AMPC

FINAL REPORT

Improvements to Robotic Bandsaw Operations

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1.0 EXECUTIVE SUMMARY

The intention of project 2016.1043 was to provide an array of potential improvements to both manual and robotic meat sawing systems through the integration of technologies for sensing, actuation, interface design, and asset management. GREYSHED has examined and developed preliminary prototypes for a number of potential strategies for simplifying the monitoring, maintenance and control of meat processing equipment. These strategies are intended to reduce the potential of costly downtime, minimize unnecessary energy and product waste caused by machine- or user-error, and encourage higher yield, quality, and operator safety. A variety of concepts were proposed and prototyped as part of this research, with varying degrees of difficulty in implementation. While most of the designed elements were combined into a single cohesive model as part of this research, the intention is that the individual parts can be integrated with existing workflows (or built into new ones) selectively as they are needed and considered viable.

The research sought to improve both manual and robotic meat sawing processes by proposing hybrid solutions which leverage automation techniques to improve the speed and safety of manual processing, while employing intuitive interface design to allow human operators to quickly diagnose and correct errors in partially or fully automated robotic systems. GREYSHED outlined and tested several sensors which can monitor various aspects of saw health (power consumption, speed, tension, etc.), to enable facilities to precisely tune the process of equipment review, repair, and preventative maintenance. These sensors were integrated with an onboard computer, projection-mapped interface, and cloud-based log (linked to QR codes on the device), so this data is immediately and intuitively accessible to machine operators and plant personnel both on the floor and offsite.

Sensors were also added to the saw which measure the number of cuts made, and the speed and frequency of these cuts. These sensors were documented as a tool for evaluating employee performance, and have the potential to discover unsafe practices before they become problematic. In the domain of manual meat processing, GREYSHED also developed a prototypical implementation of a mechanized blade guard/guide and gauge plate, which automatically sets the cut height and gauge based on the 3D scanned primal. Workers will often not take the time to adjust the blade guard in the fast-paced factory setting, exposing themselves to higher risk of injury, and generally increasing the kerf waste as well. Small improvements such as automatically controlling the height of the guard, or monitoring the motor current (which can be used to evaluate excessive or insufficient feed rate tendencies) can go a long way to ensuring safer and more efficient practices.

Many of the methods explored to monitor equipment for manually-operated processing equipment can also be ported to automated systems with similar advantages. Monitoring the load on the saw motor, for example, allows for real-time evaluation of feed rates and electrical consumption. This information can be used to optimize throughput and minimize unnecessary loads by altering the speed of the robot, either incrementally or in a closed-loop system. The use of projected overlays onto the automated workcell can also serve to allow maintenance personnel to quickly detect machine or process errors before they occur, and to easily diagnose and correct them if they do.

The concepts developed as part of this research provide several strategies for improving the accessibility of complex processing equipment, which can directly impact the safety, efficiency, and throughput of meat processing facilities. While each of these concepts would need to be tailored to the requirements of the setting in which they were being installed, they can be integrated and developed further in stages, and as is required. For example, it is relatively simple and inexpensive to tag equipment with QR codes linked to maintenance schedules and other pertinent information. While immediately useful, this network can later be expanded to be automatically updated with information from machine-mounted sensors. A screen- or projection-based user interface can also supplement an existing system, and its development can be largely decoupled from the earlier development of the sensors or automated routine.

2.0 INTRODUCTION

Robotic automation and hybrid processes for bandsawing in the red meat industry have a wide array of potential advantages, including faster processing times, lower production costs, reduced worker fatigue, increased workplace safety and hygiene, and a higher yield of high-value cuts through efficient cut placement algorithms and precision control of the thin-kerf bandsaw blade. Automation is thus not simply a means of replacing a human bandsaw operator with a machine that is less prone to injury and fatigue, but an opportunity to rethink the sawing process such that it can take full advantage of digital control—delivering a better product more efficiently.

While the combination of robotic automation and sensing technologies in the red meat industry has enabled—and continues to enable—countless improvements to cost, throughput, yield, safety and efficiency, there is still an immense gap between the current state of production and a completely mainstream, error- and maintenance-free, fully-automated future. The promise of prevalent, outright "lights-out" manufacturing (Jaikumar, 1986) has proven elusive in most industries, but is especially challenging in red meat processing where there is a tremendous range of deviation between one carcase and the next. The success of automation in the red meat industry, (and in numerous AMPC supported projects) comes largely from the ability to bridge the prohibitive expense, technological shortcomings and inevitable errors of fully automated systems (Inglis,2011) with human intervention, manual backup, and hybrid production lines.

Despite the reality of occasional errors and necessary human intervention, automation is frequently developed "based on the assumption that human intervention is rarely, if ever needed, and, thus, little or no consideration is given to the operator-automation interface." (Brann et al, 1996) In such cases, inevitable operator intervention can be problematic, tedious and entirely unintuitive.

Rather than integrating automation and sensing technologies as a "black box" (in which the correlation between the sensing hardware, cut planning algorithms and robotic motion are unapparent to the human observer), it is essential to design systems which are specifically intended to be easily diagnosed and corrected by a human operator when necessary. As such, visual guides are critical even in fully automated systems: in order for an operator to inform an automated process, the operator must also be given information about that process and what intervention is necessary ("operator-informed/informed-operator" manufacturing) (Johns et al 2014).

AMPC has previously facilitated the development of effective hybrid manual assist devices such as

HookAssist [1], which leverage partial automation to augment existing human operator skill. In exploring visualization methods, we must recognize that such hybrid systems can work both ways: just as the machine can assist the human operator with certain tasks, if given the correct information, the human can also augment the machine with his adaptive cognition and physical flexibility.

As such, this research project develops a number of methods for intuitively providing information with regards to equipment motion and algorithmic cut-planning, such that it can be easily understood and utilized by workers or repair personnel. This information is made available either through an app-based infrastructure with QR-tagged equipment, touchscreen interfaces, or as an augmented-reality overlay which is projected directly onto the relevant equipment and which requires no specialized wearable devices.

In order to further the improvement and efficiency of bandsaw operations, however, it is also necessary to look beyond the operator (robotic or human) or operation-logic of the saw, and to study the saw itself and the coordination of the two. As such, this project examines a number of sensors as potential feedback mechanisms for optimizing operator motion and reducing the likelihood of debilitating errors.

This final report discusses the following project developments and outputs:

- Integration of saw-mounted sensors for measuring motor load, motor speed, blade tension and continuity.
- IoT methods for coordinating saw sensors with asset management systems, including preventative maintenance scheduling and repair alerts.
- Development of a simplified routine for scanning and processing primals for the purpose of testing the various sensors and visualizations.
- Prototyping a number of methods for digitally-assisted manual processing, including sensors for productivity tracking, an interface for monitoring the saw and visualizing planned cuts, and actuators for automatically adjusting the blade guard and gauge plate.
- Integration and documentation of sensor data, and projective visualizations with a sample robotic process for picking and cutting parts.

3.0 PROJECT OBJECTIVES

The primary objective of this project was to conduct an in-depth exploration of a variety of methods and technologies which have the potential to improve both robotic and manual bandsaw operations, and which might be ported into other meat processing tasks. The developed methods are intended to introduce new concepts which can be further evaluated and integrated as deemed fit by AMPC and related partner facilities. The specific objectives are outlined below.

3.1 Bandsaw Sensing System

In order to facilitate the optimization of both manual and robotic beef cutting systems, we sought a number of sensors which are capable of monitoring various relevant aspects of the bandsaw state. By prototyping a select few of these sensors, and embedding them into the saw, it becomes possible to record various attributes of the saw, and use this information to analyze the performance of a given cutting routine. We were primarily interested in sensors which provide data with regards to aspects of the saw which can be influenced by poorly calibrated cut parameters, and which are likely to influence maintenance or repair schedules. We identified several sensors for monitoring motor load, blade speed, blade tension, cut frequency and blade completion. Information from these sensors is made available to facilitate corrections to inappropriate tool use and to trigger necessary repairs.

One of the primary reasons for monitoring saw sensors is for its potential utility in optimizing cutting feed rates for faster throughput with reduced wear on the equipment, electrical consumption, and blade breakage. Excessive feed rates can increase blade strain and motor load, reducing tool life and causing costly down time during part failure. Conversely, keeping feed rates too low has the obvious implications of reducing processing speed and plant throughput. Bandsaw feed rates are largely determined by the thickness of the cut, the speed of the saw, the geometry of the tooth, and the properties of the material. While other industries can set fixed feedrates for cutting uniformly dense, standard thickness components, the variable properties and complex geometries of beef carcase components renders such practices highly inefficient. The mechanical bandsaw works by shearing small amounts of material with each individual tooth. Cut rate is determined in part by the gullet (or the cavity between the teeth), which accumulates this shorn material over the course of the cut. Aggressive feed rates cause the gullet to fill prematurely, blocking the teeth for subsequent cuts and leading to stalls or failure. Because this limitation on speed is caused by a geometric limitation of tooth size, it follows intuitively that cut speed is related to the geometry of the material being cut: namely, thicker sections of material require slower feed rates. (Lehmann, 1993)(Fig 1). By coupling speed data with the scanned part thickness, and monitoring the effect of speed settings on the motor load (which exhibits clearly observable fluctuations based on the thickness of the part being cut), it is possible to intelligently modulate cut speed in order to accelerate production while minimizing the probability of tool failure.

