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Faculty of Engineering and Surveying

The Integration of Sensory Control for Sugar Cane Harvesters

A Dissertation submitted by

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BEng (Hons)

For the award of

Doctor of Philosophy

2003

Abstract

The research concerns the design and implementation of mechatronic systems to assist in the operation and control of a sugar cane harvester. Two functions were chosen for attention, the primary separation system, and the ‘topper’ that discards the leafy crown. Although these operations are given low priority by the operator of the harvester, their optimisation is of particular significance to the industry.

Optimum separation requires a fine balance between discarding ‘trash’ that would contaminate the quality of the cane billets and losing good sugar-bearing material through over cleaning. Poor control of the topper can create extra load for the separation system and cause it to operate at a low efficiency with high loss. Alternatively it can cause a length of sugar-bearing cane stalk to be lost before it even enters the harvester system at all.

A variety of mechatronic techniques were explored, that addressed the problem of providing useful data directly from the harvester functions and the electronic instrumentation to allow the data to be collected in a useful form in real-time. Computer control issues were also investigated, to make best use of the data stream.

Novel acoustic transducers were introduced to the sensory separation system to provide a signal that indicated material striking the fan blades. A rotary transformer was required to allow transmission of the signal, and a signal interface system was implemented to record the returned data. Many real-time time-series analyses were conducted, and from these a suitable algorithm to extract an impact signal was developed. This system was assessed under harvesting conditions with results that confirmed its ability to quantify the amount of cane lost from the harvest.

An investigation was conducted to detect the optimum topping height on a sugar cane stalk. The techniques considered both the internal and external attributes of the stalk, and a method was selected to measure the sugar concentration with a

chemical sensor. An important design parameter was that the sensor must operate on the harvester in real time. The novel refractometer worked well in laboratory conditions, yielding repeatable and accurate results. The field environment complicated the application of this system, however this was partly overcome with introduction of a custom sample-crushing mechanism. This device provided the necessary juice sample from a selection of the topped cane stalks. The complete sampling and measuring mechanism operated well on cane stalks, and returned encouraging results.

Both sets of data returned useful information regarding the operation of the particular harvester operations. The control of either the separation system or the topper requires careful balancing, and novel control techniques that consider the ergonomics for the operator are discussed. These include visual indication devices through to automatic control algorithms.

With the integration of mechatronic techniques into the functioning of the sugar cane harvester, the overall efficiency of many of its functions may be improved, and the operator’s task may be greatly simplified. The ultimate objective is to maximise the yield with an improved level of harvested and separated cane.

Certificate of Dissertation

I certify that the ideas, experimental work, results, analysis and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged.

I also certify that the work is original and has not been previously submitted for any other award.

______________________________________ ______________

Signature of Candidate – Stuart G. McCarthy Date

Endorsement

______________________________________ ______________

Signature of Supervisor – Professor John Billingsley Date

Acknowledgments

The work described in this dissertation was conducted at the Faculty of Engineering and Surveying, University of Southern Queensland between February 1999 and November 2002.

It is with much gratitude I acknowledge the Sugar Research and Development Corporation for sponsoring this project during the course of the studies, and also the National Centre for Engineering in Agriculture for the financial assistance it has provided.

The contributions and assistance of the following people are also gratefully acknowledged:

Professor John Billingsley for his direction, enthusiasm and support that kept things fun and interesting over the course of the project, and of course the opportunity to ride an elephant. Thank you for the opportunity to study under you, JB!

Dr Harry Harris for his efforts to secure the project sponsorship, and his experience and support, especially with the cane field trials. Also thank you for tolerating my (over?) use of Araldite, duct tape and zip ties during testing – soon enough these items will become recognised engineering tools.

Staff of the National Centre for Engineering in Agriculture: Director Matthew Durack, my road trip partner Damian Spinaze, Simon Zillman, Nick Stone, Jason Stone and David Jones.

Faculty of Engineering and Surveying staff: Chris Galligan, Brian Aston, Glen Bartowski, Dean Beliveau, Terry Byrne, Jim Scott and Chris Lock.

Dr Tania van den Ancker for her chemistry expertise and her contributions in the developmental stages of the chemical sensing.

Jeff Budd and the other members of the Murwillumbah Co-op who allowed me to conduct field trials in the beautiful South Tweed. Thank you for your time, and more often than not your patience!

Gary Sandell, BSES, for his efforts in getting the field data sensory separation system.

My parents, George and Lesley, and my sisters, Elizabeth, Cheryl and Alison who have always provided me with unconditional support.

And of course Liana, who joined me near the completion of this fun voyage, but who will be there with me for all new adventures in the future ☺

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List of Publications

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   This paper also appeared in the book:

   Billingsley, J. (ed.) 2000, Mechatronics and Machine Vision, Research Studies Press Ltd, Hertfordshire, England.

2. McCarthy, S.G., Billingsley, J., and Harris, H. 2001, ‘Where the Sweetness Ends’, Proceedings of the 8th IEEE International Conference on Mechatronics and Machine Vision in Practice, Hong Kong.

3. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, ‘Development of an advanced cane loss monitoring system’, Proceedings of the Australian Society of Sugar Cane Technologists, Cairns Queensland.

4. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, ‘A Sensor For The Sugar Cane Harvester Topper’, Sensor Review, vol. 22, no. 3, pp. 242-246.

5. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, ‘Control of the Sugar Cane Harvester Topper’, Proceedings of the 9th IEEE International Conference on Mechatronics and Machine Vision in Practice, Chiang Mai.

   This paper also appeared in the book:

Billingsley, J. and Bradbeer, R.S. (eds.) 2002, Mechatronics and Machine Vision 2002: current practice, Research Studies Press Ltd, Hertfordshire, England.

6. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, ‘A Sugar Cane Harvester System’, Proceedings of the 2002 International Conference on Engineering in Agriculture, Wagga Wagga NSW.

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Chapter 1

Introduction

1.1. The Sugar Cane Harvester Control Concept

All sugar cane grown in Australia is harvested mechanically. There have been severe economic pressures to optimise production efficiency and product quality.

The harvesting process is a demanding task for the harvester operator as there are many different functions to control under difficult visual conditions. The transition from burnt to green cane harvesting in recent times has resulted in a substantially greater workload demanded of the operator. This, compounded with the lower green cane harvesting rate increases operator fatigue.

There is a great deal of potential to improve the efficiency of the mechanical harvesting process. By quantifying the inefficiencies of the cutting and cleaning systems with intelligent sensors, monitoring systems or even automatic control could be developed to take over functions traditionally controlled by the operator. This would reduce the responsibilities of the operator, and result in an improvement in the performance and efficiency of the harvesting process.

This research has culminated in workable and useable advancements in the field of sensory control. The chosen application of a mechanical sugar cane harvester provides tremendous opportunity for these technologies to be integrated to reduce the demands on the operator, and to improve the quality and quantity of the harvested cane.

An improvement in the efficiency of the harvester would increase the yield returned to the sugar mill for processing, and hence would be of considerable financial benefit to the Australian sugar industry.

1.2 Project Objectives

The proposition for this research was based on simplifying the operation of a mechanical harvester to reduce the demands on the operator during the harvesting process. Any reduction in the responsibilities of an operator will decrease the inherent human error involved with controlling the harvester. In other words, an improvement in the operating conditions for the operator will greatly increase the efficiency of the harvesting process, and will maximise the yield returned to the sugar mill.

It was proposed that events during harvesting should be detected and communicated directly from their source, be it from the cutting, cleaning or any other selected system's interface with the cane product. The necessary information will be extracted from the signal returned from these systems and will be applied appropriately.

By identifying the principal functions of the harvester, sensory systems will be developed, introduced and integrated to provide relevant real-time information to the operator, or to automatically control the functions, or a combination of the two.

To support the proposition the objectives of this research program were as follows.

1. Investigate the application environment and select appropriate functions of a cane harvester to introduce sensory control.

2. Investigate existing instrumentation and control of cane harvesters to determine deficiencies and/or drawbacks in their current design, measurement technique, and performance, and investigate advantages of introducing novel techniques.

3. Describe and model innovative methods for the sensing of certain events and parameters needed for control of the functions of a cane harvester, in particular the introduction of mechatronic methods.

4. Consider ergonomic aspects of the presentation of additional information to a human controller.

5. Devise and develop prototype sensory control or monitoring systems to meet objectives using novel technologies.

6. Evaluate performance capabilities and limitations of prototyped sensory systems.

1.3 Project Achievements

Two functions of the harvester have been investigated – the cleaning system and the topper. The operator controls both of these functions, however they represent only a small portion of the workload and are often given low priority.

A method of assessing cane loss was developed in which cane billet impacts on the primary extractor fan blades were detected by a novel audio transducer. The signals from this transducer were coupled from the moving blades to the stationary frame, where these signals were collected. The method demonstrated the relationship between fan speed and cane loss and showed promise of providing an accurate real time assessment of cane loss.

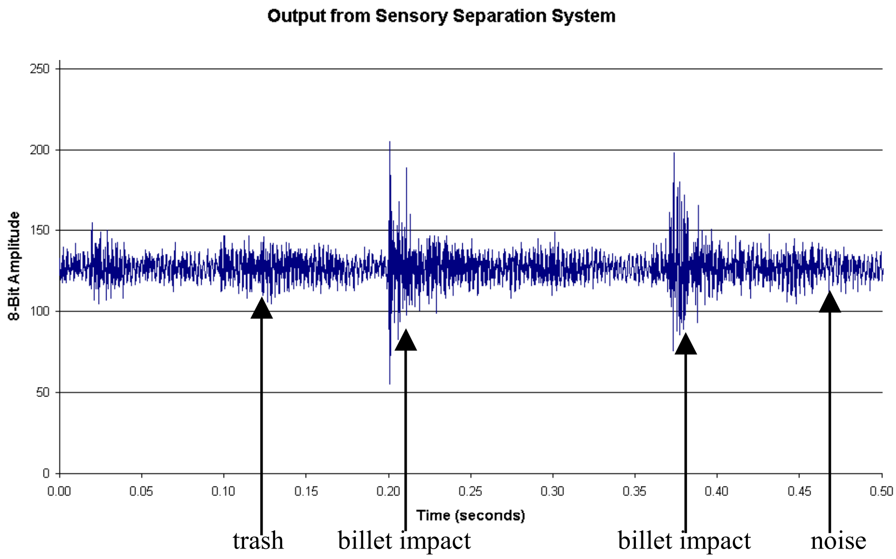


Figure 1.1: Sample of data returned from sensory separation system[*]

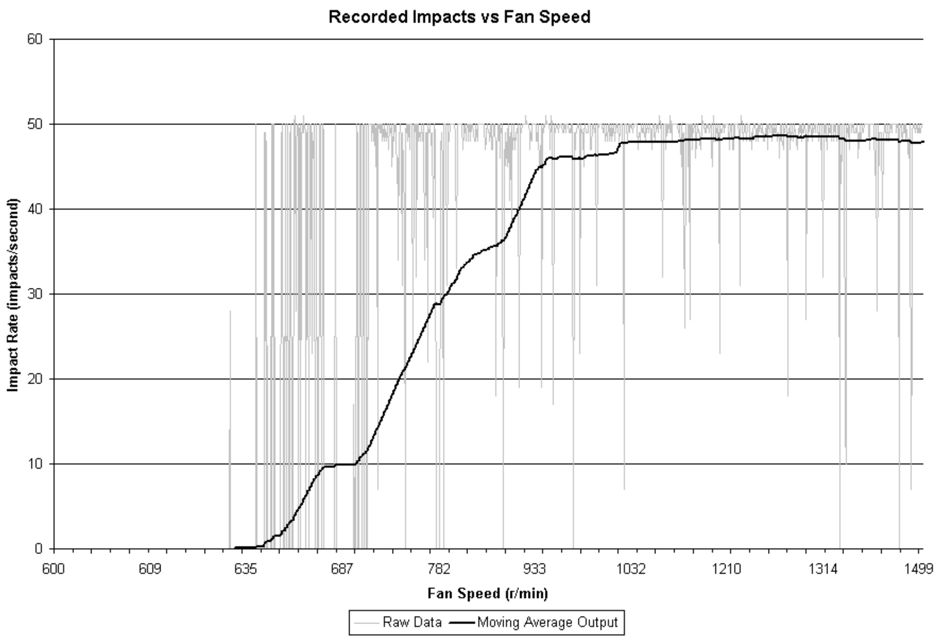


Figure 1.2: Relationship between recorded impacts and fan speed

To establish the optimum topping height, a real-time measurement of the sugar concentration at the lowest point of contact between topper and cane stalk was considered to be the most appropriate approach. A novel mechatronic sensor was developed to identify a chemical property of the cane stalk to indicate the correct cutting height. This sensor operates on similar principles to those in commercial

[*] Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

refractometers, and proved to measure sugar samples that had been artificially created - as well as from a sugar cane stalk - with an error of less than 10%.

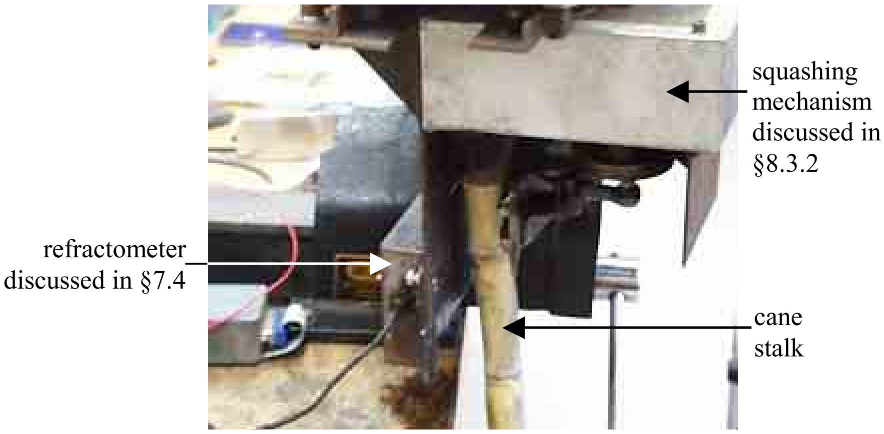


Figure 1.3: Squashing mechanism in laboratory crushing sugar cane stalk*

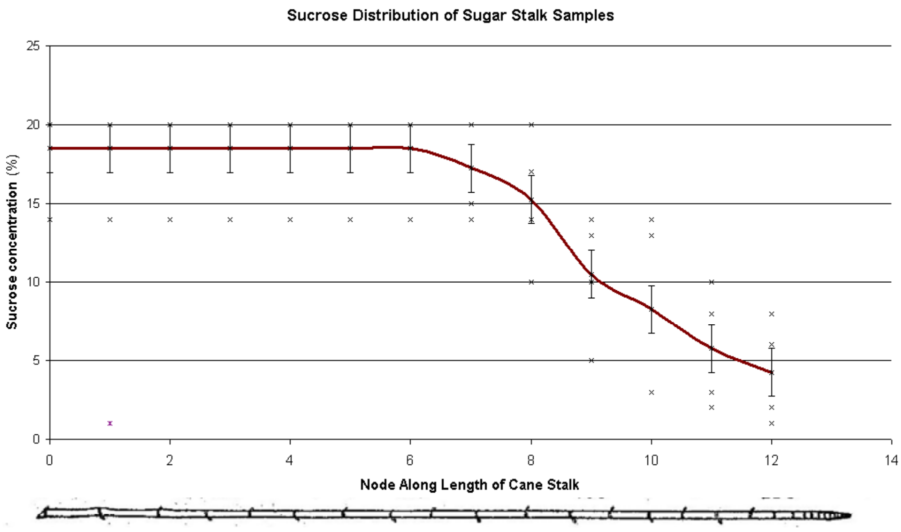


Figure 1.4: Distribution of sugar concentration from refractometer with samples from stalk (left) up to top (right)

To provide the necessary assistance to the operator, feedback should be applied to create a closed-loop system for each of the considered harvester functions. Thus the measured quantity will provide an indication of the adjustment required to maintain an output signal at the required level.

* Video footage is accessible by 'clicking' on the figure in the dissertation CDROM

Ultimately the developed control systems will be integrated to form the basis of a more efficient sugar cane harvester.

1.4 The Dissertation

This chapter has provided an introduction to the thesis, and the application of the developed technologies to the sugar cane industry. The layout of the remainder of the dissertation is addressed in this section.
A brief introduction to the sugar industry, its logistics and the modern mechanical cane harvester is provided in Chapter 2.

Chapter 3 discusses the measuring environment, and identifies the obvious lack of technologies in integral harvesting mechanisms. Two harvester operations are selected for further study – the separation system and topper.

The fiscal concerns of poor and inefficient operation of the selected functions are the topic of Chapter 4. The efficiencies of the two systems are linked, and this is identified.

The concept of a sensory separation system is introduced in Chapter 5. Substantial familiarity was required in the measuring environment, and this is reflected in the development stages of the system.

A novel sensory separation system was developed and finalised for field-testing, and the results are discussed in Chapter 6. The returned signals from the system revealed interesting methods for quantifying cane loss. Various time-series analyses to identify lost cane are presented, and the results achieved from applying the most successful of these are included.

The concept of the development of sensing mechanisms to be applied to various harvester functions continues in Chapter 7, and this time the focus is the topper. Appropriate sensing techniques are considered, and the development stages of the most appropriate system are discussed.

