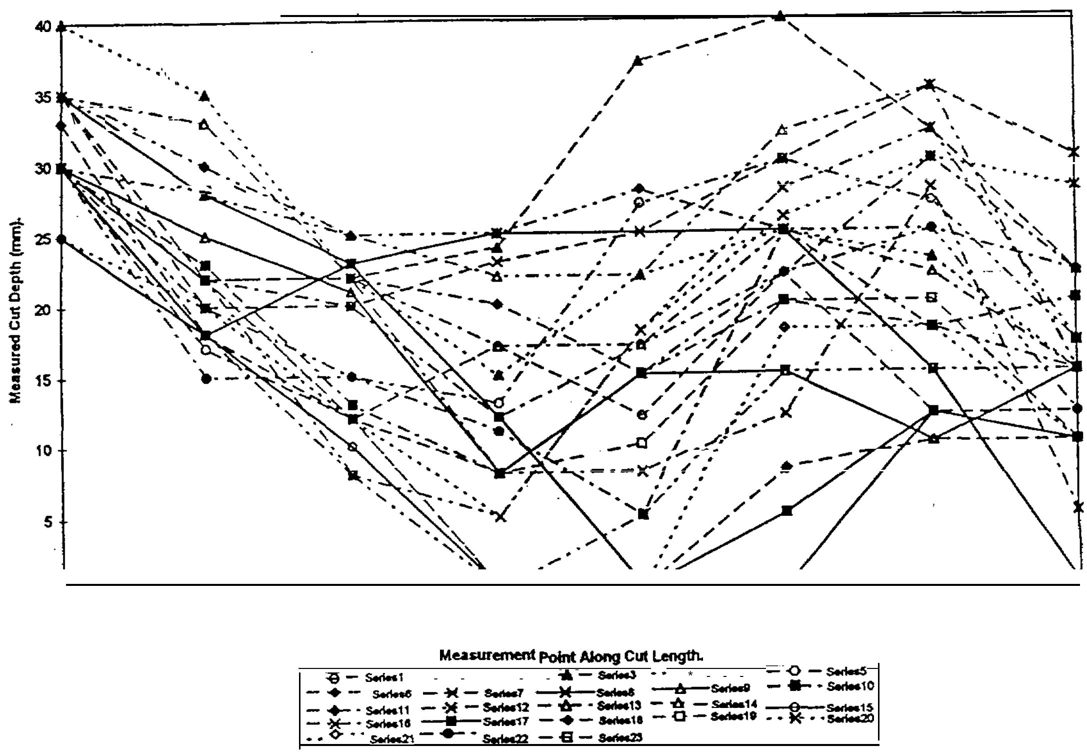


Figure 30a: Ham skin cut depth

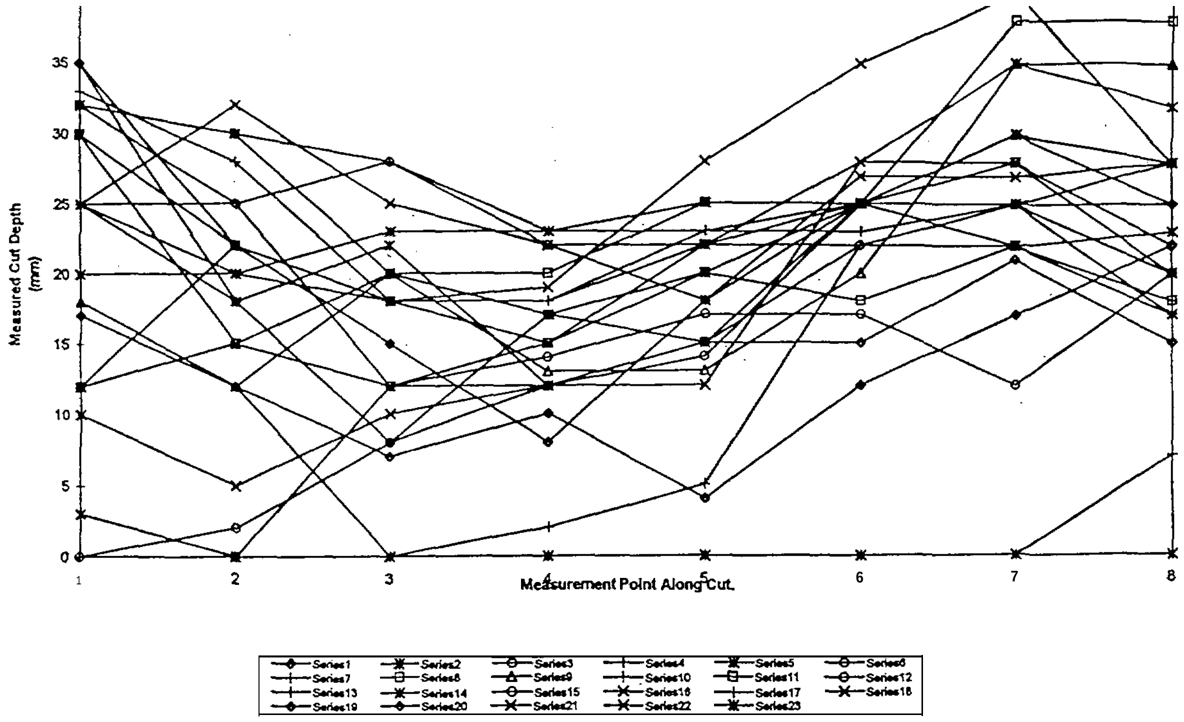


Figure 30(b): Chop skin cut depth

Final Trials

The final trials of the robotic butchery system were intended to prove the principle of using robotic technology to make the cuts of the butchery scheme. To do this the one robotic system makes the skin cuts, the chop skin and shoulder primal are manually removed and the meat/bone cuts are made by a second robotic system to produce the belly, chop and ham primals to FACCSA's requirements. The skin cuts performed in the RCD trials had proven that the cuts could be made to the correct depth to allow the chop skin and shoulder primal to be removed manually. The earlier RCB trials had proven that the meat/bone cuts could be made sufficiently accurately, therefore the final trials were intended to prove that the path of the skin cuts and the path of the meat/bone cuts could be made coincident.

To assess the coincidence of the paths the amount of skin left on the chop primal, which should be free of skin, was measured after the meat/bone cuts had been made. The chop primal is trimmed after it has been removed from the carcass so a small amount of skin remaining on the primal is acceptable to FACCSA.

A total of 14 carcass sides were processed in this way. The difference between the ham skin cut and ham meat/bone cut was shown to be 4 to 14 mm, that is some skin is always left on the chop primal. The difference for the chop skin cut and chop meat bone cut is measured in two areas the upper part of the chop primal, towards the ham primal, and the lower part, towards the shoulder primal. The mismatch between the two cuts in the upper area of the cut was not large, for 8 out of 10 carcasses there was no measurable skin on the chop primal. In the lower area there was a greater mismatch