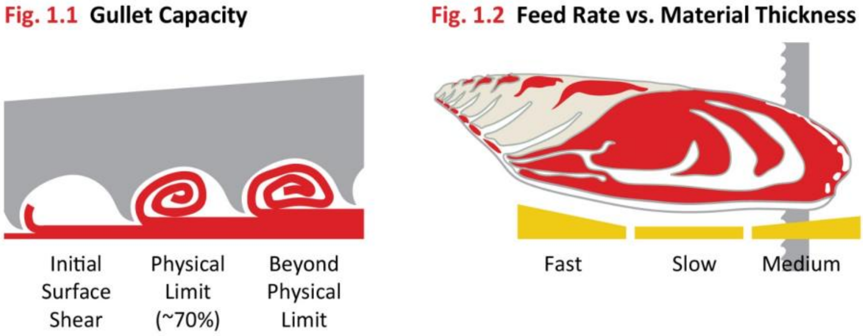


Fig 1 Gullet capacity, feed rate, and material thickness.

3.2 Cloud Based Asset Management

Sensor data is only useful to human operators if it can be observed on site, or recorded for later processing. To make this data easily available, the saw is equipped with an onboard computer for recording and displaying sensor data. Similarly, by establishing an infrastructure which allows for cloud-based storage of this sensor-data, we create a central location where essential real-time data, equipment manuals and service logs for all plant assets can be accessed from anywhere with a PC or mobile device. By placing unique quick response (QR) codes on each asset, equipment can be quickly scanned using a mobile device, and the associated information can be instantly retrieved for diagnosis or preventative maintenance.

3.3 Digital Assist for Manual Processing

Augmenting the physical world with digital information and digitally-controlled tools can greatly accelerate and improve the accuracy of manual tasks. Augmented visualizations have the potential to increase the efficacy of human error detection and can reduce latency in human processing time by conveying information which is quickly processed by computers. Many existing projects demonstrate the utility of displaying information and instructions through tangible interfaces (Cox, 2016)(Rivers, 2013)(Johns, 2014)(Ratti et al, 2004). This marriage of digital information with tangible objects and workstations can provide the human operator with a level of precision and efficiency otherwise restricted to machines.

In this project, we seek to combine 3D scanners, digital actuators, and visualization tools to augment manual meat processing. The 3D scanner is used to measure the incoming carcase component, while the actuators automatically regulate the height of the blade guard and gauge plate based on these measurements. Visualization methods allow for this measurement data, and other content such as cut paths and sensor information to be conveyed as digital diagrams directly onto the surface of the work area and the part to be processed.

In combination with the sensors used to read saw status, we also examine the potential of sensors to measure operator performance by recording the number of cuts, speed, and movements made by the operator. This information can be used to promote individual improvement, or to diagnose and correct unsafe practices before they lead to larger problems.

3.4 Projective Augmented Manufacturing

While factory maintenance in the past relied on an operator who physically observed system faults and repaired them, this is becoming increasingly difficult with complex, computer-controlled equipment. It is often impossible to visually “see” errors in computerized systems—which generally leads to a slow, expensive, and tedious debugging process that can only be undertaken by a specialist. Generally speaking, the more information that is provided about an error or maintenance issue, the easier it is for a human operator to quickly repair it.

Projective augmented reality techniques have the potential of enabling workstations where intuitive graphics clearly depict both physical and digital system failures or warnings in a way that can be quickly diagnosed, avoided or repaired. In this final report, we document a prototypical example of a workcell which projects cut planning information, saw-sensor values, machine prompts, error messages, and temperature values directly onto the robot and its surrounds.

4.0 METHODOLOGY

4.1 Bandsaw Sensor Integration

4.1.1 Motor/Blade Speed

Measuring rotational speed is a common necessity in industrial automation, and GREYSHED considered several strategies for measuring the rotation of the bandsaw motor and wheels. In the specific

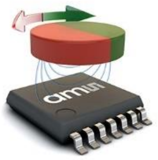


Fig 2 Ams 5048A and 2-pole magnet

application of the bandsaw, the readings from these sensors (tachometers) can be correlated with the current readings to determine if the blade has stalled, and can be correlated with one another to determine if the blade or belt is slipping or broken (by looking for changes in the differential speed between two sensors). We examined several viable sensor options, including optical encoders, magnetic switches (reed switches and hall effect sensors), and magnetic rotary encoders. For this purpose, magnetic rotary encoders were found to be the most effective due to their ease of installation (a single dipole magnet is mounted on the center of the spinning shaft, opposite the sensor), high resolution, absolute position readings, and resistance to external noise and occlusion. Specifically, we use the AS5048A sensor from AMS—a single IC component consisting of an array of hall-effect sensors and capable of taking up to 16384 angle readings per revolution. (Fig 2 &3) [2] As with all of the sensors explored in this project, the AS5048A readings are processed by a microcontroller (which converts the angular velocity values to rotations-per-minute) and are sent to a monitoring computer via serial communication.

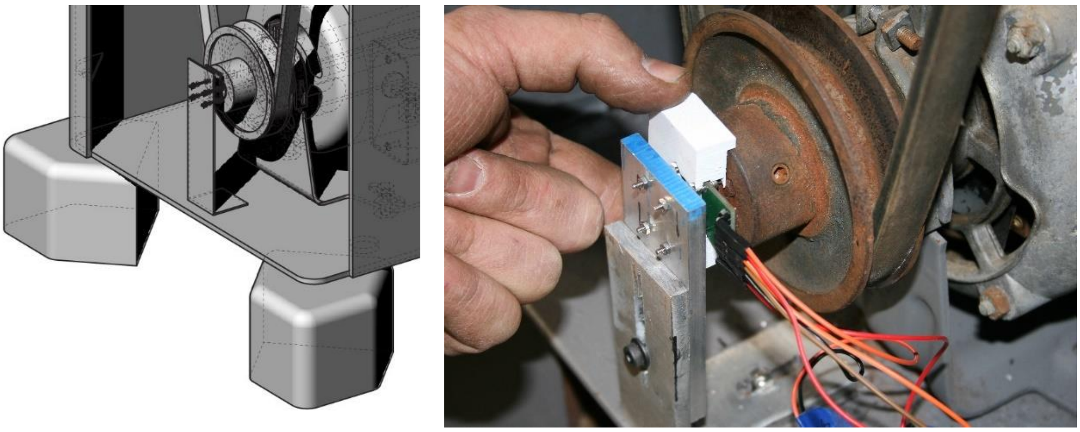


Fig 3 3D model of sensor placement and alignment using 3D printed positioning jig.

4.1.2 Motor Load

Measuring the current draw of the motor has been tested as a simple and effective method of reading motor load. We have used a non-invasive split-core current transformer (SEN-11005)[3] in combination with an op-amp circuit and MCU, in a schematic similar to (McNally, 2010). This is the simplest of our sensors to integrate into the system, and potentially the most valuable in terms of provided data. The sensor simply clips around the outside of the saw's power supply wire and measures the current passing through the line. The sensor values demonstrate a clear correlation of material properties and saw load, as the incoming values are correlated with the thickness of the cut. (Fig 4) These measurements also indicate when the saw is on, off, stalling, and how much electricity it is consuming. In addition to being useful for optimizing feed rates and recognizing errors, this sensor is a practical tool for conducting energy audits in order to minimize electrical consumption and meet sustainability goals.

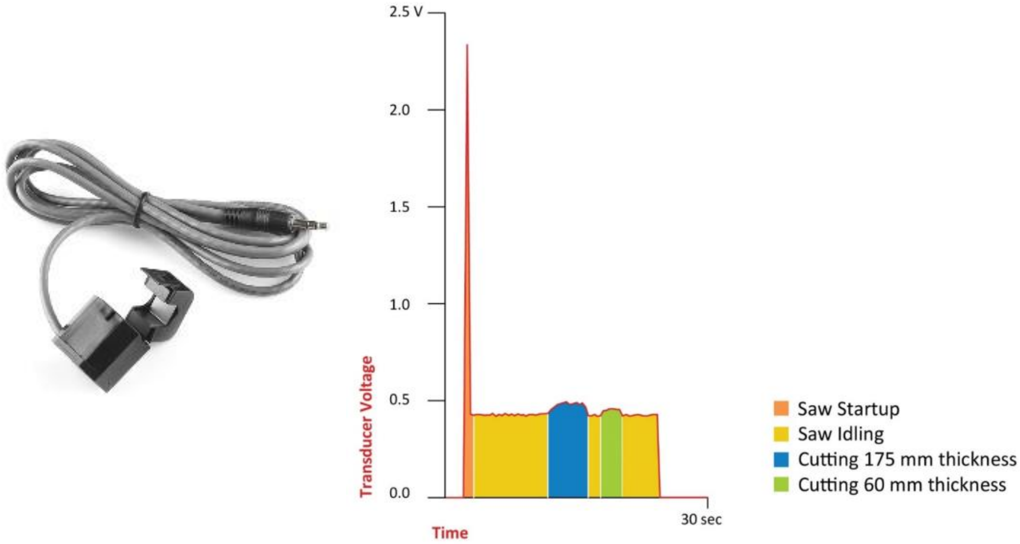


Fig 4 Non-contact current sensor and Measured signal during saw startup, idling, and cutting.