Chapter 8 discusses the results of the sensory topping system. The novel sensor was tested in the field on numerous occasions, and the iterations in the development to a laboratory-working device are presented.

The integration of the developed sensory systems is the topic of Chapter 9. For maximum effectiveness, the returned signals must be utilised in an optimal fashion. Several methods of providing feedback to the mechatronic systems are presented.

Completion of the objectives has allowed recommendations to be made to the industry regarding the introduction of devices to improve selected operations to mechatronic systems. Generally the introduction of these systems has great potential to improve the overall performance of the harvester.

1.5 CDROM Contents

An appendix to the dissertation takes the form of a CDROM. In this format, it can contain multimedia files to give familiarity with the measuring environment. It also contains source code, so that the achievements of the project can more readily be transferred to future work than listings on paper.

In addition, the CD contains files representing a number of publications concerning this research.

Chapter 2

Background

2.1 The Australian Sugar Industry

Sugar is Australia's second largest export crop, and contributes up to $2 billion dollars annually to the economy. Over 545 000 hectares (ha) are devoted to sugar cane growing in Australia (Queensland Sugar Corporation 1997). This area is generally on coastal plains and river valleys along 2100 km of the eastern coastline between Mossman in north Queensland and Grafton in the northern part of New South Wales. Additionally, in 1996 the Ord River region of Western Australia had its first full season.

Australia produces 4% of the world's sugar. However the domestic consumption of sugar is quite low, and as a result, the sugar produced here represents 12% of the total global free sugar trade.

Figure 2.1: Mechanical harvesting of a sugar cane crop

In the 1997 season, Australia produced 5.74 million tonnes (Mt) of raw sugar from 41 Mt of sugar cane harvested from 420 kha. Australia's average cane production was 98 t/ha and sugar production was 13.8 t/ha – though these figures can vary quite drastically.

2.2 Sugar Cane

Sugar cane is a giant grass of the family Gramineae of the genus Saccharum (Barnes 1964); its botanical name is Saccharum officinarum L.

Sugar cane has the ability to trap the sun's energy and convert that energy into sucrose (sugar) more effectively than most other crops. Sugar is produced in the leaves of a cane plant through photosynthesis. Chlorophyll absorbs energy from the sun and combines with carbon dioxide and water to produce high concentrations of sugars stored as juice.

The sugar cane plant, which at maturity is between 2.5m to 3.5m high, can be divided into four principal sections. From the top down there are the flower (or arrow), the leaves (top and leaf), the stalk, and the root system. The area of the plant of greatest interest for the grower is the stalk (culm, stem) because this is where the commercial product, sucrose, is stored. A cross-section of the stalk is generally roughly cylindrical (oval for some varieties) and the diameters vary considerably, from 12 to 50mm. The outer portion, consisting of a tough rind, encloses a softer, fleshy, internal portion of juice-soaked fibres.

2.3 Growing Sugar Cane

The Australian industry has more than doubled its productivity in the last 60 years through advanced farming practices and new cane varieties (Queensland Sugar Corporation 1997). The average yield of cane in the 1930s was 40 tonnes per hectare that produced five tonnes of raw sugar. A hectare of land nowadays in Australia typically yields between 80-100 tonnes of cane from which 10-15 tonnes of raw sugar is produced.

Sugar cane is grown from setts (cuttings from mature cane stalks) containing two or more eyes (growing points) that are planted in rows approximately 1.5m apart. The setts are usually billets that are supplied straight from the harvester. The propensity of sugar cane to produce new shoots from planted stalks allows several crops to be harvested from the original plant. The subsequent crops are called ratoon crops, and they are usually limited to three before fresh seeds are planted.

The composition of the cane stalk is best considered as two members, vegetative and chemical, and both of these vary in different varieties, and are influenced by the conditions under which the cane is grown. Factors affecting the composition of the cane of any variety include soil, environment, climate, water supply (rain or irrigation), cultural treatment (fertilizer application), and age.

Sugar cane generally grows for 10 to 18 months before being harvested, usually during the winter months when cane growth is slowest and sugar content is at or near its peak. In Australia, the harvest season is generally between June and December.

2.4 Mechanical Harvesting

In many parts of the world, the harvesting of sugar cane is still performed manually. Sugar cane is one of the most difficult crops to harvest mechanically because of the size of plants, varying crop density, the number of different crop varieties, and irregularities in growing patterns (Schneider & Baker 1997). For example cane does not always grow perpendicular to the ground. If heavy rain and winds occur during the growing season the cane may be blown over or even collapse from the weight of the wet tops combined with the soft ground. These plants continue to grow, however the cane stalks now take the shape of a large hook (lodged crops) as the tops continue to turn upward toward the sun.

All of these factors have needed to be considered during the development of the mechanical harvester. Harvesting of sugar cane via mechanical means was pioneered in Australia, and is a process that began evolving as far back as 1889 (Spargo & Baxter 1975), but it was not until much later that any significant progress towards improving the mechanical harvesting process was made.

The years 1930 to 1955 included the development of many different models of 'whole stalk' cutters, most of which were developed by inventive farmers. These machines performed well in erect crops, however could not harvest efficiently in badly sprawled or lodged and tangled cane stalks. The functional limitation of whole stalk cutters is their inability to handle bent stalks after they are cut. To operate most efficiently, the requirement is to lay the cut stalks on the ground in a series of aligned and compact bundles to be collected in a transport. This is a relatively simple task to achieve if the stalks are straight, but if it is a lodged crop the stalks may be severely bent and twisted.

This was a severe limitation of the whole stalk harvester, and as a result up until 1959 a mere 1.6% of the Australian crop was mechanically harvested. This was also the year that the chopped cane harvester was commercially introduced, and in one decade the percentage of Australian crops mechanically harvested jumped to 71.6% (Figure 2.2). It was not until the 1960's that the mechanical harvester had become a commercially viable and attractive alternative to growers, and the manual cutting of cane started to be seriously phased out. By the early 1970's the transition to mechanical harvesting was virtually complete, with the chopper harvester being the most successful for Australian conditions.

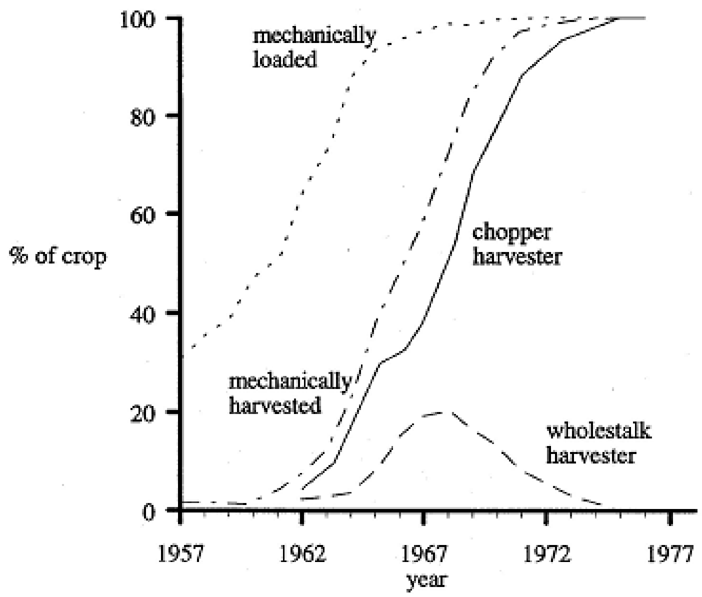


Figure 2.2: Mechanisation from 1957 to 1977 (Ridge, 1987)

In many other sugar growing countries, whole stalk harvesting still proves popular because the deterioration of whole stalks is slower than that of smaller chopped up billets, and also there is less extraneous and other waste matter included in the cane supply. Despite these factors the chopper harvester still became most popular. The advantages were higher productivity, the ability to harvest lodged cane, and producing a uniform material that could be easily transported to the sugar mill using the existing efficient transport and scheduling systems.

There are two methods commonly used for harvesting sugar cane:

- **Burnt cane harvesting** is the traditional condition under which cane was cut. To prepare for harvesting, the crop was burnt to remove leaves, weeds and other matter that may impede harvesting and milling operations, and also as a measure to control the disease spread by rats. This method is becoming less popular because of the damage caused to the field via weed germination and moisture loss.
- **Green cane harvesting** involves cutting the crop as it stands without prior preparation, and has in recent times become the more popular method. Using this technique the leafy tops fall to the ground and provide a protective trash blanket to organically mulch the field as well as reducing the level of soil erosion and preserving soil nutrition for crop growth. It also provides a cost saving to farmers because weed germination is prevented. However in some growing areas the trash blanket may waterlog the field, particularly where there is poor drainage. In cooler climates the blanket lowers the soil temperature, which can impede early plant growth. In modern times, some mill areas green harvest up to 90% of the crops.

2.4.1 The Chopper Harvester

The modern mechanical harvester is still an evolving piece of technology. It is an awkward machine consisting of numerous functions, most of which are controlled by the operator.

The series of events of a self-propelled mechanical harvester in operation are as follows (Figure 2.3). The harvester leads by separating the rows and lifts lodged cane with the crop dividers (Kroes 1997). Directly above the dividers is the topper that removes the leafy material at the top of the stem (topping) and this material is allowed to fall back onto the field. A knockdown roller then pushes the cane over to ensure that the butts of the stalks enter the harvester first. The stalk is cut off at ground level with the base cutters, a pair of counter-rotating discs fitted with blades. The inward rotation of the basecutters assists with the transportation of cane towards the feed train. A finned feed roller and a butt-lifter roller then guides the stalks into the feed train to the choppers. The stalks are cut into lengths or billets by the choppers, and are sprayed into the bowl of the harvester elevator across the base of the extraction chamber. A majority of the leaves, tops and dirt are separated from the cane in the extraction chamber by the primary extractor fan that is mounted above. The cane travels up the conveyor, or elevator, and the secondary extractor fan removes more extraneous matter. The billets are then deposited into a waiting haul-out bin that is pulled by a tractor beside the harvester. Each harvester will generally have multiple haul-out vehicles to reduce lengthy stoppage times. The full bins are then taken from the field to a cane railway siding or a road haulage delivery point for transport to the sugar mill.

Modern harvesters are available with tracks (see Figure 2.1) or with wheels. The wheeled harvesters have rubber tyres, and are steered with the front wheels. The tracked harvesters have been developed for wet conditions, and are steered in a similar fashion to a bobcat; that is, the left and right sides are independent of each other.

The course of this research has selected two of the functions of the harvester to be investigated. The operator controls both of these functions, however they represent only a small portion of the workload and are often given low priority.

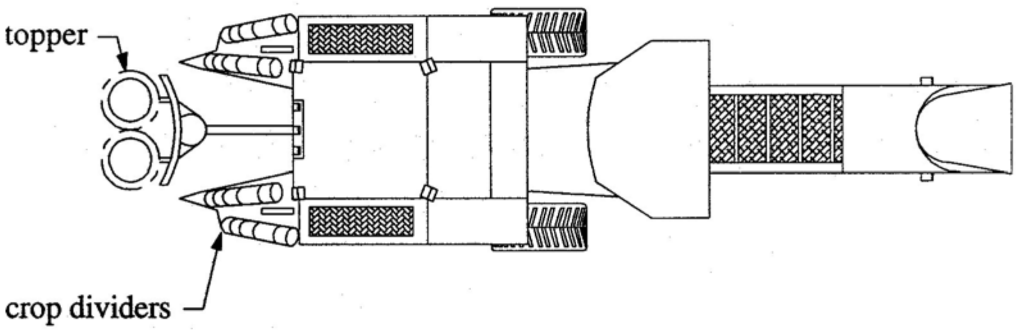


Figure 2.3a: Plan view of a mechanical sugar cane harvester

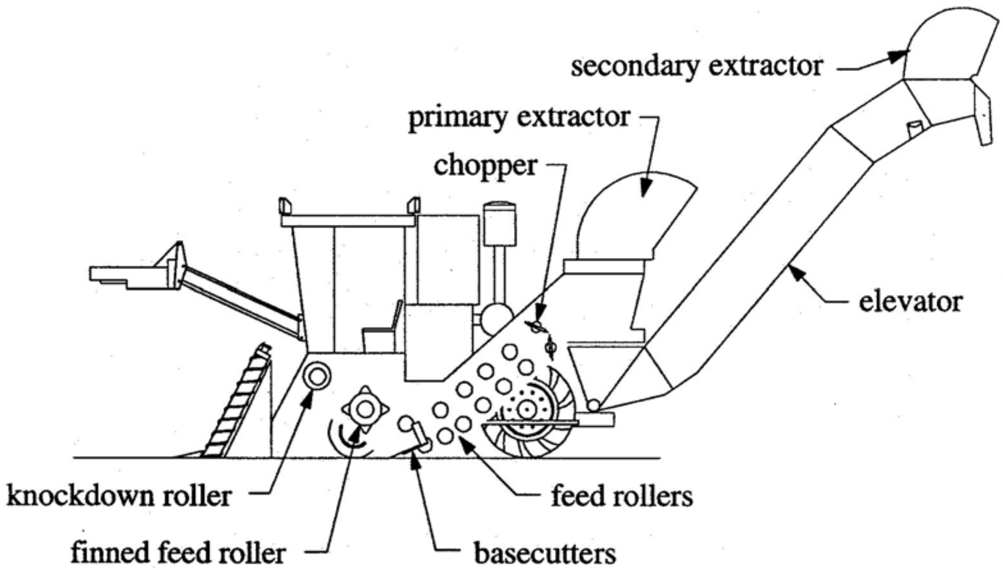


Figure 2.3b: Side elevation of a mechanical sugar cane harvester

2.4.2 Cleaning System*

The mechanical sugar cane harvester's principal on-board cleaning system is the primary extractor fan. This fan cleans the cane by pneumatically separating billets from trash and other extraneous material during the harvesting process. The trash is ejected from the extraction chamber and is thrown back onto the field, however many billets are also lost. The operator currently controls the extractor fan by subjectively selecting an operating speed before each crop, or change in crop conditions.

* Video footage is accessible by 'clicking' on the heading in the dissertation CDROM

2.4.3 Topper*

The function of the topper is to gather, sever and discard the leafy, immature, and non-productive tops of the sugar cane stalk. Modern toppers are called ‘shredder toppers’ because of their ability to gather and shred the cane tops before discarding the waste back onto the field. Physically the topper is a large hydraulically powered, vertically rotating drum with many razor knives on the rotating drum and gathering walls. The operator currently controls the height of the topper by subjectively judging the optimum topping point on the cane stalk.

* Video footage is accessible by ‘clicking’ on the heading in the dissertation CDROM

Chapter 3

The 'Smarter Harvester'

3.1 Justification of Study

Modern mechanical harvesters are complex machines that are often difficult to manoeuvre. There are numerous simultaneous functions that must be directly controlled by the operator. A majority of these have to be controlled under extremely difficult visual conditions, if they can be seen at all.

Figure 3.1 gives an indication of the operator's view of the crop as it is being harvested.

Figure 3.1: View from harvester cabin

Despite the difficult operating conditions, cane harvesters of the near future will probably operate on similar principles to the machines in operation now, the only major differences being in the materials, the operator comfort and control achieved, and the technique used to maximise their performance (Kerr & Blyth 1992).

The proposed research aims to simplify the operation of a mechanical harvester to reduce the demands on the operator during the harvesting process. Any reduction in the responsibilities of an operator will decrease the possibility of error that is inevitably involved with human control of the harvester. An improvement in the operating conditions for the operator will greatly increase the efficiency of the harvesting process, and will maximise the yield returned to the sugar mill.

3.2 Preceding Work

The idea for the proposition continues from earlier work conducted by Pandey and Billingsley (1998) at the University of Southern Queensland. This research was concerned with the automatic control of both the steering and base cutter height of a cane harvester.

Many of the harvester’s operations rely on mechanical blades, be it for cutting or cleaning, and this earlier work demonstrated that if these operations were sensed at the point of contact via acoustic means, information relevant for the automatic control of these operations could be extracted from the returned data.

The methods explored by Pandey and Billingsley (1998) proved to be relatively successful, but their work also demonstrated that there is potential for a great deal more research and development in the field of cane harvester automation.

There have been many attempts at automating a cane harvester. These techniques have not yet been shown to be completely reliable - as will be discussed in §3.2 - and as a consequence the harvester operator still controls all of the harvester functions.

The cane harvester is required to operate in an extremely hostile environment. Mechanical components, such as blades, are subjected to abrasive and acidic conditions that cause severe wear. As a consequence, the harvesting environment is an important consideration when designing any sensory system for the harvester.

