Automated Deboning System
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Summary
The project is to develop a machine to debone a cattle forequarter, which is currently a problem in the meat industry mainly due to high labour cost. The deboning is the process of cutting on both sides of the each rib bone in such a way that the rib bone can be pulled out clean.

This project attempted to find an automated solution that would fulfil the requirements of the meat industry. The project originally started out as a manual machine, but because of the difficulty of training a person to use the system, an automated solution had to be found.

The deboning machine is a hydraulic system comprising of three hydraulic rams, cutting head and vacuum system. The control side consists of sensors to detect the loading of the cutting tool against the bone, torque sensor and positional sensors.

The machine was controlled by a Personal Computer connected to a Programmable Logic Controller.

This system worked well, and produced acceptable and repeatable cuts along the rib bones. There is one remaining problem, that is there is no sensor commercially available which will detect the meat-bone interface, therefore it is assumed that the beef carcasses are of similar sizes.

Objectives of Project
The objective of this project was to design a machine to remove the bones from beef forequarters. This design had to be more efficient economically than the human operator. The machine was required to remove close to 100% of the meat off the bone. This is required to happen at the current speed of production. The machine must be suited to the hygienic setting of the meat factory.
There is a large market in the meat industry in Ireland and other Western European countries as well as the U.S and Australia for an automated beef deboning machine. The reasons why there is such a large market are:

- The cost of manually deboning the meat
- The meat loss in the current operation
- The speed of the current deboning system
- Labour shortages.

A full examination of all the above reasons shall now be made.

The cost of manually deboning the meat

In modern meat processing plants in Western Europe, the workers who debone the meat also known as boners, are paid by piece. This means that they are paid per piece of meat they debone. Since this project is mainly concerned with the forequarter, the latter will be concentrated on in this report. The piece price for deboning the forequarter is £1.50. Eight to ten forequarters can be deboned by one person in an hour. This means that the boners in meat factories are paid more than the middle management. The manual process of deboning beef is extremely dangerous and therefore meat processing companies have to pay high insurance rates.

The meat loss in the current operation

The percentage of meat remaining on the bone is difficult to ascertain, but from a visual examination it was determined that enough meat remained on the bone to warrant a substantial loss over a day. The amount of meat remaining on the bone was extremely dependent on the boner. Most of this loss can be removed by a machine that accurately cuts along the membrane on the bone.

The speed of the current deboning process

Even though the current deboning system is fast, at 10 forequarters on average per person per hour, it is inconsistent. The production rate can vary from day to day due to illness, and holidays. A machine however can be run continuously at a set rate. This means that it is possible to adequately predict the daily production rate.
Labour shortages

The high cost of recruiting and increasing shortages of staff in the labour intensive food sector coupled with the often unpleasant, repetitious and hazardous working environment make the application of robotics and automated systems extremely desirable.

All these above conditions make automation very applicable to the meat industry. So why haven't robots been used yet? The reason why is that because of the high skill required by the boner, the task of replicating it is extremely complex.

Before it is possible to understand the machine it is necessary to have some understanding of the anatomy of a beef carcass. The geometry of the carcass is the most inhibiting factor to an automated process. In figure 1 a sketch of the half carcass is shown.

![Figure 1: A half carcass of beef](image)

In general there are 13 rib bones between breast bone and backbone. It is possible, although rare, to find 12 or 14 bones. As already mentioned the geometry of the bone is highly irregular as can be seen from the sketch of a typical rib bone in figure 2.

![Figure 2: sketch showing the complex and irregular shape of the rib bones](image)

One of the most important facts about the anatomy of the bone is the membrane surrounding the bone as shown in figure 3.
Figure 3: Sketch showing relationships between meat, bone and membrane

The membrane connects the meat to the bone, so if this can be successfully removed from the bone then the bone will come out cleanly. The method decided upon to break the membrane was to shear the membrane between the cutting tool and bone as shown in figure 4.

Figure 4: Sketch showing tool removing meat of bone by shearing membrane.
Machines Operation

To explain the operation of the machine, a sketch is shown below displaying a representation of the meat in the machine, and the position of the three rams which give the three axis of motion.

Figure 5: Sketch showing a representation of the meat on the machine.

Below in figure 6 are three diagrams a) b) and c) showing the machine with one of the rams in its extreme position.
In operation the forequarter would be placed on the vacuum box as in figure 5. The vacuum would be turned on keeping the meat in place. The cutting tool would move along the rib bone approximately in the direction of motion provided by ram B. Ram A would keep the cutting tool against the rib bone. Ram C would keep the height of the cutting tool correct.