4.1.3 Blade Tension

Meat saws are generally equipped with a linear tensioning mechanism which exerts force against the upper saw wheel in order to maintain blade tension. By measuring the force exerted by this tensioning mechanism, we can monitor sudden changes in tension which can in turn reveal blade breakage (sudden decrease in tension) or forced deflection (sudden increase in tension). We measure this force using an IP66 rated load cell (strain gauge) installed in-line with the tensioning mechanism. [4] (Fig. 5)

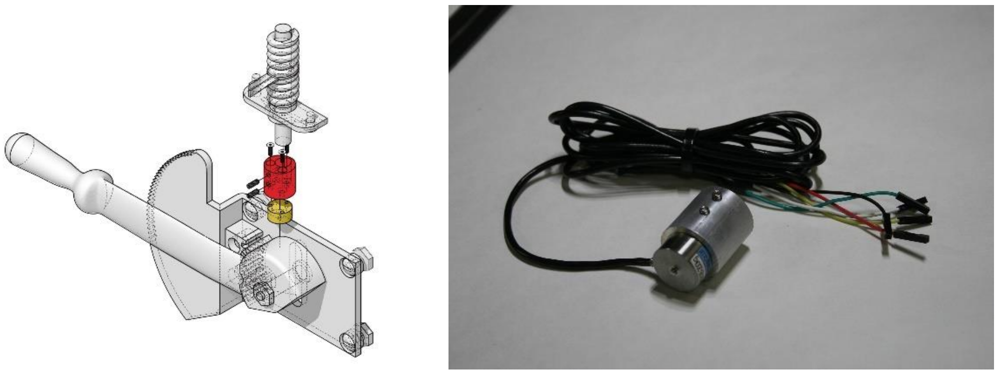


Fig. 5 Load Cell assembly 3D model (left) and fabricated part (right)

While considered to be an effective tool for measuring the blade tension, and sudden decreases in blade tension are indicated by a rapid falloff of values, this sensor was not used extensively throughout the project due to inconsistencies in measured blade tension. This is most likely due to the nonstandard configuration of the cam-based tensioning mechanism on the meat saw used in this trial. Because the cam presses directly onto the tip of the load cell in this application (and the two surfaces are not always parallel), this introduces lateral strain on the load cell which causes inconsistent data. Further work would be necessary to optimize this sensor, but it shows promise as a tool for measuring blade completion, forced deflection, and correct blade tension (which can decrease blade vibration if appropriately tight, and decrease the likelihood of failure if appropriately loose).

4.2 Cloud Based Asset Management

In order to better utilize the data mined by the sensors and to apply it to a preventative maintenance and repair routine, GREYSHED combined existing asset management strategies with the capabilities of the custom sensors fitted to the "smart saw."

Several AMPC research projects have discussed the potential utility of QR (quick-response) code tagging of beef products in the red meat industry (SAGE, 2016), or have used them to store and retrieve information with vision systems for automated beef packaging [5]. In this research, we leverage such technology towards the equipment within the processing plant instead. Plants with any combination of automated or manual beef processing equipment have a wide range of machines which must be regularly inspected, serviced, and repaired, and each machine might have its own maintenance schedule, service manual and replacement parts. As automation equipment becomes more complex, traditional pen-and-paper maintenance logging and scheduling methods become increasingly impractical. QR codes can solve such problems by providing the ability to link these physical assets with digital information, which can be centrally stored and analyzed on the scale of an entire plant, or scanned by a serviceperson at the machine to retrieve detailed, machine-specific information.

4.2.1 Slate Pages

GREYSHED built the prototypical data logging method on the backbone of the existing infrastructure setup by Slate Pages, one of several companies which provide QR-code based asset management services. [6] Slate Pages has the advantage of a tested app and web portal, and no continued cost for data services or management (it charges a small one-time fee for the purchase of the anodized aluminum tag).

Fig 6 More than the traditional nameplate (above), the slate (below) offers a comparatively infinite array of information accessible through the cloud

Manual Field Editing

In the simplest sense, the Slate Pages app can be understood as digital logbook, capable of storing a wide range of data, such as repair dates, installation notes, links to product manuals, part photos, etc.

These fields are stored on the cloud, and can be recalled instantly by scanning the tag with a mobile device, or logging into the web portal on a PC. A serviceperson, can, for example, enter the date of last service, take photos of what changes were made, and make a note of which parts were replaced. This information can then be retrieved at any point by any other personnel with a mobile device. (Fig. 6 & 7)

Automated Field Editing

Our addition to the more conventional and manually-updated QR-system is the creation of a hybrid logging system, which allows for both manually input data, and automatically updated sensor data. By accessing the Slate Pages API, our internet-connected “Smart Saw” can automatically post and retrieve updates to the app. The saw software updates the information on the app (specific to its own tag) at regular intervals (<1 min) with information parsed from the saw sensors, such as cumulative daily/weekly power consumption or motor revolutions. These numbers can be observed across an entire plant in order to determine which machines are running less efficiently and might be in need of service. Additionally, these numbers can be compared with manually input fields to set up automatic triggers: for example, one might have a requirement for blade replacement after a certain number of revolutions. Whenever a serviceperson resets the blade-replacement field, the sensing software automatically resets the counter.

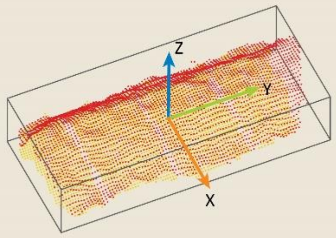
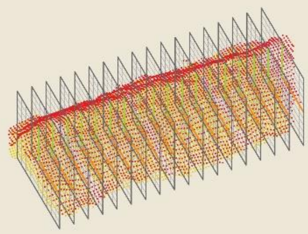
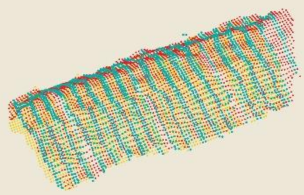
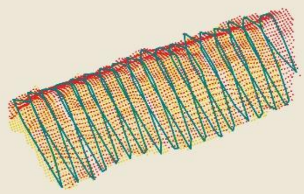
Fig 7 Instantaneous retrieval of manual and automatically generated saw statistics

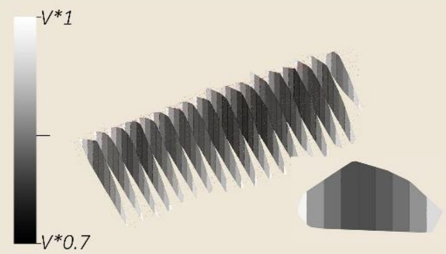
4.3 Scanning and Processing Routine

In order to test the efficacy of the sensing, recording and visualization methods developed in this research project, GREYSHED developed a simple routine for measuring and processing cuts in a scanned part, that can be used for both robotic and manual red meat processing. As such sensor-based automated-meat-cutting setups have much precedence in both machine development and computer vision (LEAP; MAR, 2011; Strategic Engineering Pty. Ltd., 2011; etc.), this is not the primary focus of the research, and is instead a simple, streamlined system which can effectively simulate a variety of automated environments and serve as the test bed for analyzing the methods of the project.

4.3.1 Setup and Algorithm

The scanning and path planning software was development in Processing, a java based programming environment. [7] The software takes measurements from a structured light scanner (Kinect V2) and communicates through the serial port with the saw sensors, and industrial robot. The software has few dependencies, and operates using the following algorithm for cut placement and speed regulation:

	ALGORITHM	MODEL VIEW
1.1	Orient the points from the local coordinate system of the structured-light-scanner into the coordinate system of the robot, and reduce the scanned points to those within the domain of our loading surface (table/conveyor).	
1.2	Iterate through the refined pointcloud to find maximum and minimum X,Y,Z coordinates. These values determine our axis-aligned bounding box (AABB), and the center of our workobject. The height is used to set the automated blade guard in manual applications.	
1.3	Determine cut planes by dividing the bounding box length by the desired cut thickness range, selecting the thickness value that provides the smallest remainder. Cut planes are aligned with the XZ plane of the bounding box, and centered about its origin. This thickness is used to set the automated gauge plate in manual applications.	
1.4	As the (3D) scanned points will never be perfectly aligned with our (planar) cut planes, we can determine the cross-section of the cut by first reducing the 3D data to include only points which lie within a given distance from the cut plane (~5mm).	
1.5	These points are then projected onto their respective cut planes, to produce a two-dimensional point cloud representing the cross-section of the loin at that cut location. Finding the planar convex hull of these points yields a closed polygonal section-cut.[8]	

1.6	For each section to be cut, determine the height of the outline at fixed intervals (~10 steps) to determine cut thickness. These thicknesses can be used to optimize cutting speed. The image on the right indicates projected speeds as a gradient between black (70% speed) and white (full speed)	

4.4 Assistive Technologies for Manual Processing

Building upon the saw sensors and cut-planning algorithm, GREYSHED developed a number of strategies for using digital technologies to augment the manual processing of red meat components. These strategies include the installation of an onboard computer for storing and displaying sensor information, automated blade guards and gauge plates for hands-free adjustment, projective overlays, and methods for measuring and evaluating individual employee performance.

4.4.1 Onboard Computer and GUI

In order to facilitate centralized, device-specific monitoring, and the presenting and posting of sensor data, we installed a computer and touchscreen onto the meat saw. For this prototypical setup, we used a Raspberry Pi Model 3 (Pi) [9] with a device-specific touchscreen display [10]. The Pi is an inexpensive (~45 AUD) single-board computer, equipped with a standard HDMI port for video signal, USB ports, 1GB RAM, and Bluetooth, Ethernet and Wi-Fi capabilities. (Fig. 8) The computer and screen are mounted together as one unit to the face of the saw using a custom fabricated mount which encases all necessary cabling. (Fig. 9) While effective for a prototypical onboard display, this setup would need to be rigorously redesigned and tested to meet the wash-down requirements of a meat processing facility (or installed separately from the saw).