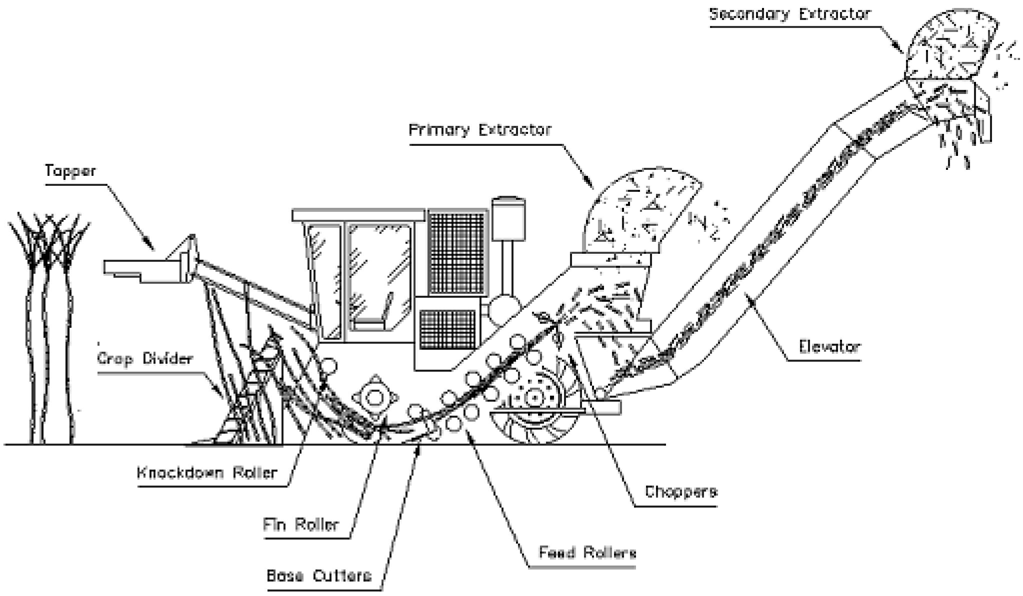


Figure 3.2: Illustration of mechanical harvester with major functions indicated

A fully functional solution has not surfaced for any harvester operation as yet, mainly due to the difficult implementation of appropriate instrumentation to identify characteristic information from the operations. A summary of the main harvester operations and the techniques previously developed for automatically controlling them follows.

- Primary extractor fan

  The efficiency of this cleaning system is gauged by how satisfactorily cane billets are separated from trash during the harvesting process. The fan speed needs to be adjusted to obtain a compromise between excessive residual trash in the harvest, and a substantial quantity of cane being lost. This function does not receive much attention during the harvesting process, and as a result a large amount of cane billets can be lost. It is estimated that losses from the extractor fan alone account for up to 10% of the potential product (Hurney et al. 1984).

  A device that detected the amount of cane being ejected, a cane loss monitor (Dick & Grevis-James 1992), was developed and the commercial product is illustrated in Figure 3.3. This monitor relied on detecting the impact of ejected cane billets on the hood of the primary extractor fan. Many lost billets fail to hit this hood, so this method is inefficient. Also, plastic shrouds have largely superseded metal hoods and thus this method of impact detection has been made more difficult.

Figure 3.3: Existing commercially-available cane loss monitor

Recently a project was completed that represented the first major change in the harvester’s primary onboard cleaning system design in over 15 years (SRDC 2001). Associate Professor Harry Harris and Simon Zillman of the National Centre for Engineering in Agriculture in collaboration with Case Austoft, developed a new cleaning system based on high pressure jets of air which separate trash from cane emerging from the choppers on a harvester. A hydraulically operated blower supplies air to the jets mounted below and behind the chopper box.

The prototype harvesters that were tested also have a reconfigured elevator bowl and elevator, as well as an improved primary extractor fan. A secondary fan is not fitted on the elevator, as the air jets and primary extractor give better cleaning of the cane than conventional two fan systems.

- Topper

The topper gathers, severs and discards the leafy non-productive tops of the cane stalk (Spargo & Baxter 1975). A system to control the height of the toppers automatically would greatly simplify the operation of this function, however little progress has been made towards achieving this result.

- Base cutters

  The function of the base cutters is to cut the cane stalk off at ground level. The base cutters are probably the most difficult operation to control because they are completely hidden from the view of the operator. They are two 600mm steel discs that have up to six blades mounted on each. These discs are mounted behind the front wheels of the harvester, and they contra-rotate at approximately 600rpm.

  The height of the base cutters is controlled by two hydraulic rams that raise or lower the front section of the harvester. Inaccurate height control contributes to both a reduction in yield, as well as excessive extraneous matter in the harvest that can cost the Australian industry up to 40 million dollars per year (SRDC 1997).

  Automatically controlling the height of the base cutters has been the most investigated function of the cane harvester. Attempts have been made to use data collected from the base cutter height sensors to automatically control the steering of the harvester along the rows of the crop. Some techniques that have been attempted include basecutter hydraulic drive fluctuations, acoustic sensing and ultrasonic height detection.

  Suggs and Abrams (1972) and Garson (1992) considered base cutter hydraulic drive fluctuations as being a technique for height control. This method attempted to monitor fluctuations about the mean of the pressure in either of the base cutter’s hydraulic drives. The fluctuations in pressure indicated that the base cutter required more power, and hence was cutting through the solid soil bed rather than the lighter cane.

  Pandey and Billingsley (1998) investigated the technique of identifying base cutter noise signatures for height control. This work introduced the method of using a sensor in the form of a microphone to listen to each of the discs. The differential raw signals from the base cutter blades gave an indication of the steering control feedback required. Height control was attempted by analysing each disc’s recording to discriminate between the blades cutting cane and the soil bed.

Schembri and Everitt (1999) attempted the most promising approach, ultrasonic height sensing, by attaching two such sensors to the harvester frame slightly ahead of the base cutters. The height measurements indicated the effect of the elevator position on the angle of incline of the harvester, which impacts on the cutting performance of the base cutters. The centre of the row was also detectable from the outputs of the sensors.

Ultrasonic techniques have also been successfully employed as a method to monitor the height of the crop dividers. The operators usually control the height above ground level of the crop dividers on harvester fronts. Imprecise control can result in soil being shovelled onto cane entering the harvester throat if dividers are set too deep, or lodged cane escaping under the divider shoe if set too high. Matt Schembri of the Sugar Research Institute (SRDC 2001) demonstrated that ultrasonic sensors could be used to measure the height of the crop divider shoe from the soil surface, and thus allow automatic control of the crop divider height regulated by a microprocessor.

New means of improving the quality of the sugar cane product returned to the mill are not restricted to design changes of the mechanical harvester. Cox, Harris and Cox (1998) developed a sensor to monitor the yield from a sugar cane harvester. This product represented a first in the world of precision agriculture for cane, and the industry has identified precision agriculture as critical for future productivity gains in the cane industry. The benefits of the system included improved fertiliser management, reduced environmental impact and enhanced overall farm management. The data acquired using the system continues to be utilised by farmers and researchers in the field.

3.3 Relevant Advances in Other Agricultural Equipment

In the past, the manufacturers and producers of agricultural machinery have emphasised raw power over technical sophistication (Romans et al. 2000), and one of the major impediments of the electronics adoption was the unreliability of early sensors in the measuring environment. However in more recent times the use of electronics was more widespread as equipment manufacturers paid more attention to operator comfort. The introduction of the enclosed cabin of modern agricultural equipment also meant more controls, monitors, and other electronic equipment could be mounted on every pillar and flat surface in the cabin.

Zander (1972) considered that the advent of mechanisation had influenced the nature of the workload in the agricultural harvesting industry, and now the main issue was the perception and processing of information, as well as controlling and regulating the work being done by machines. In particular, this study focussed on the ergonomic system-analysis of the operation of a self- propelled combine harvester.

The grain industry has for some time had technology to monitor the amount of grain lost during the harvesting process. Many products are now available that measure a combine harvester’s throughput and loss, and these quantities are useful to control the ground speed of the harvester so that a desired material flow rate may be maintained (Downs & Stone 1988). These sensors detect the sound of the grain striking the plate and send a pulse back to the monitor for each seed strike. The meter calculates the average frequency of seed strikes and displays a relative reading.

Another relevant advance in the grain industry is the infrared grain analyser. This product calculates protein or moisture and oil content for the grain of interest continuously during the harvesting process (Sheppard 1999). It is envisaged that this system will allow the separation of high- and low-quality grains into bins directly from the combine harvester.

The discipline of agricultural field vehicle guidance is a topic that continues to be well explored. Various methods have been reported including such techniques as buried-wire guidance of tractors, guidance of agricultural vehicles via trailed implements, crop feeler systems for harvesters, vision systems, and in more current times the use of GPS as a tool has become perhaps the most accurate method yet.

3.4 Chapter Summary

Clearly the mechanical harvesting of su7ar cane is a process that has potential for improvement. Through the introduction of mechatronic techniques, the efficiencies of this particular facet of the Australian sugar industry may be substantially enhanced.

Chapter 4

Sugar Cane Harvesting Logistics

4.1 Economics

The manner in which a sugar cane harvester is operated has a considerable effect on the financial return to the growers, millers and harvester owners. This is significant because of two factors: cane quality, and loss of millable cane (Brotherton & Pope 1995). Cane quality relates to the presence of extraneous matter (EM) in the product. Fuelling (1982) describes extraneous matter in chopped cane as consisting of tops, trash (green and dry leaf), dead cane, and dirt.

Topping low to reduce the extraneous matter results in loss of cane on the proportion of taller stalks (Brotherton & Pope 1995). Similarly topping high to reduce this loss results in inclusion of increased quantity of tops in the product, as well as increasing demand on the separation systems.

The ideal topping height for individual stalks in lodged crops is varied and it is nearly impossible to prevent tops entering the harvester.

Inclusion of tops normally represents a major proportion of the extraneous matter in the cane supply that is delivered to mills. In chopped cane, the top is of cane billet length and approximately the same density. Often it forms part of a billet of cane, and so it is very difficult to separate from the cane without undue losses. Leaving the cane stalks untopped during the harvesting process increases tonnage, and has a negative impact on sugar quality. High levels of extraneous matter are undesirable because of their adverse effect on the commercial cane sugar (CCS) content of the cane supply. Commercial cane sugar represents the sugar content of cane as sugar mills purchase it, and it is generally accepted that it is substantially decreased for each percentage unit increase in extraneous matter.

A trial in Far-North Queensland in 1997 (Agnew 1999) showed that untopped treatments had 4% more tonnes cane/ha but the net income to the grower was reduced by 5% because of the reduction in CCS from including the tops and increasing harvesting and transporting costs.

Therefore the efficiency of the harvesting process influences the quantity and CCS of the cane received by the mill. It follows that the amount and distribution of profits is extremely dependent on the harvesting process.

Brotherton and Pope (1995) developed relationships between extraneous matter and cane losses for topping and extractor fans. There is an inverse relationship between the amount of cane lost in discarded tops and the extraneous matter due to tops inclusion. Also an inverse relationship exists between extractor fan cane loss and the associated extraneous matter. These relationships are illustrated in Figure 4.1.

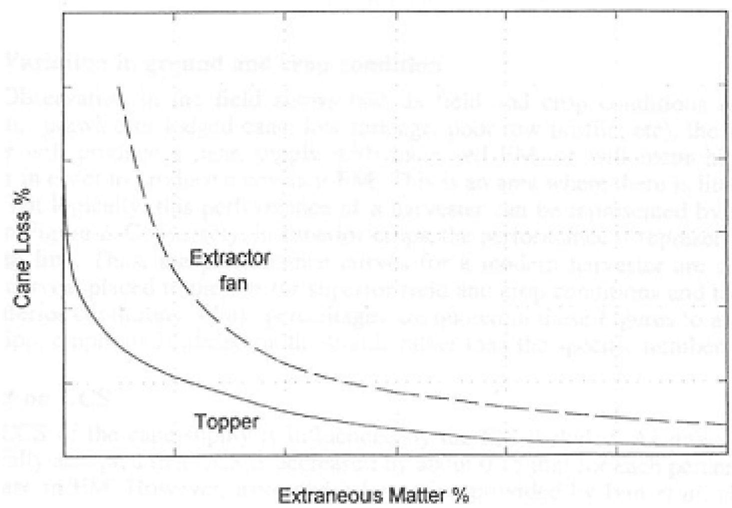


Figure 4.1: Trend relationships between extraneous matter and cane loss for topping and for separation systems (Brotherton & Pope 1995)

The significance of improving the mechanical harvesting system is clear. Sugar mills have urged the provision of cane with minimal extraneous matter, and enforce financial penalties through the CCS return. Therefore the harvesting system must be made more efficient to alleviate the detrimental influence of the inclusion of extraneous matter.

4.2 Responsibilities of the Harvester Operator

Operation of a mechanical sugar cane harvester is a very labour intensive task that occurs under extremely difficult visual and physical conditions. During harvesting season, the operator must work long shifts with few rest days. The cabin is a confined space filled with controls for harvester functions, and gauges indicating the status of these. Figure 4.2 illustrates the harvester cabin from different angles.

power and control panel positioned overhead | controls and swiches mounted on right arm-rest | gauges mounted on windscreen frame

Figure 4.2: Controls and gauges in harvester cabin

A major proportion of these harvester functions require regular monitoring and efficient controlling. The responsibilities expected of the harvester operator are listed here (in no specific order) with a short description of each (Agnew 1999).

1. The **basecutter** blades cut the cane stalks near the base, ideally at ground level. The operator sets the height of the two basecutters. This adjustment is usually based on the hydraulic drive pressure, or the amount of dirt being collected in the harvest.
2. The **buttlifter** is the first feed element in the feed train, and it directs the cane into the rollers. It also lifts the cane bundle above the fan of soil that sprays off the basecutters. The feed train depends on a steady intake of cane, but higher buttlifter rotational speeds also increase the dirt intake.

3. **Choppers** cut the cane stalks fed by the feed train into billet lengths. The set rotational speed of the choppers produces billets of characteristic length.
4. Inconsistencies between the row spacing (ideally 1.5m) and equipment track width (1.83m) result in **compaction** in the near-row and over-the-row area. The compaction caused by the wide and heavy machinery is difficult and costly to correct. The operator must ensure that harvesting occurs under the driest soil condition possible. The number of passes must be restricted and care taken when turning the harvester to minimise paddock disturbance.
5. The height of the **crop dividers** must follow the terrain to prevent grading of soil into the basecutters, and where possible, this is determined visually by the operator.
6. The adjustable **deflector plate** is mounted above the choppers, and directs the pouring of billets and trash into the elevator bowl. Optimum deflector plate settings improve trash extraction and minimise cane loss, and the plate should be adjusted to cope with different crop or harvesting conditions.
7. The **elevator** lifts the clean billets to be carefully poured into the mobile collection bins. It is essential to provide a consistent feed of harvested cane to the transport, and to minimise lost cane at the collection point.
8. The speed of the primary and secondary **extractor fans** needs to be controlled to minimise the amount of trash and extraneous material in the cane supply, and possibly more importantly the cane loss.
9. **Floating shoes** prevent cane from escaping the feed train. They should always be in contact with the ground, but they should be set up to reduce grading of soil into the basecutters.
10. The **forward speed** of the harvester must be suitable for the operating conditions. Excessive forward speed causes problems in the feeding, cleaning, loss and harvested cane quality mechanisms.
11. Adequate maintenance of **hydraulic** pumps and motors is necessary for optimum feeding and cleaning of cane.

12. Rotating **paddles** mounted in the cleaning chamber behind the chopper deflect billets down and away from the extractor fan while still allowing trash to flow out with the air stream. Substantial reductions in cane loss are achieved when operated correctly.
13. All **rollers** should be run at the same speed, and this will provide a consistent thin mat of material through the machine, producing quality billets with improved feeding, dirt rejection and cleaning without excessive cane loss.
14. The shredder **topper** should be operated to gather and chop up tops.

The performance of most of these functions may be monitored either visually, or by the indicator gauges mounted in the cabin of the harvester. From this summary of the operator's responsibilities, it can be appreciated that a great deal of skill, experience and judgment is involved in operating a mechanical harvester.

4.3 Inefficiencies Exposed

Unfortunately the complexity of operating the cane harvester often leads to the system not performing as efficiently as possible. The toppers and primary extractor fan of the harvester have been identified as being particularly inefficient, partly because of the obvious difficulties in controlling their operation, and also they are frequently under-prioritised by the operator. Operation of these two functions has already been briefly described, but theoretical losses associated with each, and their inter-dependence will be discussed.

4.3.1 Primary Extractor Fan

Raising the fan speed is a relatively ineffective way of reducing extraneous matter, because a great deal of cane is lost back onto the paddock. Figure 4.3 illustrates the increasing cane loss that results from increasing the fan speed. Setting a lower fan speed may ensure very low cane loss, however the increase of extraneous matter levels in the collected harvest may then be unacceptably high, as well as the bin weights being too low.

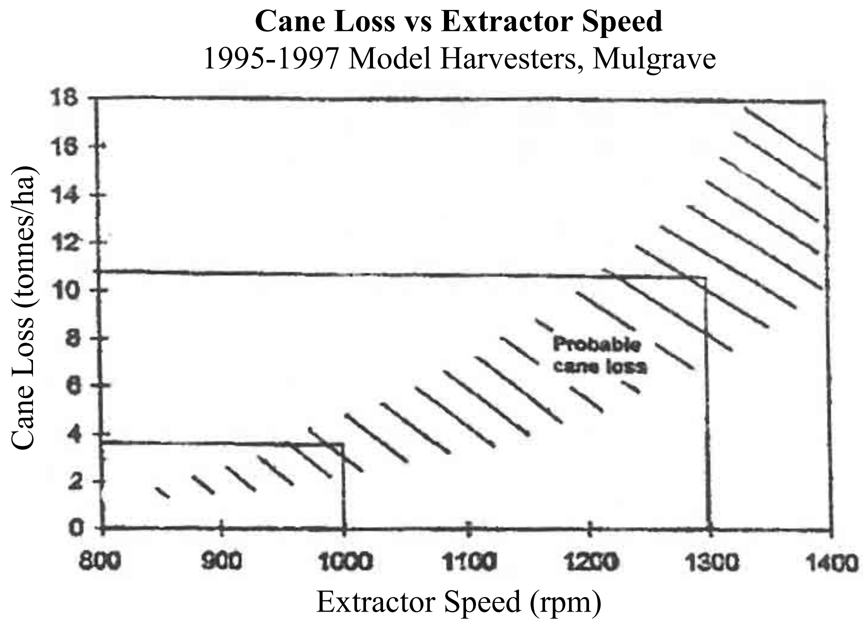


Figure 4.3: The effect of fan speed on cane loss (Agnew 1999)

Ideally the primary extractor fan speed should be adjusted to suit differing crop conditions, even while harvesting in the one field. Regular monitoring of the fan speed is a difficult task for the operator because of the numerous other tasks, and as a result cane loss due to the extractor of to 25 tonnes/hectare is not uncommon.