which is believed to be caused by the curved nature of the cut paths and the difference in diameter of the skin cutting blade and the bone cutting blade. The area of skin remaining on the chop primal was triangular in shape at its widest near the shoulder primal. The measurements taken represent the maximum width of the triangle and the length of the triangle.

From these trials it can be concluded that the skin cuts and meat/bone cuts can be made to coincide to an accuracy of between O and 15 mm for the ham cuts, and O to 10 mm for the chop cuts.

CONCLUDING REMARKS

Initially, the project team agreed to concentrate on the meat/bone cuts since these offered the most potential for achieving an economically viable butchery system. With the technology developed for these cuts the skin cuts would be automated. In the final trial the skin cuts would be made first, the chop skin and shoulder primal manually removed and the meat/bone cuts made by the robot. These trials have proved the viability of using robotic technology to perform 40% of the cuts in the butchery process which meets with the original target of the research.

The overall performance of the system through the implementation and integration of the new technologies has been quantified by a series of cutting trials. These were carried out at FACCSA to refine the system and to meet FACCSA's accuracy requirements, especially the size and shape of the chop primal.

The accuracy of the position of the bone/meat chop cut which separates the chop and belly primals is key to profitability of the factory. FACCSA aimed to meet, or improve, the cut accuracies currently achieved by the manual butchery line. The accuracy of the cut is a direct measurement of the cutting performance of the overall robotic system in terms of accuracy of the path planning, vision system, robot and fixturing system.