Fig 8 Raspbery Pi Model 3

In this setup, the Pi receives sensor readings via USB serial messages, and is running a custom GUI software written by GREYSHED which consolidates the sensor information and displays it as easily understood graphs and gauges. An intuitive interface allows the user to swipe between various sub-screens which convey relevant groupings of gauges, graphs, statistics, and error messages. The interface provides an environment for quickly monitoring sensor data and assessing saw efficiency and cut parameters. It can also be used to manually adjust the electronically controlled blade guard and gauge plate.

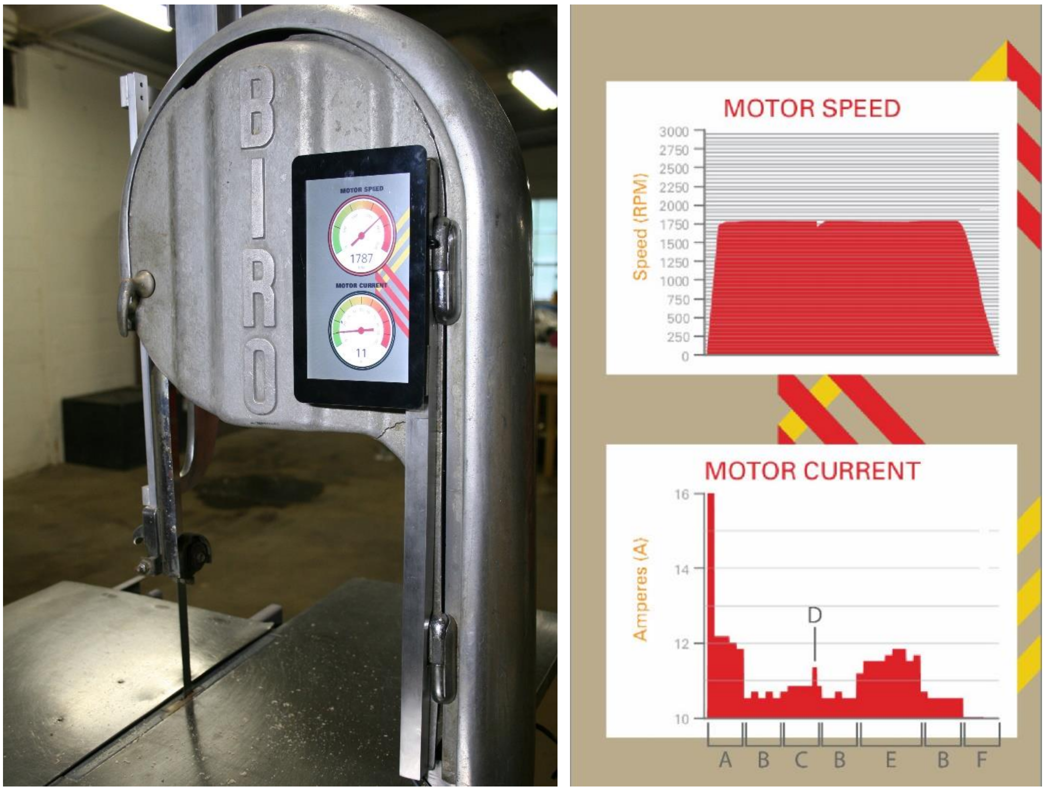


Fig 9 Left) Smart Saw LCD touchscreen displaying motor speed and current gauges *Right)* Capture of real-time motor speed and motor current graph from GUI, demonstrating: A) Saw Startup B) Saw Idling C) Cutting 40 mm material D) Momentary motor stall from aggressive cutting E) Cutting 90 mm material F) Saw Powering Down

4.4.2 Smart Guard

GREYSHED has observed that many meatsaw operators habitually leave the guide/guard bar in the fully-raised state while cutting. This is certainly due to the fast pace of the work environment, and the time saved by not adjusting the guard between each cut. This practice increases kerf waste caused by excessive blade vibration (Kirbach and Bonac, 1977; Lengoc, 1993), and increases the likelihood of major accidents caused by such a large area of exposed blade (many saw manufacturers suggest keeping the guard within 15 mm of the workobject at all times). As a strategy for combatting this problem, GREYSHED developed an automated blade guard which uses a screw-driven linear actuator to drive the saw-guide-assembly. The guard can be positioned using serial messages indicating the desired guide-height. These height values are sent from the control software discussed in section 4.3.1, which determines the height of the primal component and sets the appropriate height of the guard accordingly. (Fig. 10) [42]

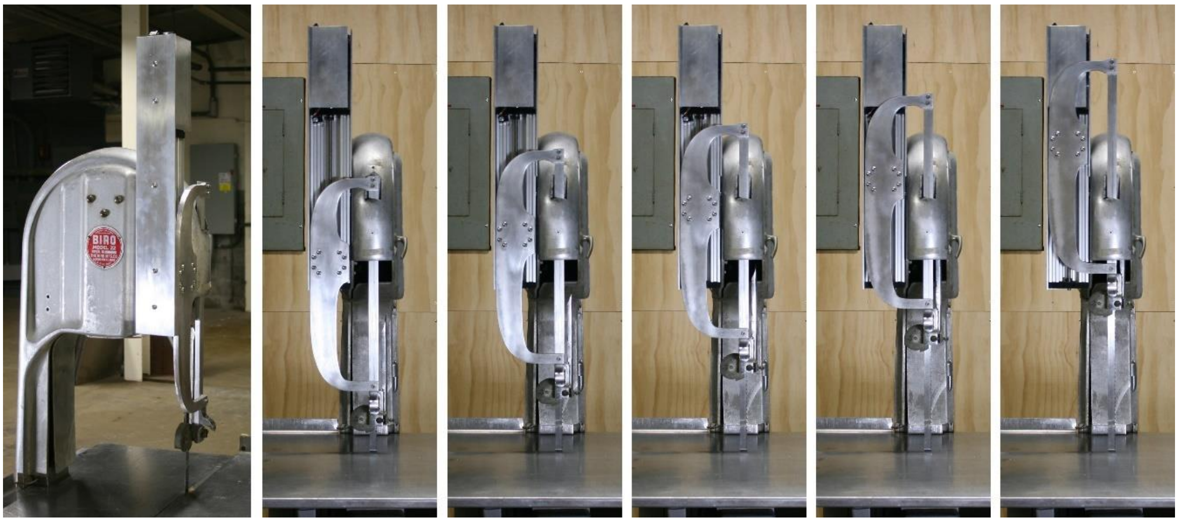


Figure 10 “SmartGuard” installation and stepper-motor-driven movement

4.4.3 Actuated Gauge Plate

Typically, in manual meat sawing, the gauge is set to a fixed size, which often results in a smaller “remainder” cut due to the irregular starting length of the primal, which is not exactly divisible by this fixed dimension. The algorithm discussed in section 4.3.1, instead, finds a thickness which is as close as possible to the desired thickness, but is evenly divisible into the 3D scanned length. While such scanning and cut planning methods are typically used in fully automated systems, we can also use them to make manual processing more efficient. By developing an electronically controlled, actuated gauge plate for the meat saw, this found thickness can be automatically set during manual processing. Modulating the thickness one or two millimeters per cut can mean no uneven, lower value “remainder” at the end of the part. The initial cost of a scanner and motorized gauge plate is significantly less than the cost of a fully operational robotic system, but leverages some of the same computational power and precision. It would be unreasonable for a worker in a fast-paced processing center to manually measure each primal and precisely adjust the blade guard and gauge plate, but a minimal application of the right software and hardware can accomplish this task in a fraction of the time: increasing the safety and efficiency of manual processing with minimal additional investment. The actuated gauge plate uses a similar mechanism as the “smart guard,” and is set automatically via serial messages from the control software that indicate the desired gauge (in mm). (Fig. 11)

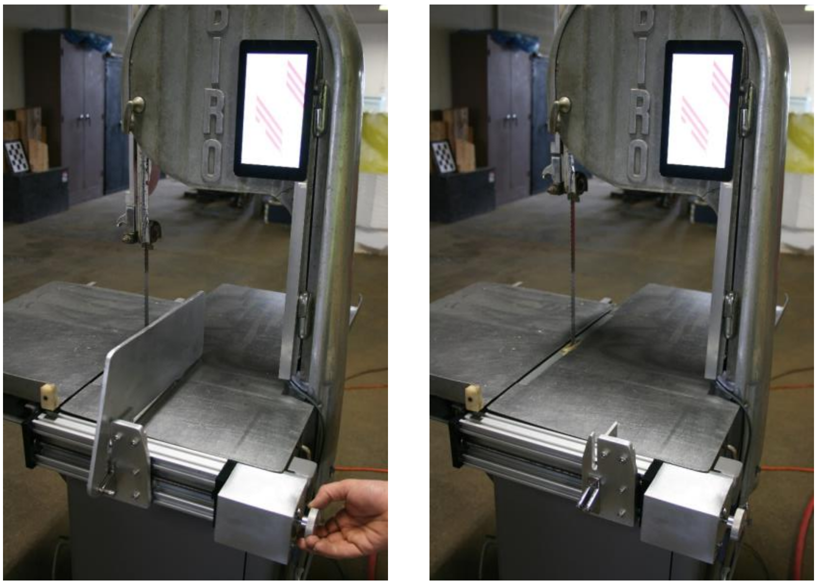


Fig 11 Automated gauge plate with manual fine-adjustment knob and gauge-plate quick-release.