4.3.2 Topper

The difference between good and bad topping is considerable. Waddell (1949) identified that the 'normal point' of topping or one internode lower was, from the grower's viewpoint, the most economic point to separate the harvest from refuse material. As illustrated in Figure 4.4, the topping of stalks either side of this "normal point" generally causes the grower to receive a lower net return per hectare from any crop of cane.

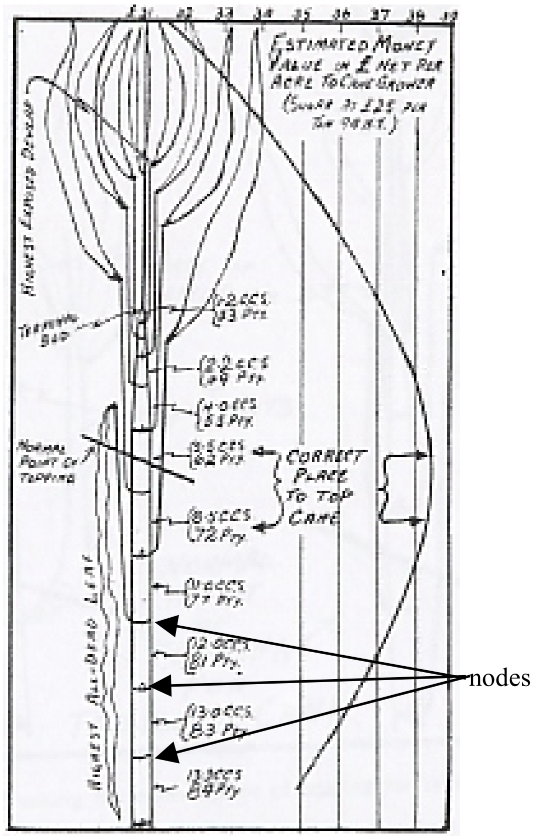


Figure 4.4: The effect of topping height on the financial return of the cane grower (Waddell 1949)

Other studies (e.g. Fernandez 1993) have developed mathematical models to describe the performance of a chopper harvester topper set at different heights relative to the cane row. Figure 4.5 shows that the cane quality is very sensitive to topper height in its higher positions and much less sensitive in the lower positions where cane losses are also increasing rapidly.

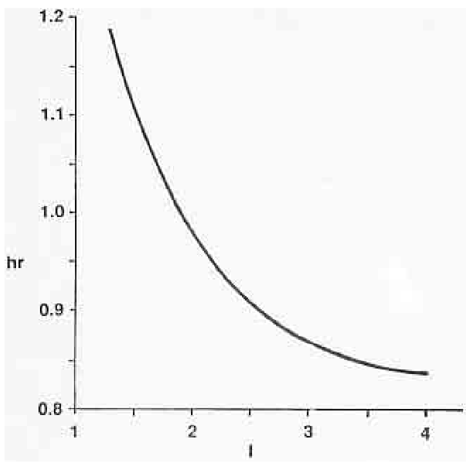


Figure 4.5: Cane quality index (I) vs relative cutting height of topper (hr) (Fernandez 1993)

4.4 Chapter Summary

The operation of a sugar cane harvester is an extremely demanding task, and this results in the system not performing as efficiently as possible. The control tasks expected of the operator have been identified, and the workspace of the operator has been illustrated. The economic aspects of poor operation of the harvester are dramatic, and there is a great deal of room for improvement of particular harvester functions.

Chapter 5

Sensory Separation System

5.1 Introduction

The objective of this study was to develop a monitoring device that could continuously detect and provide a measure of the number of billets passing through the primary extractor fan. Investigations have been conducted into the application of mechatronic tools to assist the harvester operator's control of this integral cleaning system. A novel sensing system has been substantially developed that generates a signal from the origin point inside the extraction chamber right through to the collection of the data in the harvester's cabin. It is envisaged that this device will provide relevant information so that the extractor fan speed can be controlled with a reduced workload for the harvester operator.

Figure 5.1: Extraction chamber indicated (left) and a closer view of hood chute

The loss of billets during the harvesting process is estimated to cost the industry \$50m per year. A majority of this loss is often attributed to poor monitoring and correction of the primary extractor fan speed. The objective of the sugar cane harvester is to provide clean cane to the sugar mill for processing. The efficiency of the harvester's cleaning system is gauged by how satisfactorily cane billets are separated from trash during the harvesting process. In order to be most effective, careful control of the fan speed is required to achieve a balance between excessive trash in the cane supply, and the ejection of cane billets.

The primary extractor fan is located behind the operator, and is completely hidden from view as indicated in Figure 5.1. The fan is housed in the extraction chamber, and this is possibly one of the most difficult measuring environments on the harvester. The primary extractor fan is hydraulically driven, and 15-20m/s up-draughts are generated by it in the extraction chamber. There is a considerable amount of material flow through this separation system (up to 10kgs per second), and this material is generally very abrasive. An indication of the abrasiveness is the frequent maintenance that is required in the chamber because of the high wear rate on the thick plate steel surroundings and also on the fan blades.

Cane loss caused by the extractor fan of a cane harvester can currently be measured by the traditional ‘blue-tarp’ method, described by Linedale et al. (1993), or the ‘mass-balance’ cane loss method. Both of these techniques only provide information after the harvest has been completed. The method presented here involves detecting the impact of cane billets on the blades of the primary extractor fan. This method is potentially superior to any existing cane loss monitoring technique because examination of the trash blanket reveals that almost all billets lost through the primary extractor have struck the fan’s blades and have either been damaged or disintegrated. Practically no billets appear to pass undamaged through the fan and strike only the hood.

5.2 Detection System Concept

The contention of the detection system concept was that billets and other material that were ejected from the primary extraction chamber, or a great proportion of these materials, in fact impacted on the underside of the fan blades. Previous work conducted by Zillman (1998) included the redesign of the primary extractor fan system, and as part of this study video footage of the cane and trash separation process was recorded. Figure 5.2 illustrates an instant where minimal activity was occurring in the extraction chamber, however this was an ideal instant to demonstrate the billet impact theory.

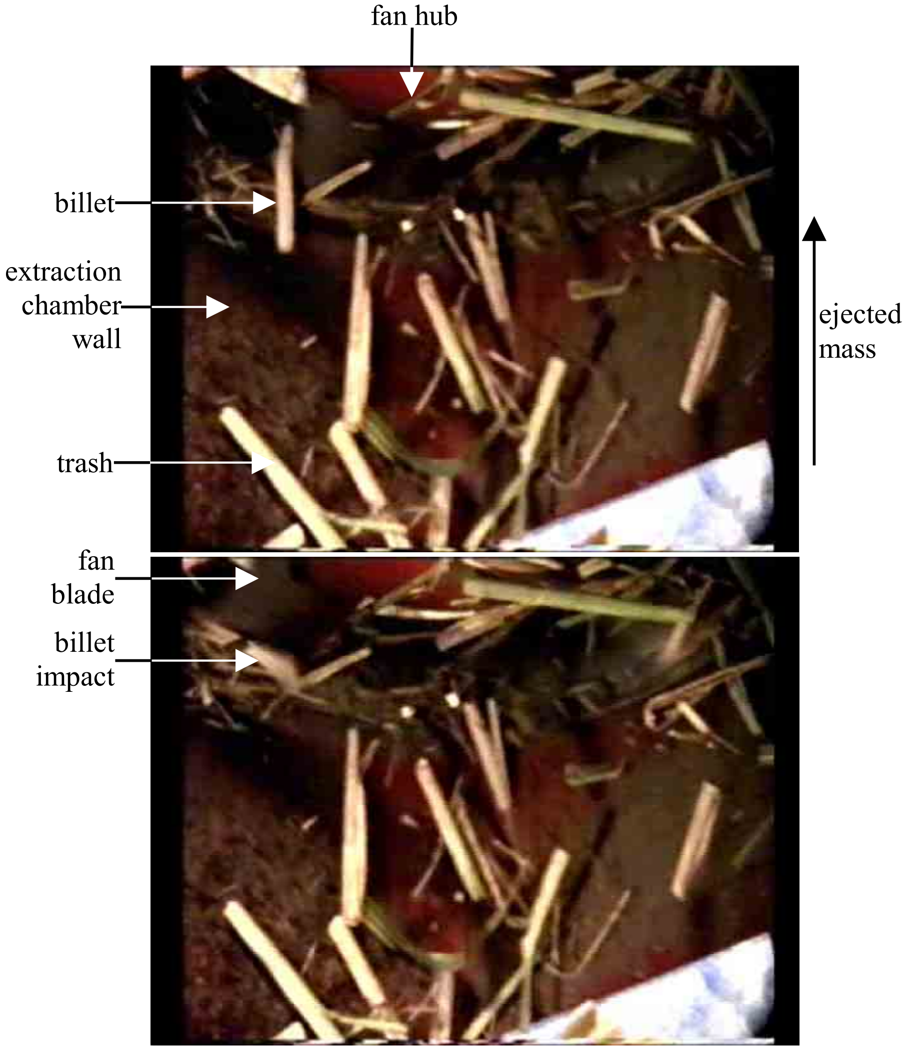


Figure 5.2: Cane billet in ejected mass before (above) and after (below) striking underside of extractor fan blade

The images in Figure 5.2 show an example of a cane billet being pneumatically extracted from the harvested product and ejected from the system. The top image is an instant before impact, and the bottom image is after impact, and the two images in sequence support the concept of detecting and quantifying the cane loss from the point of contact between billets and fan blades.

5.2.1 Sensor

When cleaning, both ejected cane billets and trash exit the harvester via the extractor fan chamber and a vast majority of this material strikes the fan blades. This is obvious by visually inspecting the wear on the blades, and by the damage caused to the discarded billets in the trash blanket. Pandey & Billingsley (1998) investigated acoustic sensing by implementing a pick-off to listen to the work conducted by the base cutter discs. The differential raw signals from the base cutter blades gave an indication of the steering and height control required.

Therefore it follows that if the impacts whilst cleaning in the extraction chamber could be detected at the point of contact between refuse material and the fan blades, a measure of cane loss would be attainable. In this case the fan blades become the sensors for the system, and the pick-off behaves as a transducer by generating the characteristic signal for collection. This approach assumes that the billet impacts on the blades would be the only acoustic signal detected, whereas in reality some acoustic noise may be generated by billet impacts on other members near the transducer.

Figure 5.3: Fan assembly inside extraction chamber

Primary extractor fan blades are held in position in the hub flange by four bolts, and it is the deflection between the hub flange and the blade that is of interest.

The plane of vibration to be considered was in the vertical direction, as indicated in Figure 5.4. The fan blade in this case can be modelled as a cantilevered beam, and this simplification allows prediction of resonant frequencies.

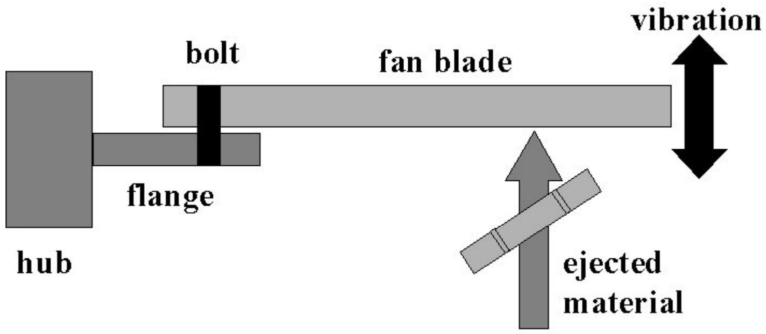


Figure 5.4: Vertical vibration of extractor fan blade

Another simple illustration of the fan is shown in Figure 5.5. Typical operation of the extractor fan with interaction with billets and standard trash may be thought of as an impulse input and white noise respectively.

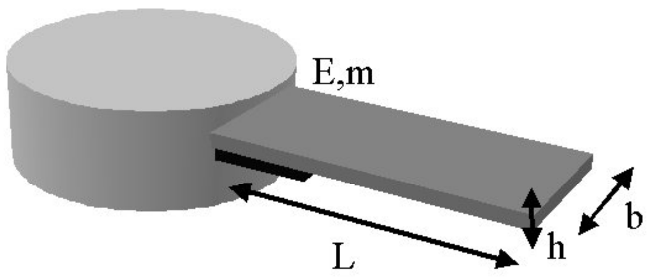


Figure 5.5: Simplified representation of fan for vibration analysis

In response to an impulse input (such as the blade being deflected, and then released), a cantilever beam will exhibit a decaying oscillatory response with a natural frequency, f, approximated by (Dimarogonas & Haddad 1992):

$$\omega = \sqrt{\frac{\frac{3EI}{L^3}}{0.235M}}$$

and w=2πf, so this becomes

$$\omega = \frac{\sqrt{\frac{3EI}{0.235ML^3}}}{2\pi} \quad where \quad I = \frac{bh^3}{12}$$

where E is Young's modulus of elasticity

M is mass of cantilever beam

L is cantilever beam length

I is area moment of inertia

b is breadth of cross-section

h is height of cross-section

It should be noted that in this case it has been assumed that the fan blade has a rectangular cross-section. In practice, the fan blades are slightly curved to improve the generated up-draughts in the extraction chamber. The blades are also slightly tapered along their length.

A new blade was 5mm thick (h). Young's modulus of elasticity was assumed to be a typical value for steel of $2.0*10^{11}$ Pa. The mass of a new blade was approximately 4.0 kg; the blade was averaged at 205 mm wide and 455 mm long. Using these values, the natural frequency of the cantilever beam was predicted to be approximately 605 Hz in response to an impulse event.

For this result, a cantilever mass of 4.0 kg was assumed, which is the mass of the steel blade only. In practice, the fan blades are covered in waste material such as mud. This extra material adds to the weight of the blade to give slightly different natural frequencies of the fan blade as shown is Table 5.1.

Mass of Fan Blade (kg)	Natural Frequency (Hz)
4.0	605
5.0	541
6.0	494

Table 5.1: Dependence of fan blade's natural frequency on mass

5.2.2 Transducer

At this stage, some assumptions were made to account for the logistics of the physical measuring environment of the primary extraction chamber. It was assumed that the transducer would be recessed into the flange of the fan hub so that the installation of new blades was not hampered, in addition to providing some protection against abrasion and impacts.

Originally, a transducer was considered on each sensor individually, i.e. on each blade, and when the fan was considered as a system, it was logical that three transducers would be required. The connection of the three transducers needed to be considered: series or parallel? If connected in series, any impact would have a substantial signal generated by that blade's transducer and this signal would be reinforced with smaller auxiliary signals from the other transducers. However, this method would suffer from increased noise and signal loss from the increased load of three transducers compared to one. The advantage of connecting the transducers in parallel would be that if one transducer was damaged and ceased functioning, a failure condition would be averted. Following this, it was assumed that the installation of only one transducer in one flange would be sufficient to detect the substantial vibrations that are caused by the impacts of cane billets. This was later confirmed with static trials of the system.

The harsh environmental conditions required the implementation of a simple, fully sealed and robust transducer design. Ideally the device should be self-powered to avoid the complications of supplying power across a rotating interface, and other systems such as batteries and even electromagnetic transmissions were considered too complex.

There are several practical methods of converting mechanical vibrations into electrical signals. Of these, only electrodynamic and piezoelectric devices meet the self-powering criteria. Piezoelectric devices are quite fragile, but more importantly their output impedance is extremely high, and this would not allow a transformer to be energised to transfer the signal across an air gap.

The most common of the electrodynamic transducers are the moving coil, moving magnet and variable reluctance. In the moving coil example, vibrations of the diaphragm cause movement of an attached coil of wire. A permanent magnet produces a magnetic field that surrounds the coil, and the motion of the coil within this field induces a current. A moving magnet transducer operates in a similar fashion, except in this case the permanent magnet is coupled to the diaphragm, and the coil is fixed. Pandey and Billingsley (1998) successfully developed an electrodynamic transducer for the base cutter application that operated on the moving magnet principle.

For the cane loss application, a custom transducer was designed and constructed based on variable reluctance principle to detect vibrations in the vertical plane. The extractor fan's blades are replaced regularly, and so it was decided that a variable reluctance transducer would be more appropriate in this application because the device would be self-contained and generally more robust. This means the magnet would not have to be carefully placed in position every time the blades were replaced. A disadvantage of this is that the signal generated would not be as large as for a moving magnet type, and the level of signal generated is dependent on the air gap between the fan blade and the transducer housing. The configuration of the prototype transducer is illustrated in Figure 5.6.