**The Work Done**
The work done on the project was in the following areas:

A. Mechanical design and construction
B. Instrumentation
C. Control System

**A. Mechanical design and construction**

The machine designed to do this cutting is a hydraulic machine, because of high force to acceleration ratio. The actuators used in this machine are double acting two port hydraulic rams. A sketch of the machine layout is shown in figure 5. The rams are controlled using proportional valves which accept a +10V or -10V to extend or retract the ram. The motion and operation of this machine is described in the previous section. This machine was originally a manually operated machine, but in order to make it operated automatically some changes had to be made to the original machine. The first change made to the machine was the removal of a fourth axis on the machine. This axis was a rotational axis, on the shaft on which the cutting tool was held. This rotational axis was replaced with a freely rotating axis. The cutting tool was offset from the axis to give an inward turning moment to keep the cutting tool against the bone at all times as shown in figure 7.

![Figure 7: This shows the offset of the cutting wheel to give a rotational moment](image)

Another mechanical change that was made to the system was the placing of a vacuum directly under the meat as shown in figure 5. This vacuum was created by building a box with the vacuum connected at the bottom and the top shaped to fit the bottom of the forequarter. This provided a tension on the meat around the bone exposing the membrane for easy removal. The cutting tool itself was made from nylon to prevent chipping of the bone. This was a problem on the previous manual machine. The cutting tool is a cylinder 100 x 15mm.

**Instrumentation**

**B1. Detecting Meat-Bone Interface**

Several options were looked at. The first option looked at was using a capacitive detector. This type of detector is used for finding the wall studs behind plaster board. This operates by measuring the electrical permactivity of the surface under the sensors. There were several problems with this system. The first problem was that the permactivity of meat and bone are very close (within 10% of each other), so that it is difficult to discern the meat/bone interface.
the meat in order to work properly as the capacitive effect is inversely proportional to the
distance from the target.

The second option looked at was ultrasonic. Ultrasonic operates by sending a high
frequency sound wave at the target, and measuring the characteristics of the wave after it has
passed through the target or the reflected wave. Since this system insists on non-contact
ultrasonic, there are two possible methods to do this. The first possible solution is air-coupled
ultrasonic, these are shown in figure 8.

![Ultrasonic system diagram](image)

This system can work by either of two possible methods. Reflective scan or through scan.
Through scan has already been ruled out by previous testing as it was too hard to align the
scanners accurately.

*Figure 8: Sketch demonstrating both methods of air coupled scanning.*

The method of reflective scanning also had its problems. The amount of the ultrasonic wave
reflected at the interface of two surfaces is proportional to the difference in density of the two
substances either side of the interface. Therefore most of the ultrasonic signal will be reflected
at the air/meat interface, and only a small part will be reflected at the meat/bone interface.
While this may be usable, it is also necessary to focus the wave to detect the bone/meat
interface to the required amount of accuracy i.e. +/- 1mm. Therefore the second solution seems
the best method for detecting the bone this is laser ultrasonic. Laser ultrasonic operates by
generating an ultrasonic wave in a material, by firing laser pulses at it. This wave can be read
off the material using a second laser. This system is demonstrated in figure 9.

![Laser ultrasonic system diagram](image)

The wave is generated using thermal expansion of the material. This should be done fast
enough and a low enough temperature change so as to not cook the meat.

Two position sensors and one proximity sensor are used to measure the position of the cutting tool in absolute space. The second proximity sensor measures the height of the cutting tool relative to the meat as shown in a simplified diagram in figure 8. The two load cells measure the forces parallel and perpendicular to the bone as shown in figure 9.

![Sketch showing forces measured by load cells](image)

Control system

The control system development consists of hardware and software subsections.
C1. Hardware Development
C2. Software Development

The controller was a personal computer which, used a visual basic program for control and data acquisition from a PLC which was connected to the various sensors and valves on the machine. A manual joystick system was also connected into the PLC to allow for override control of the rams. All automated control of the machine was contained in the visual basic program. There were several different sections to the program, there were the functions controlling the height and load on the cutting tool, and the functions controlling the length of cut and other motions of the machine.

The offsets were calculated from the edge of each bone. A separate offset figure was used for each offset used.

Results

Machine’s performance can be looked at using criteria such as power (requirements & consumption), efficiency (number of good bones cut/number of total bones), quality of cut (amount of meat remaining), speed, noise level, and manual supervision required, etc.

The machines ability for deboning operation is hard to qualify. The machine cuts along the bone such that there was no meat adhering to the bottom and sides of the bone, leaving only a small layer of fat on the top of the bone. How does this compare with the boner? In all sets of ribs examined at the factory which were done manually there was a higher percentage of meat remaining on the bone. The percentage meat removal is close to 100%. The main problems were those mentioned above in the discussion, i.e. that the machine moved too slowly and the machine tend to land on the bone twice in every set of ribs.
This machine is operated at a speed that will allow it to debone 6 forequarters an hour. This is very slow in comparison with a normal boner off the line who can completely debone (not just the rib bones) 10 forequarters an hour. There are several limits on the speed of the machine, but the main bottleneck is the control system. The control system is a PC using a PLC as a data acquisition unit. The reason this system was used, was that it was easy to read off data on the computer, and quick to make changes where necessary. This system speeded up the time to develop a prototype system. The main problems with this system are that is slow in comparison to a proper data acquisition card or a good PLC.