4.4.4 Projective Augmented Meatsawing

This project documents a strategy for projecting relevant information directly onto the meat processing work area in both manual and robotic applications. Sensor information, cut metrics and saw data are projected onto the saw, walls, table surfaces and onto the meat itself. Such projective augmented reality techniques—which map digital data directly onto physical surfaces—have the benefit of requiring no extra peripherals or user expertise: they can provide clear graphics that require minimal reading of text.

The coordinate system of the projector, 3D scanner, table, and meat saw are calibrated with one another using the method described in section 4.3.1 of the third milestone report. In this way, any three-dimensional data (points, lines, etc.) scanned by the Kinect or drawn by the software can be mapped from its location in the base 3D coordinate system to the correct pixel in the 2D projector image plane, such that that pixel creates a ray of light which intersects with the physical object at the desired location. This calibration allows for projected images to be correctly aligned with non-moving objects and objects that are in view of the 3D scanner. (Fig. 12)

To maintain the projected image on objects which are freely moved by hand (i.e. to project cut paths onto the handheld primal), it is necessary to have a supplemental tracking system to detect motion outside the range of the scanner used for part measurements. GREYSHED prototyped a custom meat carrier tray equipped with a Vive controller, tracked by the Lighthouse tracking system, which provides a fast and reasonably accurate method of 6 DoF motion capture. [11] [12] The calibration protocol for coordinating the local coordinate system of the Lighthouse units with the base, meat, and projector coordinate systems is discussed in section 4.2.3 of the fourth milestone report. The results of this preliminary combination of cut planning, projection mapping, and real-time tracking are pictured in Figure 13.

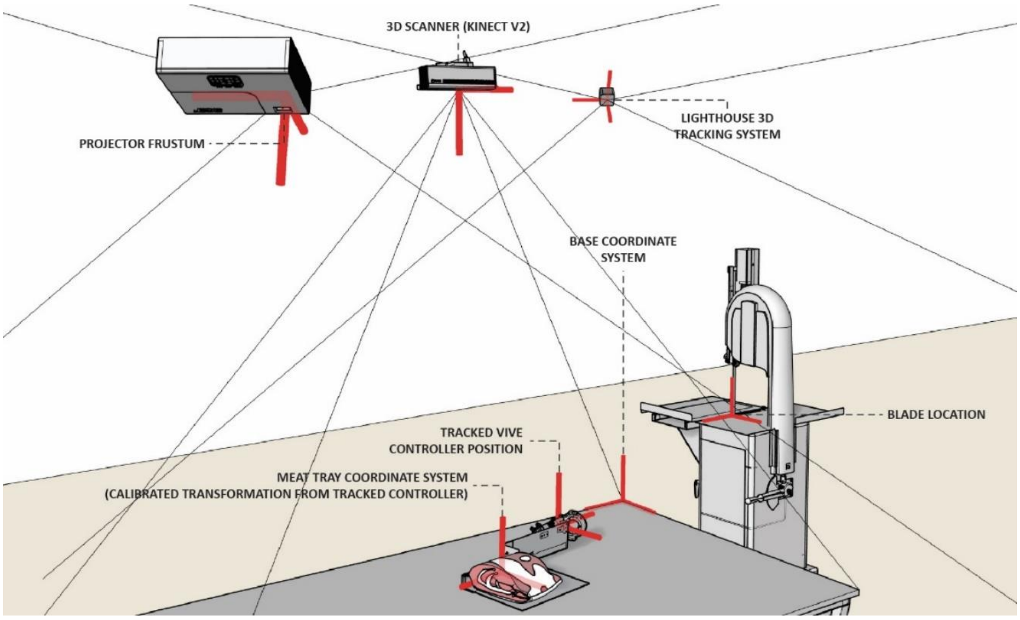


Fig 12 Projection mapping system diagram indicating the synchronized coordinate system between a variety of sensors, equipment and projector.

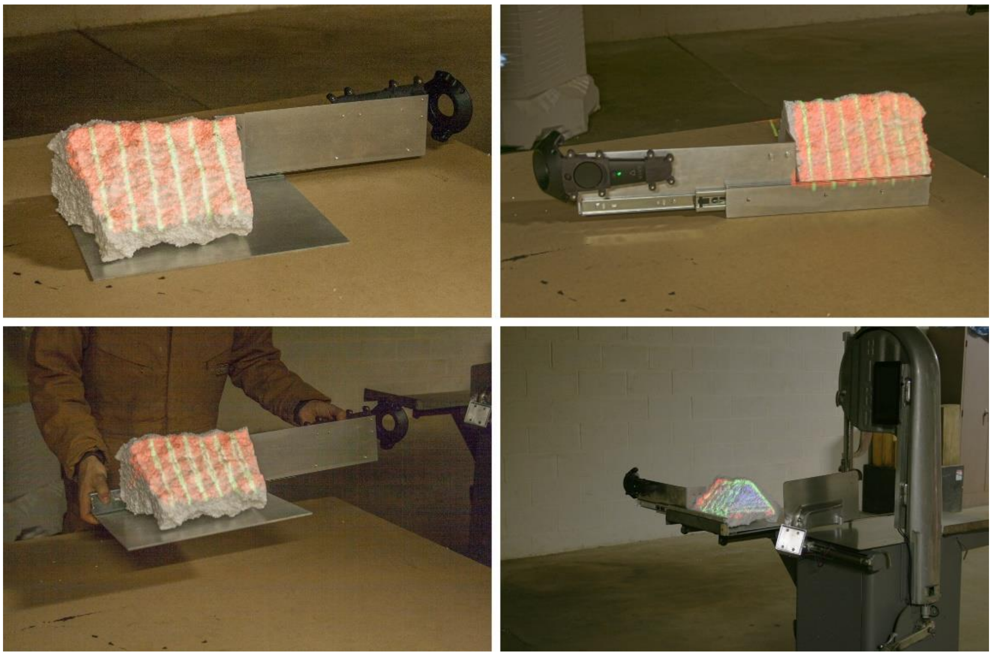


Fig 13 Cut lines are automatically determined from the 3D scan, and are projected onto the workpiece. Tracking the position of the moving tray allows for the projected image to remain fixed on the object.

GREYSHED combined the saw sensors, cut planning, automatic blade guard and gauge plate setting, and projection mapping into one sample workflow. This workflow was documented as a representative model of the range of technologies which might be integrated into manual meat processing. The results of this integrated workflow were documented in an available video [13], and are also depicted below (Fig. 14).

In this process, the operator places the primal component onto the worksurface, where its geometry is captured by the structured light scanner mounted overhead. This data is fed into the software, which determines the correct number of cuts, their height, and maximum thickness. The cut lines are projected onto the scanned part, and the relevant information about the part (length, gauge, count, thickness) is projected as text onto the table surface. Once approved by the operator (with a button press), the height and gauge data are sent to the saw, which sets the gauge plate and blade guard to the correct levels. The saw is projected with indicative colors and icons, which show that it is on, that the blade is spinning, and the motor load. The load of the motor is mapped to the color of the saw, such that it is blue when off, and a hue between green (idling) and red (peak load) based on the current draw. Appropriate cuts are in the green-yellow range, while excessive feedrates and initial startup causes the motor to become red in color. This provides instant feedback for correcting excessive or insufficient feedrates, and clearly indicates a stalled blade to both the operator and anyone nearby. The surrounding walls of the work area also contain projected gauges and charts which indicate the current motor speed and load, and chart this data over time. Total power use and saw “mileage” are also projected onto the wall, which can be used to encourage maintenance or reduce power consumption when possible. For this documentation, the tracked meat carrier tray was not utilized for projection mapping onto the moving primal, as the gauge plate occluded the projector, and the cut thickness was set by the gauge plate in any case. It would be necessary to mount a second projector on or near the saw to prevent any potential shadow areas for future implementations.

Fig 14 Unedited video-still of manual bandsawing station with real-time projection mapping.

4.4.5 Productivity Tracking

As discussed in the AMPC report on wearable technologies, "technology that records the body pose of the wearer…provides opportunities to evaluate performance of specific tasks" and can "be presented to the employee" to motivate improvement and produce "a real-time feedback loop of progress and capability development" (Cox, 2016). Just as the information provided by a pedometer or fitness tracker encourages people to walk or exercise more frequently, so can similar metrics be used to encourage good habits while discouraging unsafe practices. To these ends, we record the positional tracking information provided by the meat carrier tray (section 4.4.4), and can analyze this data to quantify and promote employee efficiency. The laser tracking system provides the ability to record the speed, angle, and position of the meat carrier tray at all times. This information can be replayed or documented to highlight problematic, unsafe, or inefficient movements. (Fig 15)

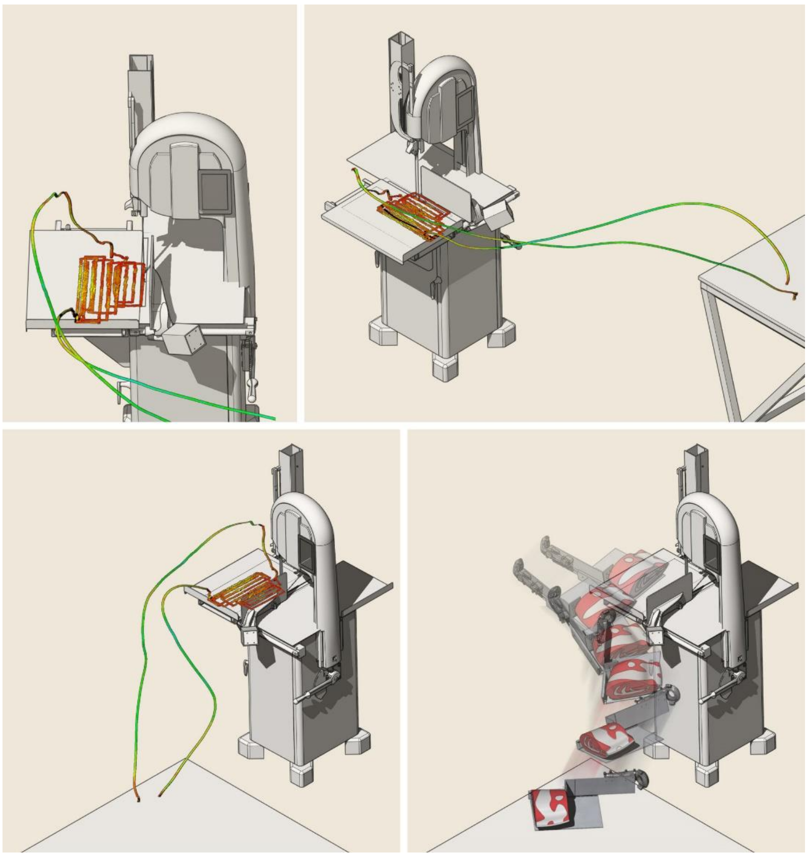


Figure 15 Visualization of recorded movements from a typical cutting routine. The color of the path curve indicates speed (transfer motion is faster than cutting motion). As the recorded data contains both position and orientation, it is possible to easily reconstruct the complete movement for visualizations (Bottom Right).