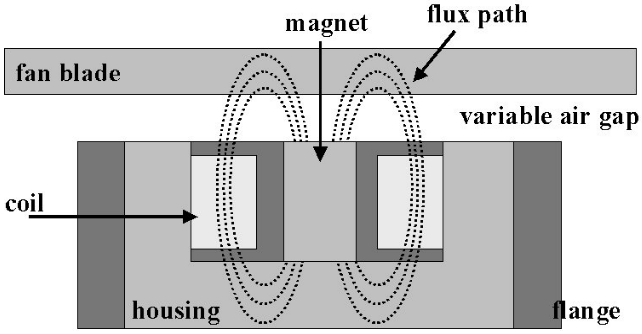


Figure 5.6: Variable reluctance transducer

The permanent magnet provides the magnetomotive force (mmf) $\mathfrak{I}$ required to induce the flux within the materials of the magnetic circuit. The reluctance $\mathfrak{R}$ in the circuit is the total opposition to the introduction of the flux Φ, and in this case is the sum of the reluctance of the steel transducer housing and fan blade $\mathfrak{R}_c$ with the reluctance of the small air gaps $\mathfrak{R}_g$. The reluctance of the steel is constant, however the air gap reluctance varies as the blade vibrates.

$$\Phi = \frac{\Im}{\Re_c + \Re_g}$$

$$\Re_c = \frac{l_c}{\mu_c A_c} \quad and \quad \Re_g = \frac{l_g}{\mu_g A_g}$$

$$e(t) = N\frac{d\Phi}{dt}$$

where l is the mean length of the core/air gap
m is the permeability of the medium
A is the cross-sectional area of the medium
e(t) is voltage across the coil
N is the number of turns in the coil
g subscript refers to the air gaps
c subscript refers to the steel components

Combining the above equations gives

$$\therefore e(t) = N\frac{d\left(\dfrac{\Im}{\Re_c + \Re_g}\right)}{dt}$$

The reluctance of the steel components can be considered negligible when compared with the air gaps

$$e(t) \approx N\Im\frac{d\left(\dfrac{1}{\Re_g}\right)}{dt}$$

$$e(t) \approx \text{constant} \times \frac{d\left(\dfrac{1}{\Re_g}\right)}{dt}$$

In other words, the voltage generated in the coil e(t) is dependant on $\Re_g$, but $\Re_g$ is dependant on blade angular and axial position relative to the sensor. Therefore e(t) is dependant on the amplitude of the steel fan blade vibration.

In practice, the magnetomotive force was induced with a cylindrical neodymium permanent magnet. These magnets have a much higher mmf than more traditional ferrite magnets. A coil consisting of approximately 500 turns of

0.8mm enamelled copper wire was wound onto a plastic bobbin to fit around the magnet. Flying leads provided electrical connections.

The transducer was embedded into the flange of the fan hub from the underside, and a small recess ensured the minimum air gap was consistent. A protective shielding was constructed to protect the leads carrying the signal until they were fed internally through the hub.

Figure 5.7 shows an acoustic transducer that has been inserted into one of the three blade mounts of a standard fan hub. When a blade is in position, the device is magnetically coupled to the blade, and produces a current proportional to the rate of change of displacement of the blade relative to the mounting surface of the flange. The impacts from the trash and billets force the blade to vibrate and hence generate a signal.

Figure 5.7: Transducer mounted in hub flange

The acoustic transducer was mounted on a primary extractor fan assembly for static testing. Cane billet impacts were simulated at different places on the fan blades, with the fan both static and rotating. An oscilloscope was used to visually verify the relative performance of the alternate mounting positions. During this stage of the testing, it was observed that impulse events occurring on the non-instrumented fan blades were identifiable. These signals were similar to those of the instrumented blade, only attenuated, so the use of one transducer – not three – was confirmed.

Before the system could be tested on a harvester in the field, a method to transfer the signal from the rotating fan to the stationary frame of the harvester had to be investigated. The method chosen was a rotary transformer.

5.2.3 Rotary Transformer

The traditional primary extractor fan assembly is quite complicated with many different sleeves, some static and some rotating. A simplified illustration of the assembly is indicated in Figure 5.8.

This view of the lower end of the fan assembly has been greatly simplified and such things as the lower stability bearings mounted on the stationary support sleeve have been ignored. All members in this diagram would be rotating when the extractor fan is operating except for the indicated stationary support sleeve. A hydraulic motor supplies the driving force to the fan and is coupled to the internal spline drive shaft. This illustration provides an appreciation of the difficulties involved in creating a method to transfer the necessary measurement signal.

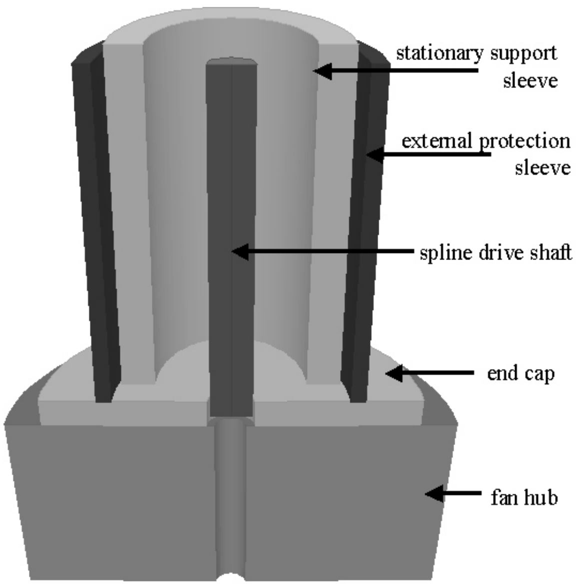


Figure 5.8: Simplified illustration of modern primary extractor fan assembly

To collect the signal generated by the fan blade transducer on the harvester the air-gap interface between the rotating-member and the machine had to be bridged. Many techniques are available to accomplish this, but in this case a passively induced rotating transformer was selected. A rotating transformer is simply a transformer that is constructed so that the primary can freely rotate about the pick-off, or vice-versa. A great deal of experimentation and many prototypes were attempted, and a selection of these will be presented in this section.

In the research by Pandey and Billingsley (1998), a similar situation was encountered. This work implemented a primary coil wrapped around the outside surface of a cylindrical rotating member, and a signal was induced across to a stationary pick-off that had a 'c-shape' that was beneficial to completing the magnetic path. This method proved satisfactory, however in the extractor fan case, other more efficient alternatives were considered to improve the level and quality of the transferred signal.

Each rotary transformer prototype had some common design elements and these will be briefly discussed here. In general terms, the transformer was considered as two halves: a primary, and a secondary. The primary was always attached to the rotating member, and hence also rotated. The primary loop was constructed from 0.8mm enamelled copper wire – the same as the transducer - and the number of turns required for maximum power transfer was calculated by matching the transducer coil impedance to the load coil which in this case doubles as the transformer primary coil.

$$\text{Length of primary coil} = \text{Length of load coil}$$
$$2\pi R_P \times N_P = 2\pi R_L \times N_L$$
$$N_L = \frac{R_P}{R_L} N_P$$

where R_P is the radius of the primary coil
R_L is the radius of the load coil
N_P is the number of turns of the primary coil
N_L is the number of turns of the load coil

For example, the transducer coil radius was 18mm, the load coil radius was 139mm and a nominal 500 turns was wound as the primary coil. Using these values, it was calculated that the load coil should consist of 65 turns.

The configuration of the transformer's secondary coil varied considerably during the concept development, from a 'c-shaped' pick-off to a radial pick-off. In each iteration, the transformer secondary coil consisted of a larger number of turns than the transformer primary coil to achieve a voltage transformation that was equal to the turns ratio. So in fact a small step-up transformer was constructed and winding as many turns as possible on the pick-off optimised the 'step-up' ratio of the transformer.

Some more specific examples of the development of the rotating transformer will now be discussed.

Initially a pair of wire loops was constructed to determine their suitability for signal transfer. Each loop was enclosed completely in a conductive material cover, and these were aligned on top of each other, and were only separated by a small air gap (Figure 5.9). This simulated the two halves of the signal transfer problem.

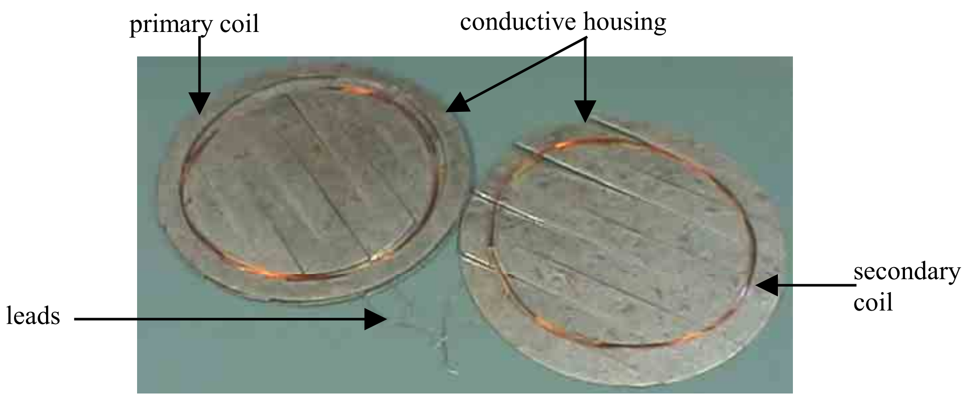


Figure 5.9: Initial passive transformer concept of two coils enclosed in a conductive housing

This method was satisfactory in a laboratory environment, however modifications were necessary to the casings (in the form of a series of small slits along their length) to reduce the effects of eddy current losses. A major disadvantage of this transformer was the physical logistics of winding the two coils on location in a harvester. Also, this passive transformer did not provide repeatable results, and the concept was not robust enough for the intended environment.

The next configuration was the first to be tested in the harsh measuring environment of the sugar cane harvester's primary extraction chamber. It was very similar to the original concept of winding the primary coil around the exterior of the main shielding shaft on top of a 'money-chain' arrangement of mumetal strips. Mumetal was selected because it was readily available at the time of manufacture, and the result is illustrated in Figure 5.10. In this case the secondary coil was a number of wire loops wrapped around a 'c-shaped' configuration of laminar strips taken from a small power transformer block. The concept was to induce the signal across the gap by creating an almost complete magnetic loop between the rotating mumetal strips across to the stationary pick-off, similar to the magnetic path described in Figure 5.13.

In this very early case of the system, the transducer was embedded in the flange of the hub, and the two fly leads were run up the exterior of the shielding shaft to the contacts of the primary coil of the rotary transformer. The pick-off of the transformer was suspended the necessary distance from the primary coil via a protective cylindrical shield that was clamped to a small stationary lip at the top of the extractor fan. This part of the instrumentation was completely sealed via another disc shield that was clamped to the exterior of the shielding shaft, which has not been illustrated here.

This method was not particularly robust and proved to be unreliable in the field. The main reason was the failure of the external wire that ran directly from the transducer to the primary winding contacts, despite the use of strong fasteners. These trials were not completely hapless however, and a small amount of data was collected, as well as a greater appreciation of the harshness of the measuring environment.

Figure 5.10: First concept field trials of the rotating transformer without (left) and with stationary cylindrical shield. A circle in the right-hand picture has indicated the pick-off device

From this trial, two things were clear. Firstly, all components of the system should be ready to be installed directly in the field, and should not have to be manufactured on site. This became clear because of differences in conditions between winding the primary coil onto the fan shaft in the field, compared with the test rig. Also, ready-to-install products are substantially more reliable and robust with more repeatable results. Secondly, it was decided that to provide the necessary robustness of the instrumentation equipment, the best solution would be to run the wires of the system up the inside of the main drive shaft of the extractor fan. This required an extensive study of the fan assembly, and considerable further development.

The first implementation of this approach was installed internally in the primary extractor fan. The terminals from the transducer signal were coupled to the transformer primary coil that was mounted on a nylon spool (Figure 5.11). This spool was attached to the upper surface of the drive shaft end-cap, and hence formed the rotating member of the transformer. The transformer secondary winding was stationary, and acted as an inductive pick-off from the primary coil. The pick-off was mounted on the lower end of a piece of cylindrical PVC piping that was inserted down the inside of the stationary support sleeve of the fan. The pipe was inserted from the top of the fan, once the hydraulic motor had been removed, and was lowered in alignment with the primary coil. The leads were then fed out of the top of the fan motor, and returned to the cabin of the harvester.

This method provided more successful results than previous efforts. The system proved to be quite robust during harvesting conditions and the quality and quantity of data returned was significant. However after a significant amount of time in the harvester, the system was dismantled, and it was noticed that the bond between the PVC tube and the nylon spool had failed, resulting in the disintegration of the pick-off. This was attributed to the high temperatures that would have resulted from the bearings that were located in close proximity. The noise from these bearings was also induced onto the returned signal.

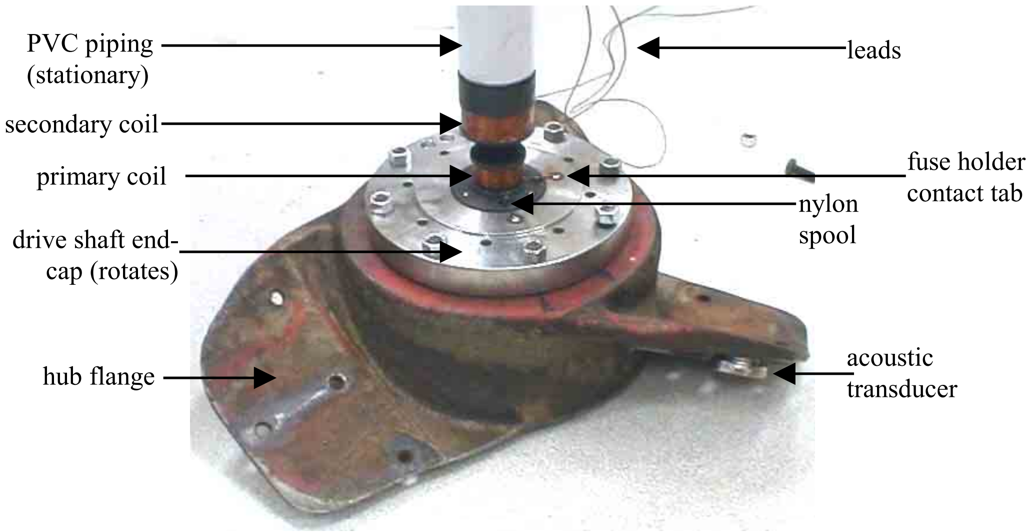


Figure 5.11: First internal rotary transformer

These findings were considered when developing an improved method. This concept was similar, but in this case the transducer signal was coupled to the transformer primary coil that was mounted on a metal spool, as illustrated in Figure 5.12. The transformer primary coil was clamped near the top of the internal spline shaft of the drive mechanism, and hence rotates also. The wire leads from the transducer were traced through the fan hub and end plate, and were secured to the exterior of the drive shaft. The transformer secondary winding was stationary and was mounted on a PVC spool that was clamped to the inside of a metal cylinder housing. This housing fitted neatly in the small space between the rotating and stationary internal members of the fan shaft, and was inserted from the top after the hydraulic motor was removed.

The small hole that has been machined into the wall of the sleeve allows the factory speed sensor to be operational. This sensor operates on similar principles to the variable reluctance transducer described in §5.2.2, and detects the teeth of the motor coupling once the fan is rotating.

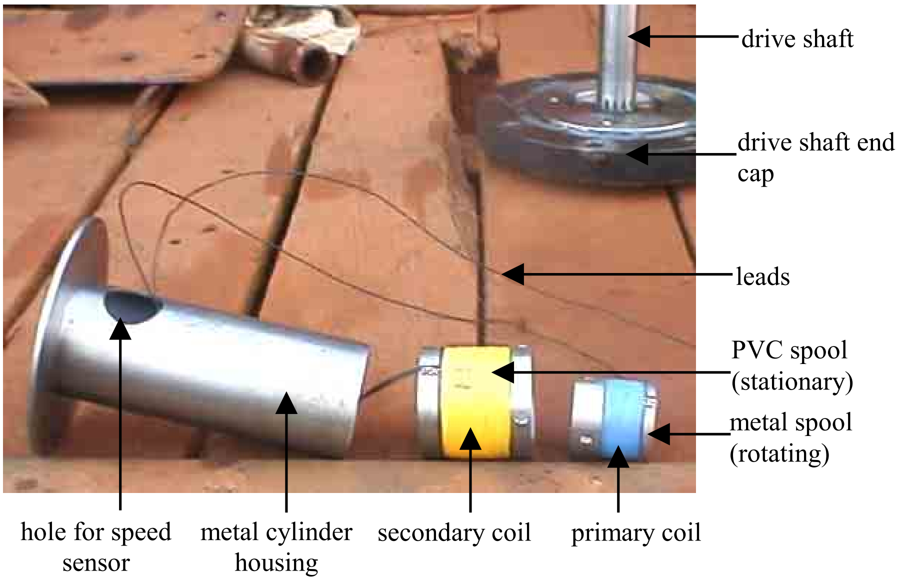


Figure 5.12: Final version of rotary transformer (foreground), and drive shaft in end cap (back-right)

The material selections described above provided the necessary magnetic path to be created that allowed for the impact signal to be induced across the small air gap (Figure 5.13). Similar to the previous iteration, the leads were then fed out of the top of the fan motor, and returned to the cabin of the harvester.