In trials on 43 carcass sides taken at random from the FACCSA line the position of the meat/bone chop cut relative to the eye muscle at the 11th vertebra was made to an accuracy of $\pm$10 mm for 80% of carcasses and to $\pm$15mm for 95% of carcasses. A sample of 30 chop primals from the current butchery line were measured and compared with chop primals produced by the robot. Compared to the current manual line an average weight increase of 190g per chop primal was achieved with an additional improvement in the straightness of the chop primal. The meat/bone ham cut could be made to an accuracy of $\pm$ 4 mm for 95'70 of carcass sides. These results represent a significant improvement in yield and quality over the current manual process and are essential in justifying the system commercially.,

The skin cuts were required to align with the meat/bone cuts to a depth through the skin and subcutaneous fat layers. The skin cuts were made using the same robotic system as the meat/bone cuts but with a compliant cutting tool and new path planner. The depth of cut was assessed during the skin cut development trials and when this was acceptable the final trials were performed.

The final trials proved that the skin cuts could be made to the correct depth to allow the chop skin and shoulder primal to be manually removed. The meat/bone cuts were then made and the match between the paths of the skin cuts and the meat/bone cuts was assessed. This showed that the cuts were aligned to an accuracy of O to 10 mm which was acceptable to FACCSA.

The meat industry can, for the first time, make use of "skilled" robotic technology in a variety of tasks. The technological aspects of the work have been significant and the effort to date has demonstrated the feasibility of the robotic devices for meat cutting. The **research has indicated that speeds of up to 450 carcasses per hour may be reached by utilising a multi-robot system** which allows manual labour to be redeployed in other parts of the plant. Early indications suggest that a **pay-back of 2-3 years** may be achievable based on the productivity and yield improvements. The research demonstrator has shown that the original targets of speed and payback could in fact be exceeded in some of the butchery applications.

The project has demonstrated that the major gains would be achieved in improvement of quality, yield and productivity as well as work conditions and safety.

Publications and Presentations resulting from and related to this project

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Mr. H. Schreiber, BANSS, made a presentation on behalf of the Consortium at the *5th EC Conference RTD on Industrial Technologies held in Brussels Congress Centre 6-8 December 1994*

Path Generation for Robotic Cutting of Carcasses, I.H.C. Wadie, K. Khodabandehloo, *International Journal of Computers and Electronics in Agriculture, Jan. 1995 Vol. 12, no. 1, pp65-80*

Robots on-line, Professor Koorosh Khodabandehloo, Neil Maddock and Helmut Schreiber , *Meat International, January 1995, Vol, .5. No. 5, pp 40-43,*

Robotics in Food Manufacturing, K. Khodabandehloo, *Workshop on Advanced Robotics and Intelligent Machines, University of Salford, 11 March 1993.*

Skilled Robotics, K. Khodabandehloo, *Second International* Conference on *Automation, Robotics and Computer "Vision" (ICARV '92) Sept. 16-19 1992, Singapore, and also published in The EEE Journal, Nanyang Technological University Singapore, July 1993, pp 95-100*

Robotic Deboning: A fundamental approach to engineering a system, G.L. Purnell, N. A. Maddock and K. Khodabandehloo, International *AIFA Conference on Artificial Intelligence for Agriculture and Food, Nimes, France, 27-29 October 1993, pp11 7-125.*

Modelling Primal Cuts on Pork Carcasses for Automated Butchery, I. H. C. Wadie and K. Khodabandehloo, *IEE Colloquium on Intelligent Automation for Processing Non Rigid Products, London, October 191994,*

Machine Learning in Robotic Meat Processing, G. L. Purnell, S. Vranes and K. Khodabandehloo, 2nd *European Robotics and Intelligent Systems Conference, Malaga, Spain, 22-25 August 1994, pp 68-77, Vol. 1.*

Development of Skilled Robotics, K. Khodabandehloo and S. Vranes, 2nd *European Robotics and Intelligent Systems Conference, Malaga, Spain, 22-25 August 1994, pp 739-749, vol. 2.*

VIDEO presentation at IFFA Fair, Frankfurt, May 1995.