In addition to the use of the installed laser tracking system, GREYSHED installed a secondary sensor directly onto the meat carriage assembly of the bandsaw for recording and analyzing cut speed and quantity. As the sliding carriage assembly of a typical bandsaw is always moving with the parts which are being cut, it can provide an analog for the number of cuts made, and the speed and frequency of those cuts. To record the position of the carriage, we developed an inexpensive and easily implemented method which relies on hall effect sensors and neodymium magnets. Hall sensors react to magnetic fields, and as such are ideal in harsh conditions—unlike optical sensors or mechanical sensors, they cannot become blocked or jammed with waste matter from the saw. By placing an array of alternating polarity magnets onto the underside of the saw carriage, and placing two fixed hall effect sensors (SS495B)[14] below those magnets, it is possible to detect both the speed and position of the saw (Fig. 16 & Fig. 17). This sensor data is processed by a microcontroller, which sends position and timestamp values to the onboard computer on the saw, which displays this information and records it for later processing. (Fig. 18)

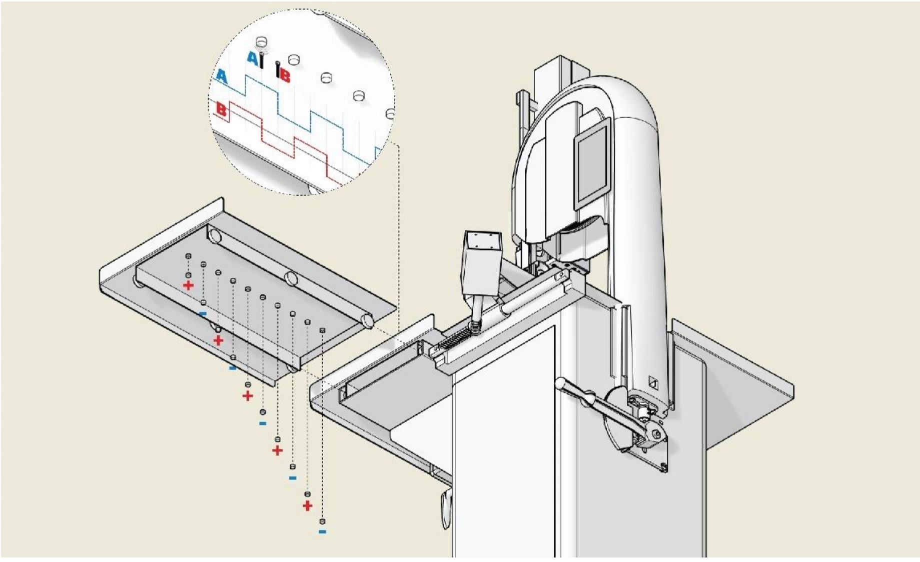


Fig 16 Diagram of quadrature encoder setup for tracking meat carriage assembly using two SS495B hall sensors and neodymium magnets of alternating polarity.

Fig 17 Neodymium magnets mounted at even intervals to the underside of meat carriage assembly.

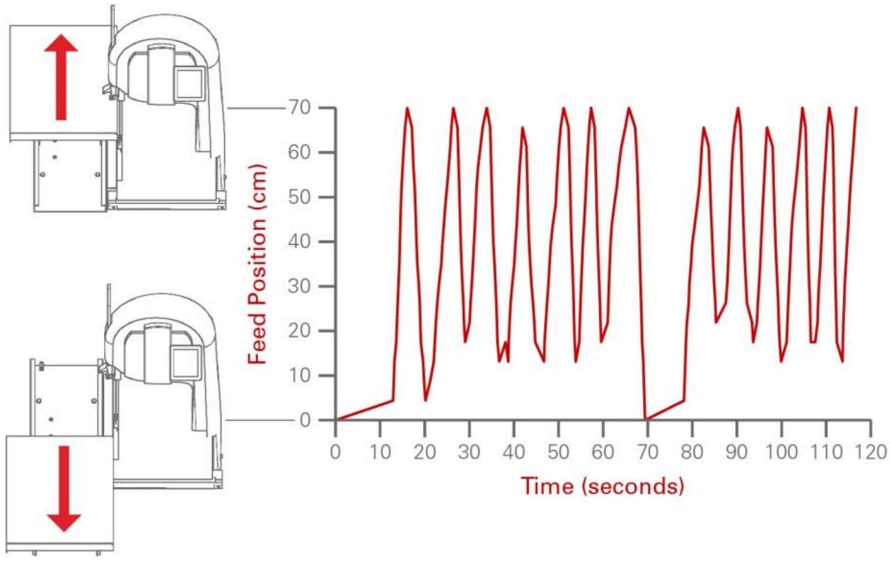


Fig 18 Graph of two minutes of meat sawing, as measured by hall sensors and magnets mounted under the meat carriage assembly. The thirteen cuts are easily distinguished, and stroke length and cut speed can be determined by the length and slope of each peak.

4.5 Robotic Workcell Integration

As part of this research project, GREYSHED developed an integrated sample of a robotic workcell which combines saw-based sensors, a simplified cut planning algorithm, and augmented projected overlays. While the specific bandsawing routine serves as a stand-in for any variety of robotic automation tasks in red meat processing, it clearly conveys the potential of a more accessible future form of automation in which human operators or managers can intuitively understand its complexities.

4.5.1 Pneumatic Gripper Design

In order to facilitate an integrated vision of a robotic bandsaw cutting system which integrates sensor monitoring and projective visualizations, it was necessary to develop a gripping end-effector with minimal complexity for the picking and cutting primal components in our tests. GREYSHED designed a simple pneumatic gripper capable of picking irregularly shaped objects which can also adapt to variations in cut thickness. The gripper was designed to accommodate both rigid and conforming claws to deal with variable material properties and applications. The gripper consists of four independently actuated claws, which are operated by cylindrical stainless-steel pneumatic linear actuators. These cylinders are each controlled by a 5-port, 3 way solenoid valve, which is controlled in-turn by the I/O signals of the industrial robot. The use of a dedicated cylinder and valve for each pair of claws allows for cut components to be released independently, and for the gripper to adapt to variations in material thickness. A fifth pneumatic cylinder is used to adjust the spacing between each of the claws (to adapt to variations in cut thickness). (Fig. 19)

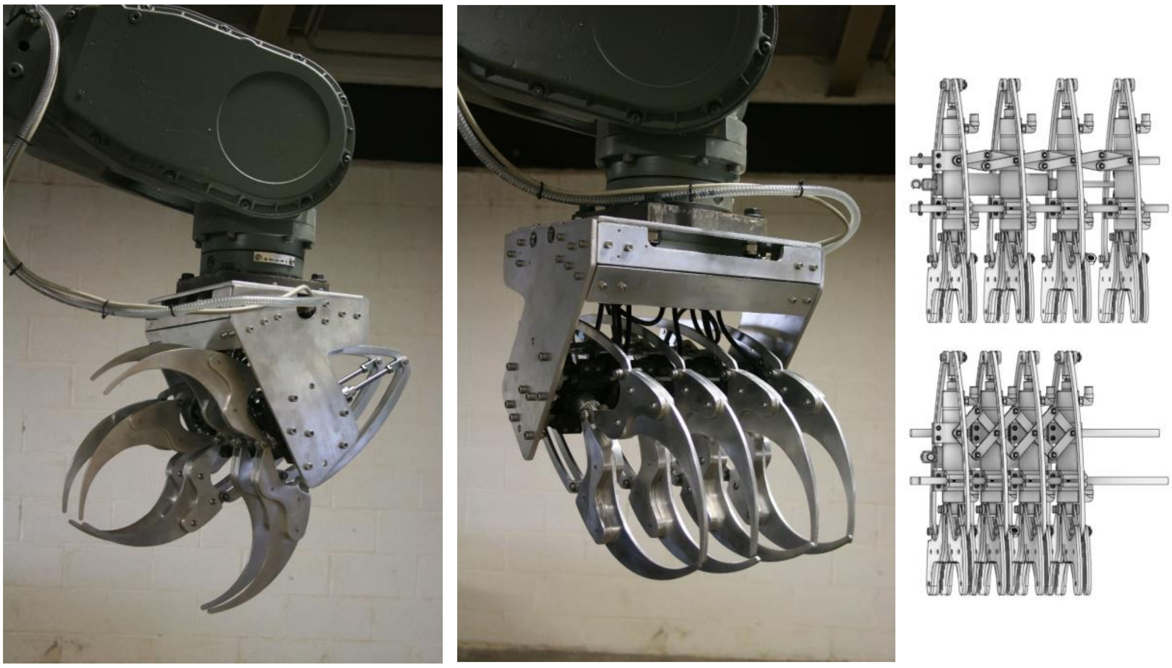


Fig 19 Pneumatic Gripper for Process Testing

In addition to the rigid claws, GREYSHED also developed an alternative gripping finger based on the Fin Ray® Effect.[1] The design uses 3D-printed hinge linkages connected in a triangular configuration to fatigue-resistant, 301-stainless-steel sidewalls. The strips curve to conform to irregular geometries, and proved effective for grasping components during the testing of the visualization system.