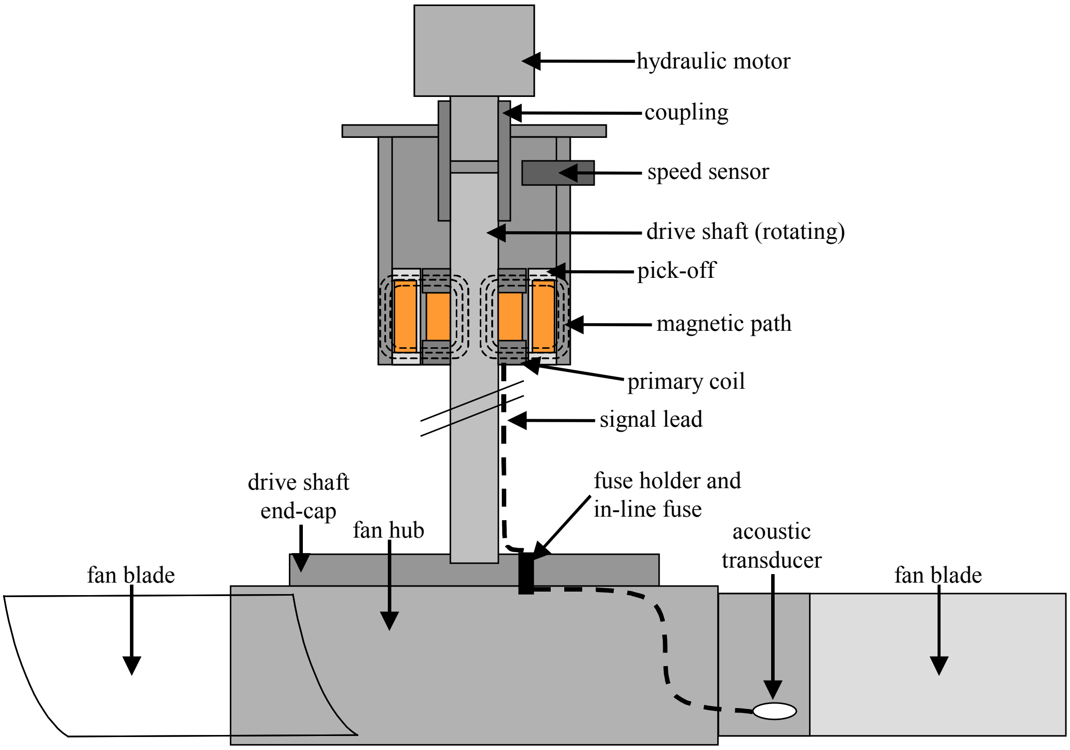


Figure 5.13: Simplified rotary transformer

For a completely modular system that could be quickly installed and would not hinder regular maintenance, the last mating face of the assembly to be addressed was the fan hub to the end-cap of the drive shaft. This was relatively simple to accomplish by inserting one end of a fuse holder in the fan hub, and the other end in the end-cap. One of these ends was spring-loaded, and this ensured that the contact was always in tension. The two ends were aligned, and a small piece of iron rod was substituted as the contact instead of a fuse. The two tabs near the primary nylon spool, seen in Figure 5.11, were the contact points for the two fuse holders.

This final rotating transformer system provided amplified output voltages when the primary coil was excited, and low noise levels were observed. The results were repeatable and reliable, and perhaps most importantly the system was very robust in detecting billet impacts that would allow an indication of cane loss to be determined.

5.2.4 Signal Interface

The implementation of the acoustic transducer coupled to the rotating transformer proved to be mechanically sufficient to survive the harsh measuring environment in the primary extractor fan chamber. The levels of signal did suffer some attenuation because of the system, and this was mainly attributed to the effect of the air gap between the primary coil of the transformer and the stationary pick-off. To alleviate this effect, a simple interface signal-processing module was designed and constructed to condition the signal, and to raise the signal amplitude to a level suitable for recording and processing. The amplifier configuration is shown in Figure 5.14.

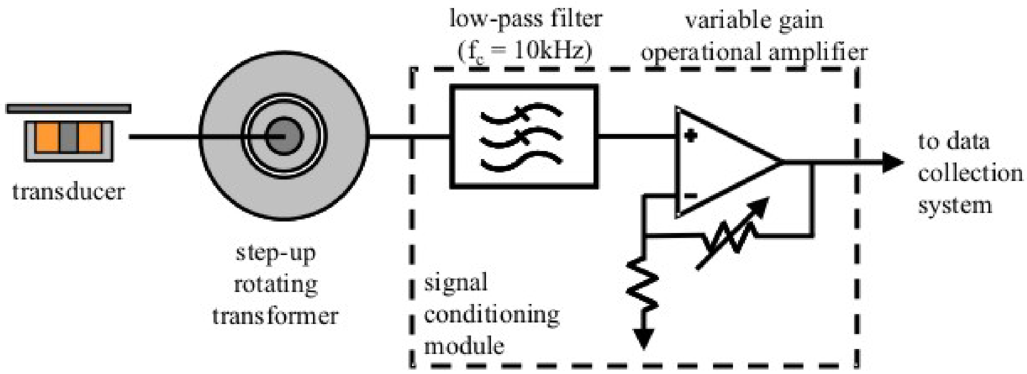


Figure 5.14: Signal interface module containing conditioning and amplifier

The first stage of the module was a simple low-pass filter that had a corner frequency of 10 kHz that reduced the effects of the inherent high-frequency electrical noise from the cane harvester chassis. This was most important when observing the raw analogue output from the system, and to reduce inherent noise in the signal before adjusting the sample rate to optimise the performance of algorithms later described in Chapter 6. Following this was a variable-gain operational amplifier stage that provided sufficient gain to provide a useful signal for recording.

The entire system was assembled in a laboratory to simulate the primary extractor fan system. A signal generator was connected in place of the transducer, and the output (after the signal interface module) was monitored to investigate the effects of the signal frequency and the air gap separation between the primary coil and pick-off. The expected dependence of the signal level to the air gap size and coil alignment was observed. For a constant small air gap, which was realistically approximated at 3mm, the amplitude versus frequency characteristic of the system was measured and the response over the expected frequency range was acceptable. This test was repeated with impulse inputs, and once again the observed output characteristics of the signals were suitable for this application.

5.2.5 Data Acquisition Technique

Initially, the output from the signal interface module was recorded primarily to assess the hardware design. Once the system returned repeatable quality results, the necessary signal processing would be implemented to give a cane loss measurement.

Various analogue-to-digital techniques were investigated to capture the returned signal on a laptop computer. After much investigation, it was decided to digitise the cane loss detection system's output by the microphone-input channel of the laptop's onboard soundcard. This ensured that the data returned from the transducer mounted in the fan hub was collected as raw audio files. The configuration of the signal recording equipment is shown in Figure 5.15.

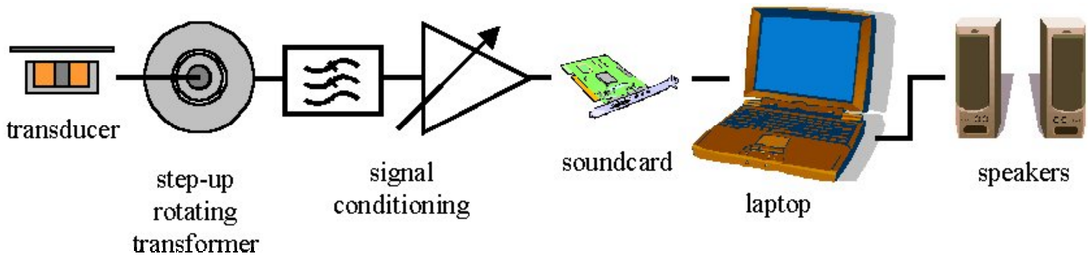


Figure 5.15: Data collection system used for initial trials

The dc power for the instruments was sourced from one of the harvester's two 12V batteries. The chosen mixing software recorded the returned signal at a sample rate of 22kHz and an 8-bit resolution. The signals were also monitored via the playback option, and by utilising this it was possible to subjectively discriminate both visually and aurally billet impacts from trash and ambient noise under different harvesting conditions.

5.3 Chapter Summary

An improved method of assessing cane loss has been described in which cane billet impacts on the primary extractor fan blades are detected by an audio transducer. The signals from this transducer are coupled from the moving blades to the stationary frame, where these signals are collected for analysis.

Chapter 6

Sensory Separation System Results

6.1 Introduction

A suitable prototype sensor system has been developed and proved to be robust in the measuring environment. In this case, the application was to detect in the primary extraction chamber of an operating sugar cane harvester. The installed hardware enabled a large quantity of data to be collected, and this has been recorded in a useful format to be analysed. Figure 6.1 demonstrates a sample of the data recorded from the final prototype.

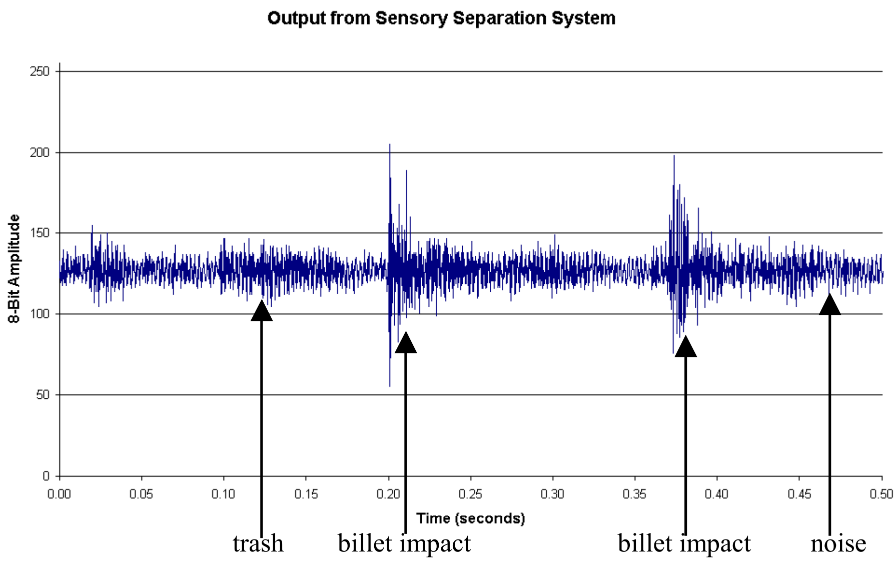


Figure 6.1: Sample including billet, trash, and other noise overtones*

Significant investigations were undertaken to determine the most appropriate method of discriminating the billet impact 'count' from the other inherent data on the recordings. The main task was to separate the cane billet impact signal from mechanical vibrations and trash noise and then to deconvolve this signal to give an impulse event. All of this must be performed in real time. Also it is desirable to minimise computing requirements.

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

The purpose of the initial data analysis was to establish the validity of the sensing concept and later to generate a numerical assessment for cane loss. Once the data from the most reliable and successful hardware had been recorded, the signal required conditioning to convert it to a more appropriate form. The expected outcome of the system was to provide a useful value of cane loss by quantifying the signal returned from the sensing system, and this in turn was to be provided in a suitable format to carefully monitor the operation of the sugar cane harvester.

Samples of recorded data are provided here to compare with the development iterations of the cane loss hardware. It was envisaged that this information would be used to close the control loop and provide a complete feedback system.

6.2 Early Detection Systems

The nature of the recorded signal was expected to consist of characteristic peaks that would indicate billet impacts masked within inherent machinery noise. In practice this assumption was found to be correct, however it was initially assumed that the signal-to-noise ratio would be a lot smaller than it was in reality. This assumption hindered the early development stages but provided valuable experience in the measuring environment.

In this section, samples of the data recorded at various development stages is provided, and there is a discussion of necessary hardware changes that were made to suit the measuring environment.

6.2.1 Simulated Field Trials

Development of the measuring system for the primary extractor fan went through many phases. To assess the suitability of preliminary designs a static test rig was constructed with an operational fan assembly.

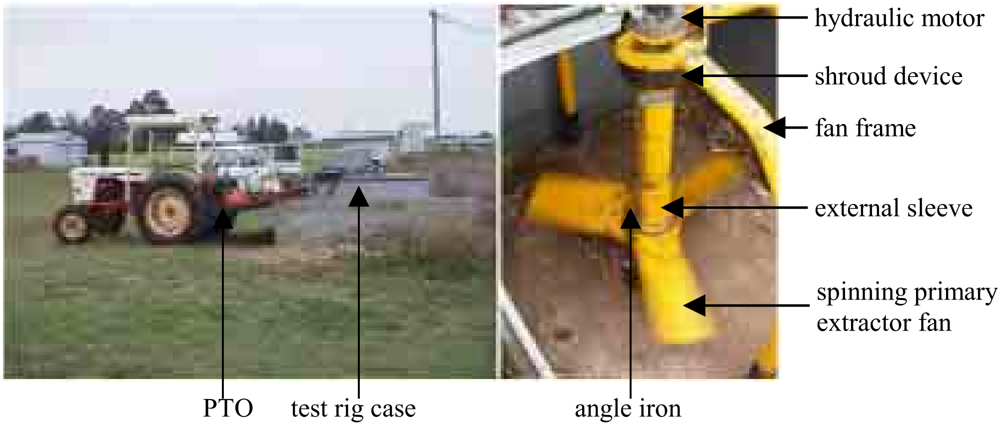


Figure 6.2: Test rig for simulated primary extractor fan trials

The test rig that was assembled is illustrated in Figure 6.2. The picture on the right shows a spinning primary extractor fan, and at the time this picture was taken a very early form of the instrumentation was in place. This consisted of a transducer mounted in one of the hub flanges, with the signal leads to the transformer primary coil being mounted on the outside of the external sleeve. In the early stages, lengths of small cross-section angle iron were fitted to protect these wires. At the top of the fan, half of the shroud device can be seen. A hydraulic motor was mounted on the top of the fan drive shaft, and the motor was supplied from the power takeoff (PTO) of the tractor shown on the left of Figure 6.2.

Figure 6.3 illustrates a sample of the original data recorded from the test rig. The waveform represents one second of data that contained a detected impact, and a more detailed view of this is also illustrated. It should be noted that the initial sampling frequency for the system was 6 kHz on one channel with 8-bit resolution.

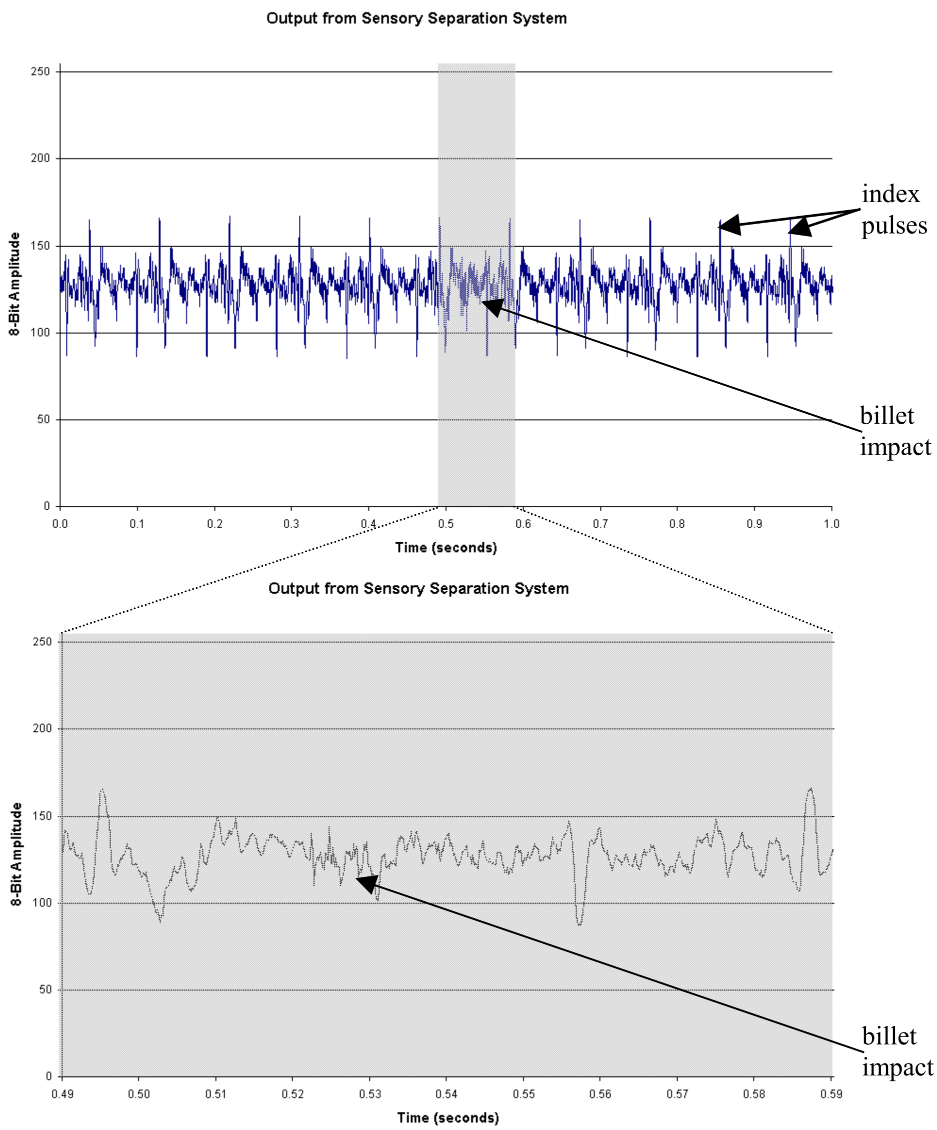


Figure 6.3: Samples recorded from instrumented test rig: upper waveform has an impact indicated, and this is shown in more detail in the lower waveform*

The upper waveform of Figure 6.3 indicates that the signal had cyclic characteristics that could be attributed to the influence of such things as mechanical vibrations and bearing noise. The signal had very low signal-to-noise ratio, and as a result it was difficult to accurately determine the occurrence of an impact. Fortunately the data was recorded as audio files, and by listening to a playback the exact location of an impact signal could be determined.