The reason why it is slow compared with a normal PLC unit is because the PC must wait till the end of the PLC program before it can read or write to the PLC. The time required for one analogue to digital conversion is 15ms, the time required for one digital to analogue conversion is 10ms. The total time required for all the digital to analogue and analogue to digital conversions is $15 \times 6 + 10 \times 4 = 130ms + 40ms$ other run time $= 150ms$. Also the time between program executions is slowed down while the information is transmitted to the computer. In this system it is possible to write or read two variables a second. This reduces the settling time in the load and height control routines, therefore the system has to be run at a slower speed, than if just a PLC was used. For this reason, once the system is fully developed, the PC/PLC system will be replaced by a PLC, probably a Siemens 300 series as this allows the program to be kept closest to what it is at the moment.

**Benefits to the postgraduate researcher:**

**Technical Benefits**

There were many benefits to the researcher. The main part of the project was completed in a machine shop, Concept engineering, Kilmalock Co. Limerick. Here the postgraduate learnt about metal fabrication, in designing the cutting head and the vacuum system for the machine. In the control part of the project, an understanding of Programmable Logic Controllers was required. This led to a good understanding of PLC programming and wiring. A controlling program was written in visual basic, which gave the researcher an understanding of computer programming and protocol conversion between a personal computer and a PLC. Various sensors were used in the project, laser and ultrasonic analogue proximity sensors, potential divider position sensors, and load cells. The use of these sensors gave understanding to there abilities and limitations. Research was carried out to try and develop a sensor to detect the meat/bone interface, this gave an understanding of the inner workings of capacitive and ultrasonic sensors.

**Operational**

The project can be divided into two sections, the design and the control of the machine. The problem with this is the integrating of these two parts of the system. At a certain stage of control, a change of design is required, and visa versa. Whether further design or control is necessary requires intuition. Some of this intuition was gained in this project.

Even though this machine is completely automated it still needs one human operator to supervise it. The machine was designed to allow for easy loading and unloading of meat in the working environment, and for easy manual override of the system. An understanding of ergonomic design was gained from this part of the project.

**Unexpected Problems**

There were several problems with the machine discussed above. Each problem will be looked at, and a number of solutions will be discussed. The main problems were

The lack of bone sensor
Geometry of bones and fat on the bones

The lack of a bone sensor

The system of just using offsets to find the next bone was working about 80% of the time i.e. 3 offsets were wrong out of 18 offsets. This is unacceptable in a production environment. The best solution to this problem is to build a sensor to detect the interface between bone and meat. The detector required needed to be non-contact, and detecting from one side only.

Geometry of bones and fat on the bones

There are several problems with the geometry of the bones, and the fat on the bones that make the cutting of them extremely difficult. There are three main problems associated with the geometry of the bones. The first problem was the thinning out of the bone on the weak side, this got so thin in certain areas that it could be broken off with the slightest pressure from the machine. To combat this the pressure on the weak side was reduced in certain areas. Another problem associated with the geometry of the bone is lipping. This is where a narrow piece of bone extrudes from the underside of the rib, but is undetectable from the top side of the bone. This causes the cutting wheel to roll up onto the bone breaking it. To combat this the machine was made go deeper in certain areas. The third problem with bone geometry was partially broken bones. This problem was difficult to combat. If the bones were broken badly they could not be cut along. More research need to go into this area to overcome this problem.

The fat on the bones also causes problems. If a large glob of fat were to be on one of the bones it might cause the height sensor to raise the cutting tool so high that it slipped off the bones. At the moment there is already a tool to remove heavy fat from forequarters

Benefits to participating companies

While the machine has not been developed up to a level where is can be marketed. If a source can be found to develop a sensor to detect the meat/bone interface the money to develop the sensor can probably be gained from outside investors. Once this has been done a fully working prototype can be developed and this can be used to gain further investment. This machine has a large market as detailed in the introduction.

The proposed next steps to commercialisation

There were several changes that need to be made to the project before it can be put on the market. The first change is the addition of a meat/bone interface sensor, because since last checked there was no such sensor on the market, this will have to be developed by an outside company. This means that the time for getting the machine to market is dependant on the complexity of developing this sensor. The time frame for developing this sensor by an external company is estimated at six months.

Another step required for the commercialisation of this machine is the speeding up of the machine to the level where it works at the equivalent speed as the current process. This can be done by replacing the current system (Personal computer and PLC) with a more expensive and complex PLC. This can be installed in two to four weeks, but is best left till the meat/bone interface sensor is built.

The final step to commercialisation is the adjusting of the machine to align with the current production process, this includes having the machine in line with EU hygiene standard for the meat industry. Getting the machine to work in the production process will require testing in a meat processing factory.