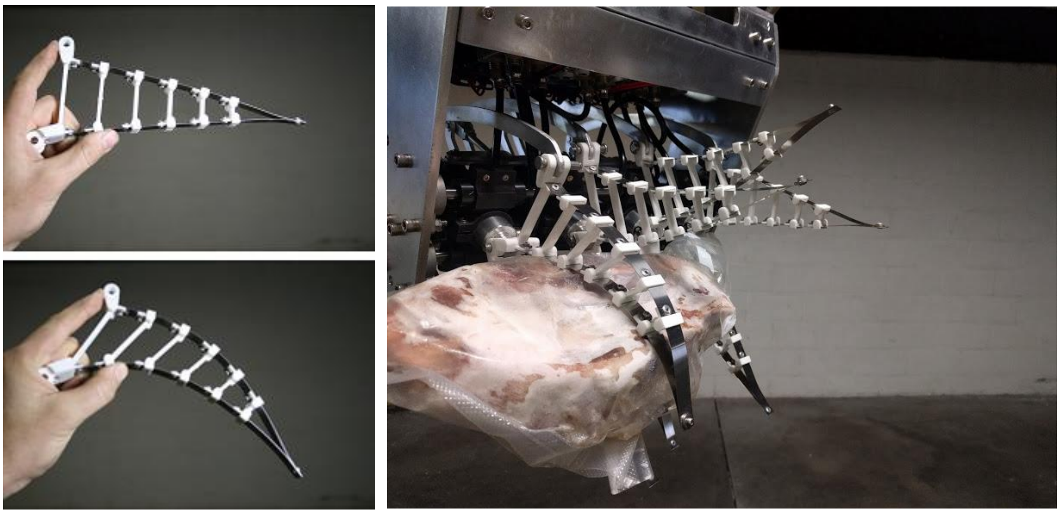


Fig 20 Left) Flexible Fin Ray® Effect inspired gripper finger Right) Independent actuation of a single conforming claw

[1] Fin Ray Effect® is a trademark of EvoLogics GmbH

4.5.2 Environment Mapping and Integration

Thermal Mapping

In an effort to convey the wider range of possibilities for industry-applied projection mapping, GREYSHED developed a projective system which conveys thermal information directly onto objects in a factory setting. Considering the strict temperature requirements in meat processing facilities, and the propensity of malfunctioning machines to produce excessive heat, there are obvious advantages to making temperature information plainly available to processing personnel. To achieve this temperature mapping, a thermal camera (Flir Lepton Module) is calibrated with an RGB-D scanner (Microsoft Kinect V2) and a short-throw DLP projector. Each 2D temperature pixel of the thermal camera can be correlated with a 3D point in the coordinate space of the Kinect. This provides a 3D point cloud where the temperature of each point is known. These points can then be correlated to the projector pixel which will strike that point in the physical world, and thus the scene can be colored based on the temperature of the objects in it. More information on the specific hardware and calibration routine can be found in the fifth milestone report for this project.

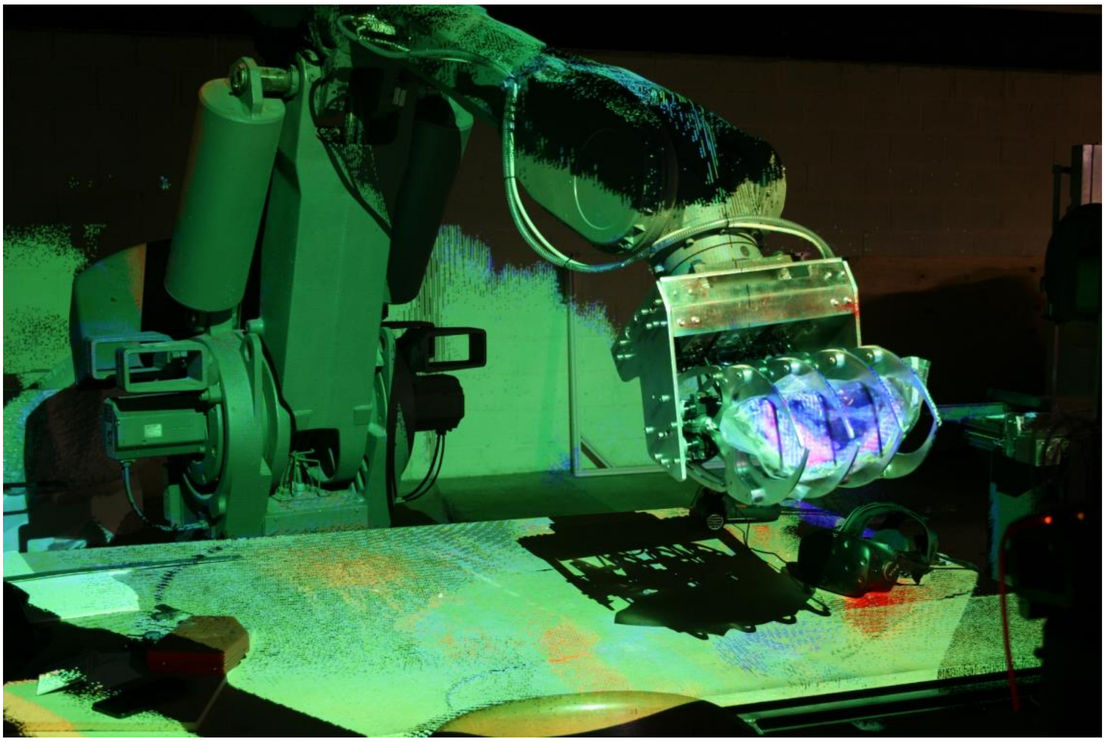


Fig 21 Unedited photograph of thermal projection mapping. Frozen beef is rendered in the blue/purple range while the warmer ambient air and equipment is green. The swath of red on the table indicates the heat emanating from the electronics.

Laser Projection Mapping

Most the projection-mapped visualizations developed during this research project use a relatively standard, short-throw DLP projector (HT1085st) which depicts pixel-based content. While the DLP projection mapping is successful in its ability to convey a great deal of information intuitively, it has the downside of appearing washed out with significant competing ambient light. This is not an issue for fully automated workcells with human observers, but is less practical for hybrid systems where humans are working alongside machines, and need bright lighting for safety purposes. As an attempt to find a projection solution that conveyed data more clearly in a bright room, GREYSHED installed and calibrated an RGB laser projector, which can provide perfect clarity with the lights on. The laser projector uses three individual laser beams (Red, Green, Blue), which are oriented towards very fast moving mirrors (galvanometers), which precisely redirect the light beam tens of thousands of times per second. While this method proved effective in displaying clear images in a bright room, there are a number of limitations which make it impractical for many applications:

- // As the laser draws vector-based geometry (rather than with a fixed number of pixels) and relies on the persistence of vision, there is a limitation on the amount of data that can be drawn per frame. Figure 22 represents a sample image at the upper end of the allowable point-count and complexity afforded by this projector. While the image is very legible, there is a significant reduction in the allowable complexity of the represented image when compared to a traditional projector.
- // Unlike pixel-based projectors, laser projectors rely largely on the development of custom software for managing the drawn image, optimizing the number of points in any given line, and managing the communication with the projector.
- // While they allow for a bright, legible image, lasers also raise concerns for eye safety, and must be mounted in such a configuration that prevents direct gaze into the beam. Given the high quantity of reflective surfaces in meat processing plants, additional efforts would need to be taken to prevent the laser from scattering reflected beams towards workers.

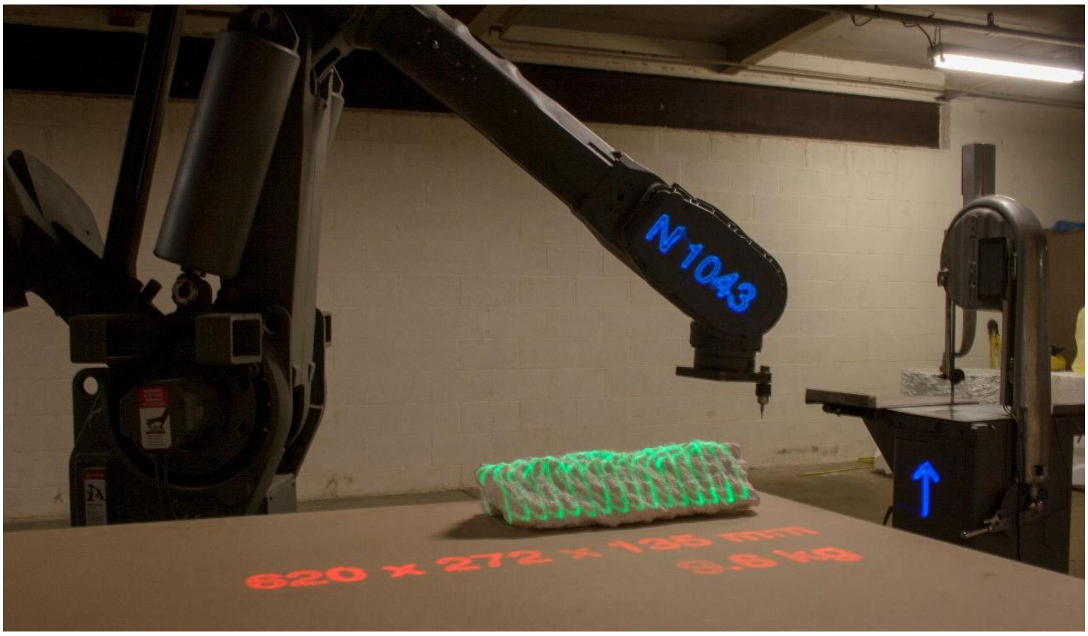


Figure 22 Unedited photograph of RGB laser projection-mapped robotic workcell.