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

It should be noted that the number of billets impacting the blades of the primary extractor fan was limited because they were manually placed in the simulated extraction chamber. This allowed a visual identification of the billets on the recorded signal, and ensured that the number of billets placed in the system consistently matched the number identified in the collected data.

As can be seen in Figure 6.3, the useful information contained in the recorded signal was very difficult to identify because of the high noise content. To simplify this, a technique suggested by Pandey and Billingsley (2000) was implemented to help alleviate the low signal and high noise issue. This technique involved a method of attenuating cyclic noise with an algorithm that averaged the cyclic ‘rumble’, and then differenced this from the newly received signal in real-time to extract the relevant data.

A similar method was attempted in the separation system application. A reference pulse was induced into the collected data by introducing a magnet onto the rotating shaft of the fan, and this provided a signal that indicated the start of a revolution. This allowed an adaptive noise template to be created that was continuously updated, and this cancellation sequence could be applied to the current cycle to attenuate cyclic noise.

A neodymium magnet, similar to the one used in the audio transducer, induced the index pulse. These magnets have a much higher magnetic field strength than ferrite magnets and so a strong index pulse could be induced. In consequence, a significant amount of freedom was allowed when positioning it relative to the stationary pick-off. Some care was needed when placing the magnet on the shaft to ensure that the induced signal was identifiable from the returned signal without saturating the input of the data collection device.

Figure 6.4 illustrates the implementation of the magnet on the external sleeve of the primary extractor fan. Note also the ‘money-belt’ arrangement of mumetal strips the primary coil was wound onto, on the external sleeve (as discussed in Chapter 5).

Also an early form of the pick-off can be seen. In this iteration the pick-off was two radio-frequency chokes connected in series that were mounted in a cast-aluminium box and were placed in close proximity to the primary winding.

Figure 6.4: Magnet placed on rotating fan sleeve to superimpose index pulse onto recorded signal to indicate start/end of a revolution for post-processing

A typical sample of data from this system is illustrated in Figure 6.5. At this stage the substantial influence of noise on the signal was reduced, and the extraction of the necessary impact data required only a simple application of the cyclic filtering algorithm. Please note that these trials on the primary extractor fan test-rig were conducted at approximately 600 rpm, which is about half the actual operating speed in practice.

This system allowed early trials to be conducted that assisted with the original development and testing of the concept. However to properly assess the suitability of this technique, trials on a harvester were required.

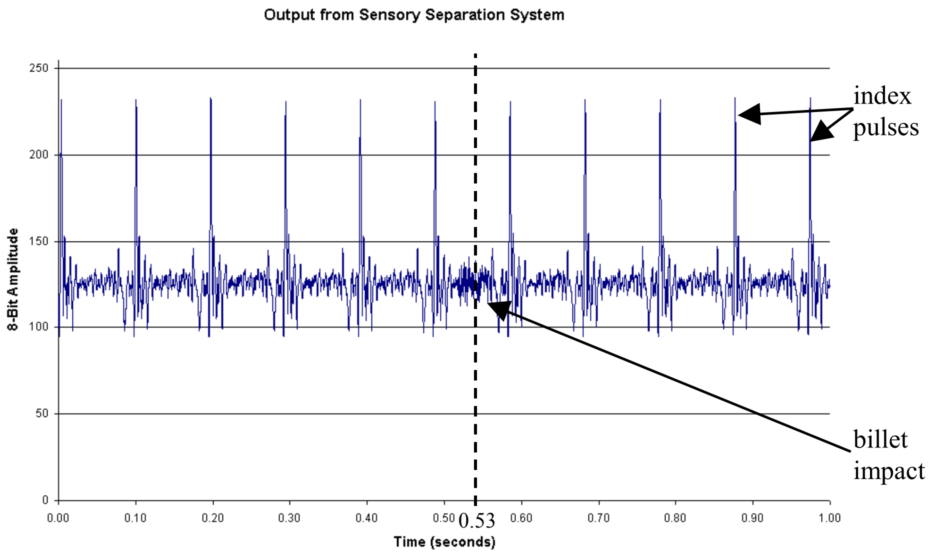


Figure 6.5: Recorded sample from test-rig with a billet impact at 0.53 seconds, and a clear induced index pulse on the signal*

6.2.2 Cane Field Trials and Preliminary Results

The application of the developed technology from the test rig to an operating sugar cane harvester was considered relatively simple, but in reality this transition provided new complications. The new issues ranged from basic installation difficulties through to system robustness problems that were described in Chapter 5.

One unforeseen issue was the physical difference in operating conditions between the test rig and the intended measuring environment, and this difference also became evident in the recorded data. More specifically, the laboratory trials were conducted at approximately 500 rpm and the test rig was bolted to a concrete surface, whereas in practice the primary extractor fan operates at approximately 1000 rpm, and is mounted high up on the harvester.

Figure 6.6 shows a sample of recorded data. A major difference from the laboratory trials was apparent here because the signal-to-noise ratio of the system was improved markedly, and because of this there was no need for the cyclic averaging post-processing. The measurement environment of the test apparatus

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

had higher levels of localised vibration than those experienced on the harvester, and thus the inducing of the index pulse was no longer required. This was advantageous because it was felt that the index pulse masked a section of each revolution's data.

Also, it was noted from returned data (e.g. Figure 6.6) that the amplitude of the index pulse varied, and this was attributed to a 'wobble' in a slightly unbalanced extractor fan.

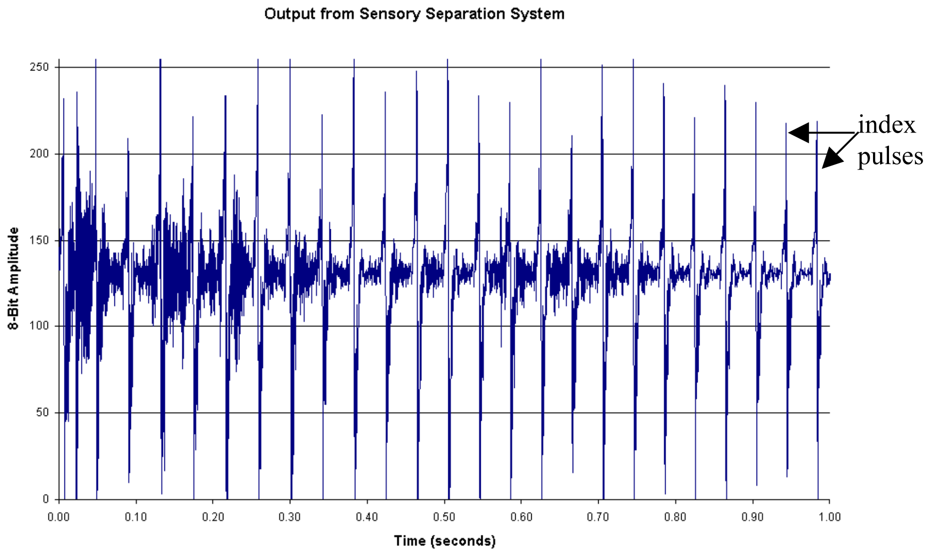


Figure 6.6: Recorded sample from extractor fan with induced index pulses*

Figure 6.7 illustrates a sample of data with identifiable activity that was aurally verified as billet impacts. As can be seen from the upper waveform there was considerable activity within a short time period, and the signal-to-noise ratio was now greatly improved than in the simulated trials. The lower waveform in this figure is a more detailed view of a particular billet impact, and is indicative of the decaying sinusoid characteristic that was consistently observed.

An important point that was obvious from any of the billet impact signals was the large variation of these in the recorded data. It seemed that no two impacts were identical, and this was explained firstly by the high level of variation in the physical attributes of the ejected billets, and then by the orientation of the billet

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

at the point of contact. Also the level of signal recorded depended on the position on the blade on which the impact occurred, and even which blade was struck. Large quantities of data were now recordable, and the next step was to extract the useful signal from the inherent noise, and then to deconvolve the impact signal to obtain a real-time measurement of cane loss. All of the algorithms that were developed had the same criteria of robustness to the different billet impact possibilities, as well as time-efficiency.

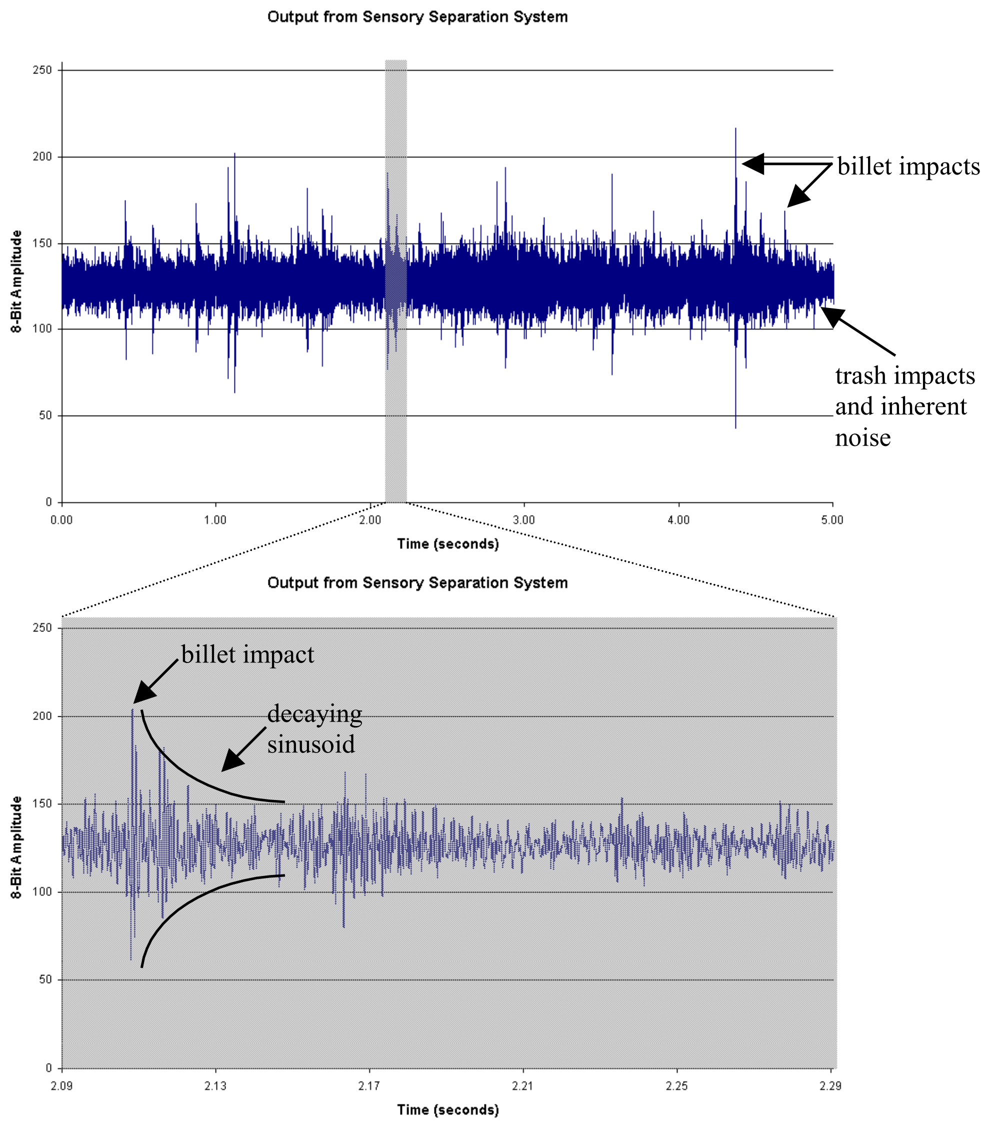


Figure 6.7: Sample recorded from instrumented cane harvester: upper waveform was a longer time sample, and a section of this is shown in more detail in the lower waveform*

* Audio sample is accessible by 'clicking' on the hyperlinks in the dissertation CDROM

6.3 Frequency Analysis of Sensory Separation System

The resonant nature of the billet impact signal has been identified both in the theoretical calculation of the natural frequency of a fan blade in Chapter 5, and in the samples of collected data that have been included in the previous section of this chapter.

The high level of oscillation that was characteristic of a billet impact provided an interesting deconvolution problem. Ideally the signal that provided the measure of cane loss should be an impulse with minimal noise content. However the high levels of vibration that occurred in the measuring environment complicated the extraction of the useful signal from the collected data. The initial analysis of the numerous noise components on the recorded data was difficult in the time domain, but fortunately this was much simpler in the frequency domain.

It should be noted that once the design of the sensory separation system started to consistently return quality data, the sample rate of the recorded data was increased to 22 kHz on one channel with an 8-bit resolution. The higher sampling rate increased the Nyquist frequency, and this allowed a broader view of the signal. If more detail was required at lower frequencies, the resolution of the sample's spectrum was increased by down sampling with desktop audio-processing software.

Figure 6.8 shows the test sample that was used for a majority of the signal analyses. This sample was selected because it contained what was judged to be the three most likely circumstances to be present in the recorded data: billet impact, trash noise, and engine noise. The different noises were discriminated visually, and were objectively classified by their amplitude, intensity and duration. This sample will be illustrated wherever appropriate in the following discussion for convenience.

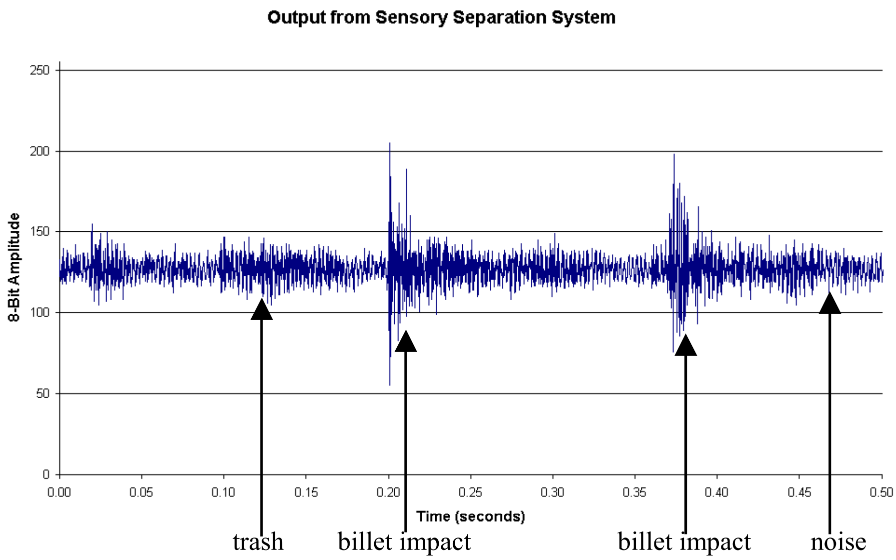


Figure 6.8: Sample including billet, trash, and other noise overtones*

Note that the independent parameter in the waveforms illustrated for analysis purposes will generally be referred to as time (in seconds), even though the signal has been digitised and is not continuous.

6.3.1 Spectrogram of Recorded Signal

The spectrogram, as shown in Figure 6.9, is a common way to display audio signals. The audio signal is broken into short segments, and generally a Fast Fourier Transform (FFT) is used to find the frequency spectrum of each segment (Smith 1997). These spectra are aligned, and converted into a grey-scale image, the more abundant a frequency (the greater a signal's amplitude component within a specific frequency range), the brighter the display colour. This method provides a graphical method of observing the frequency response relative to time.

The spectrogram has been aligned with the original test sample, and it can be seen that there were several consistently dominant frequencies across the whole test sample. The two major impact signals result in strong influences from the range of frequencies up to the Nyquist frequency. The natural frequency of the cantilever beam, predicted in Section 5.2.1 to be approximately 2300 Hz in

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

response to an impulse event, can be identified as the boundary of the dominant frequencies in Figure 6.9 – in this case, the horizontal boundary between the predominately light and dark regions.