Integrated DLP Projection Mapping

As a primary component of this research project, GREYSEHD developed and documented an integrated vision of a robotic workcell which combines saw sensors, algorithmic cut planning, and projective augmented visualizations into an automated process for red meat bandsawing. This workflow relies on a number of calibrated components which communicate with a centralized control software. These components include a DLP Projector (BenQ HT1085ST), RGB-D scanner (Kinect V2), Lighhouse tracking system, sensor-equipped smart saw, and an industrial robot (ABB IRB 6400) equipped with a pneumatic gripper. (Fig. 23) The results of this integrated robotic workcell were documented in an available video [15], and are also depicted below (Fig. 24).

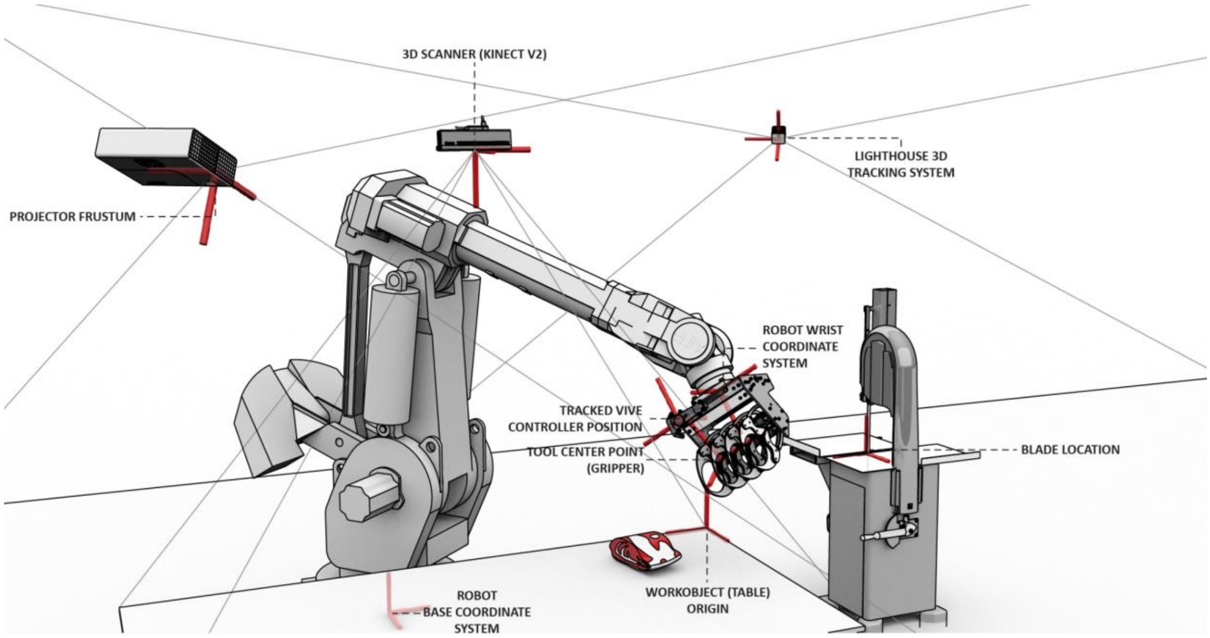


Fig 23 Projection mapping system diagram indicating the synchronized coordinate system between a variety of sensors, equipment and projector.

As with the augmented manual bandsawing, this process involves the use of a structured light scanner to evaluate the geometry of a primal component placed in front of the robot. The central software uses this geometry data to determine the correct number of cuts, the cut thickness, and the correct location and orientation from which the robot should pick up the part. The planned cut information and measurement data are projected onto the meat and surrounding loading station such that an outside observer can quickly recognize any incongruities in the cutting routine, the number of parts processed that day, or any other relevant metric. The picking-position and cut data are streamed to the robot controller, which manages the picking up of the part, and the processing of the cuts.

During the loading, picking, transferring and cutting sequence, the robot sends status reports back to the central software, which are used to trigger updates to the projected image. By tracking the position of the robot[2] at all times, it is possible to project the status of each robot movement directly onto the body of the robot: for example, when picking up a part, the robot arm is clearly labelled with the text "loading part…", and while cutting, it is labelled with the progress made for that specific primal (i.e. "Cut 2 of 14"). This information makes the robotic process accessible to any observer, and provides a clear breakdown of robotic tasks that can be used during troubleshooting should any problems arise.

[2] A detailed description of this calibration routine can be found in the fifth milestone report.

As with the setup for projection-mapped manual production, the saw in this workcell is mapped with icons and colors which clearly indicate whether it is on or off, and how much load the motor is under at any given time. This approach can also be used to indicate any specific failure states, such as a broken blade or belt. The surrounding walls also contain projection-mapped images for sensor data and can be modified to illustrate any other information deemed valuable.

Fig 24 Unedited video-still of robotic bandsawing station with real-time projection mapping.

5.0 PROJECT OUTCOMES

This project has researched, designed, and prototyped a wide range of possible improvements to both robotic and manual operation of bandsaws for red meat processing. For both processes, we have illustrated the potential utility and application of saw-embedded sensors and web-connected logging devices to make repairs and preventative maintenance more intuitive. By measuring the electrical consumption, motor load, and motor/blade revolutions, it becomes possible to more accurately predict failure states, and to prevent them before they cause unnecessary downtime.

For manual processing, the research has demonstrated strategies for increasing safety, accuracy and throughput by automatically setting both the gauge plate and blade guard based on the scanned dimensions of each part. GREYSHED also documented strategies for logging worker movements using inexpensive laser tracking systems and linear encoders mounted to the meat carrier tray, pusher plate or carriage assembly. This data can be used to measure the number of parts processed, to reward processing goals, and to preemptively recognize and correct unsafe or inefficient habits. Augmented overlays are presented as a strategy for making the complex components of manual processing more accessible.

For automated processing, we have demonstrated possibilities of using sensor feedback and 3D scanning to optimize feed rates, and for projective augmented reality techniques and online sensor monitoring to allow for fast error detection and correction by human operators.

6.0 DISCUSSION

The intention of project 2016.1043 was to make a number of suggested improvements to robotic and manual meat sawing practices in order to promote more efficient processing and to increase the potential of hybrid systems. One common theme in all aspects of the research is the necessity to find an appropriate balance between full automation and manual labor. While automation is generally the goal of industrial research across all industries, there is a long road ahead before it is possible to operate a completely failure- and maintenance- free, fully-automated meat processing facility. It is essential to plan for intermediate stages, and to utilize human labor for what it is best at: cognitive and physical adaptability. By creating bridge applications which apply computational speed and mechanical precision to manual processes, and which use human intelligence to correct for errors in automated systems, we can smooth the transition towards automation and maintain the best aspects of the current workforce.

This research was largely focused on robotic bandsawing in name; in practice, however, many of the concepts developed in this project could be applied to equipment and routines in most aspects of red meat processing. The bandsaw served as a good testing case for this research, and GREYSHED developed a simple gripper and processing algorithm for cut planning in order to test the broader concepts of sensor feedback, saw-based actuators, and augmented interfaces. The specific application of cutting parallel, evenly portioned cuts might be better achieved in practice with a purpose-built device such as the Marelec Portio 3. [16] However, cut planning was not a primary objective in this research, and our methods can be applied to much more complicated processing routines (i.e. those which require x-ray analysis, non-linear cut paths, etc).

7.0 CONCLUSIONS/RECOMMENDATIONS

This project presents several experimentally-successful prototypes for integrating sensing, scanning and visualization techniques into automated meat-sawing systems. While more work would be necessary to make these methods robust enough to be fully operational in the setting of a processing plant, these examples demonstrate the potential of combining human-interface-design strategies and centralized, continuous sensor monitoring with both robotic and manual bandsawing systems. As the industry moves towards increasing automation and process complexity, it is necessary to consider such strategies that bridge technological gaps with hybrid, human-assisted devices, and to continue to recognize the specialized roles of human operators even in “fully automated” systems.

Several aspects of this research are relatively straightforward in their implementation, and can be integrated into a factory setting with little expense. For example, tagging equipment with QR-based maintenance-logs provides an easier method for managing the wide range of assets found in a typical red meat processing facility. Storing and creating automatic triggers for maintenance data increases the likelihood that device-specific errors are corrected before they become larger problems or safety concerns. These initial measures can later be expanded, after further improvements and testing, with sensor data, intelligent actuators, and better interfaces for detecting and correcting problems.

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