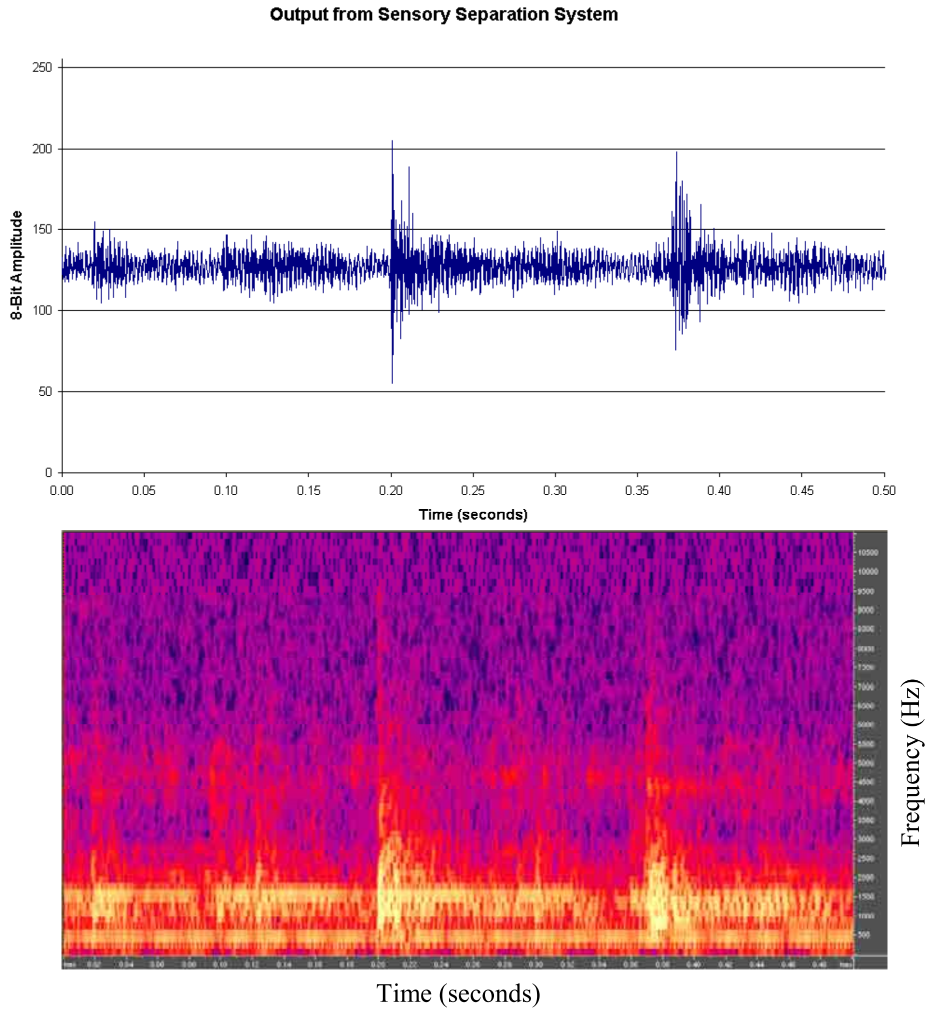


Figure 6.9: Spectrogram (below) of test sample (above) at 22 kHz with 8-bit resolution

6.3.2 Discrete Fourier Transform of Recorded Signal

The spectrum of the test sample was further analysed with more accuracy and clarity by the implementation of a Discrete Fourier Transform (DFT) that yielded the results illustrated in Figure 6.10. The DFTs were calculated by correlating the input test signal with each basis function. The sample was firstly processed with a Blackman window to reduce the abruptness of the truncated ends and thereby improve the frequency response.

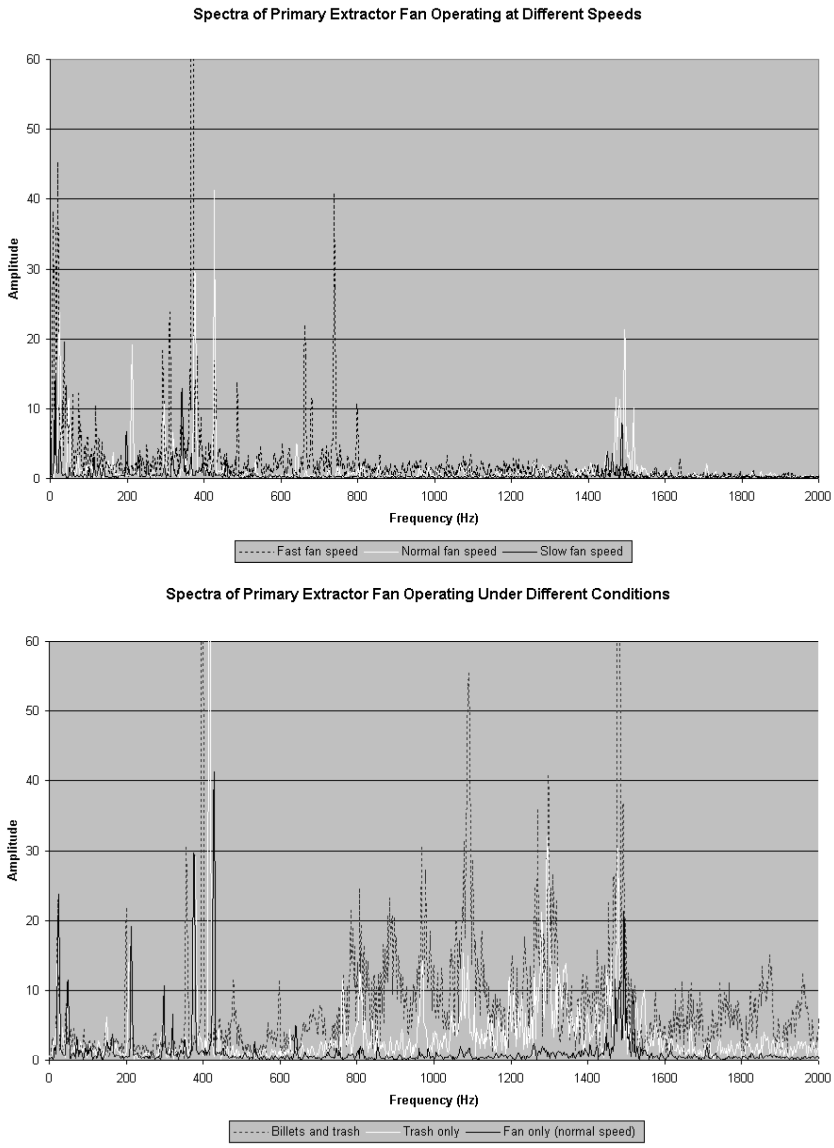


Figure 6.10: DFT of samples demonstrating characteristic frequency responses: different fan speeds (above) and different operating conditions (below)

The top spectrum of Figure 6.10 illustrates the characteristic frequencies of the extraction chamber system with only the fan spinning at three different speeds. This spectrum shows the inherent frequencies that were present in the system and these were attributed to characteristic noise signatures of the machinery. As the fan speed was increased, the frequency components became more dominant. In particular, it can be seen that the peaks at 500 Hz and below, 600-800 Hz, and 1500 Hz were a result of miscellaneous noises created by mechanical vibrations and other inherent sources. Another likely cause of the strong peaks was considered to be either a result of the induced cyclic bearing noise, or some imperfection in one of the magnetic fields of the rotary transformer. Also, in Table 5.1 of §5.2.1, it was predicted that the natural frequency of the instrumented fan blade was approximately 500 Hz, depending on the mass of the blade, and this can be verified in Figure 6.10.

In the lower spectrum of Figure 6.10, there are three larger peaks at approximately 1.1 kHz, 1.3 kHz and 1.5 kHz. These three peaked frequencies would each represent one of the fan blades when impacted with the ejected material: 1.5 kHz was the instrumented fan blade, and the other two frequencies were impact echoes detected by the other two fan blades. Even though the spectrum indicates that these are the dominant frequencies, there is a substantial noise level that tends to surround the signal in the frequency range of interest.

The high levels of spectral noise from 800 – 2000 Hz were attributed to the impacts on the fan blades by the many objects being ejected from the extraction chamber. The lower end of this range would have been billets, both whole and damaged, as well as other more dense materials. The higher end of this range represented the large quantity of separated trash.

This spectrum analysis was particularly useful when determining the validity of the sensory separation system because the quality and level of information encoded in the recorded samples could be more easily verified than in the time-domain.

6.4 Discrete Time-Series Analysis of Sensory Separation System

Samples of collected data have been illustrated, but the required outcome of these analyses was to determine the most appropriate method to quickly and accurately determine a measure of cane loss to close the control loop on the fan speed operation.

Several approaches were attempted in the time domain to simplify the quantifying process by eliminating the time-consuming task of transforming the information from time to frequency domain. The following section will discuss the approaches that yielded interesting results.

6.4.1 Statistical Analysis

The collected data is a time series containing useful information that can be used to measure cane loss. Statistic analysis is a useful tool to interpret numerical data, and more specifically, the histogram is a simple way to visualise the mean and standard deviation of an acquired signal (Smith 1997).

The histogram displays the number of samples there are in the signal, and contains the number of occurrences of each of these possible values. The sum of all the values in the histogram is equal to the number of samples in the signal.

$$N = \sum_{i=0}^{M-1} H_i$$

where Hi is the number of samples that have a value of i

N is the number of occurrences of a sample in the signal

M is the number of possible values that each sample can have

The test sample was divided into three equal sections, and the histogram of each was plotted in Figure 6.11. Note that the histogram is normally rotated 90 degrees and placed at the side of the signal it represents.

For this analysis, the recorded sample rate of the signal was retained so the number of samples was maximised, and this allowed the histograms to have smoother appearances. For convenience, the illustrated histograms were focused on the resolution values that were non-zero.

The three histograms in Figure 6.11 show a clear variation in the amplitude (height) and the standard deviation (width), while the means are all the same, as expected with a stationary signal. The two sections containing the billet impacts (sections 2 and 3) had a much higher width to height ratio compared to section 1, and this indicates that were peaked signals rather than one concentrated about the mean. In other words, the sections containing the billet impacts (sections 2 and 3) had higher standard deviations than the section without billet impacts (section 1). This technique was a useful tool to weight the occurrence of each value of resolution, but the utility of its application as a measurement at this level was dubious.

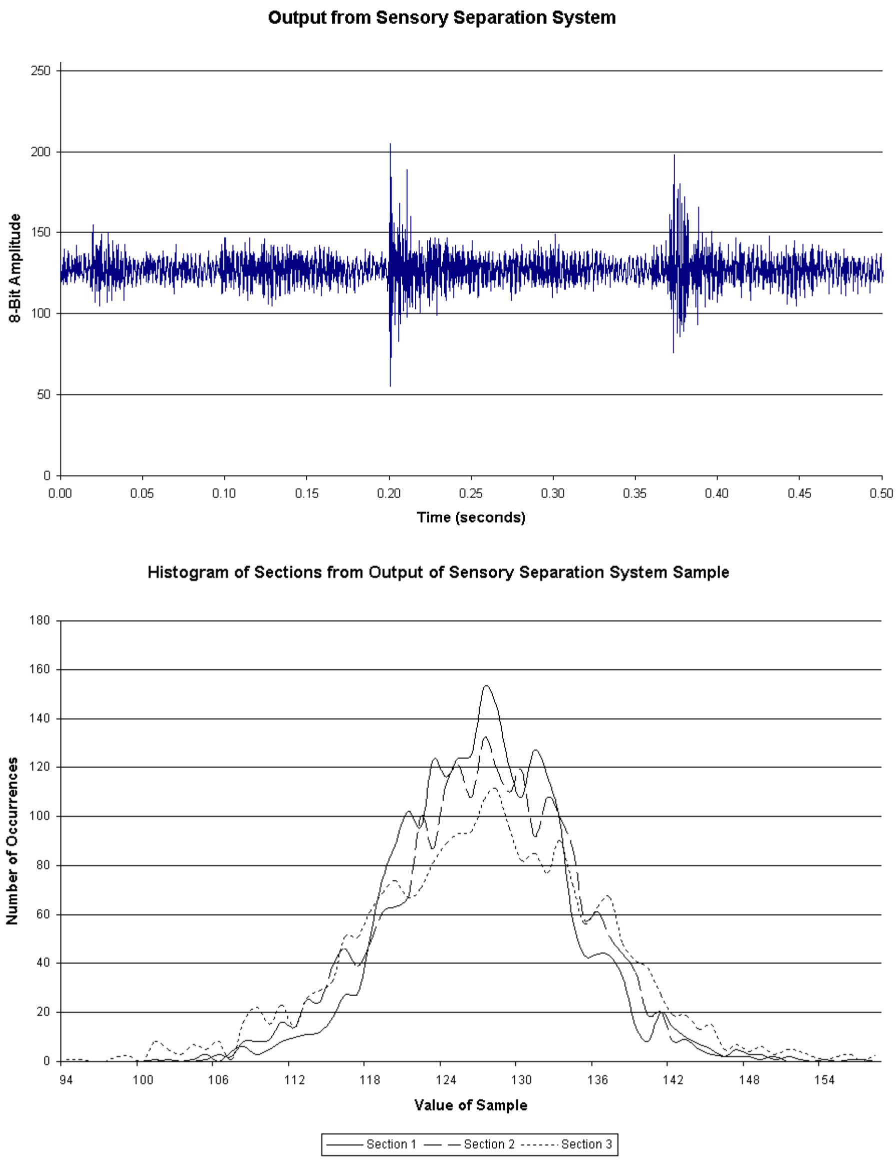


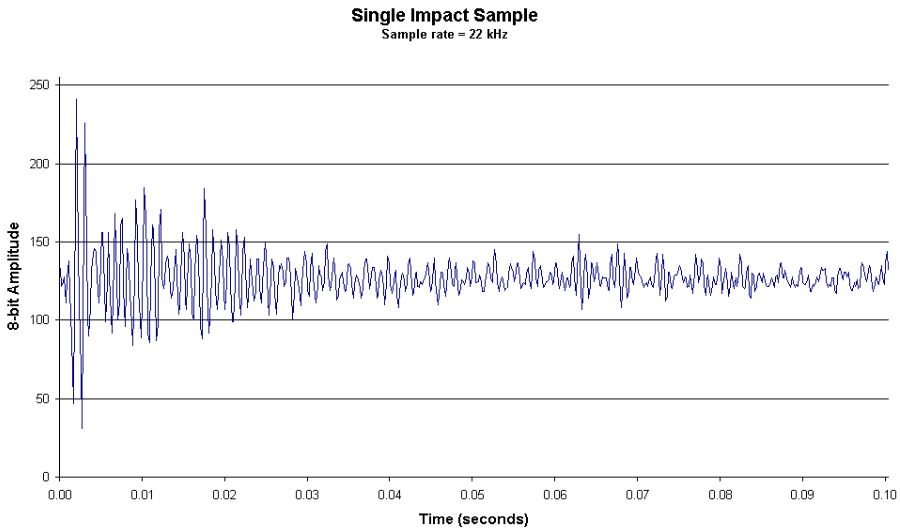
Figure 6.11: Histogram (below) of three sections from test sample (above)

6.4.2 Correlation Functions

Correlation is the optimal technique for detecting a known waveform in random noise (Smith 1997). The autocorrelation function of a zero-mean random signal $r_{xx}[k]$ is defined as the correlation between two samples x[n] and x[n+k] separated by a time lag k (Orfanidis 1996). It is a measure of the dependence of successive samples on the previous ones.

$$r_{xx}[k] = \frac{1}{N}\sum_{n=0}^{N-1} x[n]x[n+k]$$

Figure 6.12 shows the autocorrelation function for the single impact sample. In these cases, the input impact signal was down-sampled to minimise the computing requirements. The illustrated autocorrelation function reinforced what was already know from the DFT of the sample data, that is, the stationary series had a high oscillatory nature, and this signal was significant many lags after the zero-lag peak.



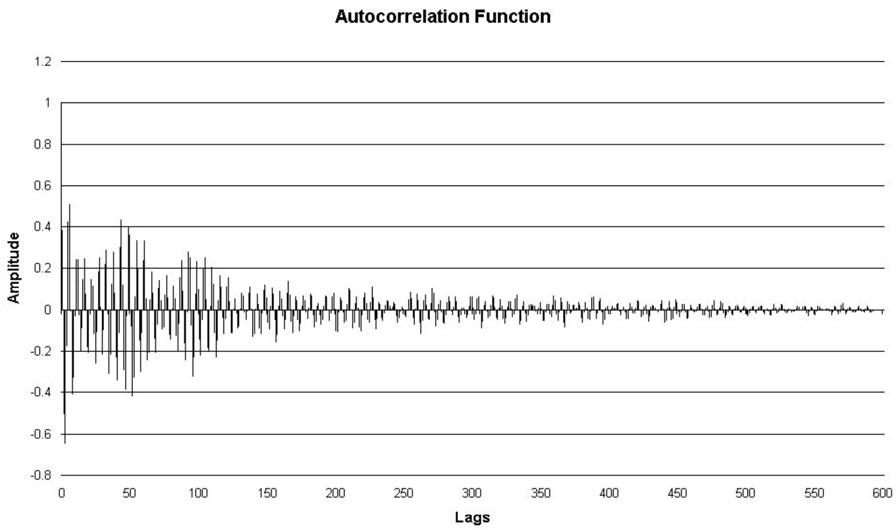


Figure 6.12: Autocorrelation function (below) for single billet impact (above)

Similarly, the cross-correlation function $r_{xx}[k]$ is defined as the similarity of a signal x[n] with a delayed version of another signal x[n+k].

$$r_{xx}[k] = \frac{1}{N}\sum_{n=0}^{N-1} x[n]y[n+k]$$

The cross-correlations of two functions with the original test sample are illustrated in Figure 6.13. When cross-correlated with the test sample, both the single impact signal and the generated tone indicated activity by amplitude peaks at the lags corresponding to where impacts were visually determined to have occurred.

Even though the content of the recorded signals had been determined to contain impact data as well as other inherent noise, correlation was a useful tool to establish the level of oscillation in a cane billet impact signal, as well as another option to automatically determine the occurrence of an impact. Unfortunately this method does require considerable computing resources.

6.4.3 Matched Filters

Matched filtering involves the correlation of a known signal with a target signal being detected using convolution (Smith 1997). The amplitude of each point in the output of signal was a measure of how well the known signal matches the corresponding segment of the input signal. When the input sequence is fed into an appropriate matched filter, the output does not necessarily look like the signal being detected (Lynn & Fuerst 1998). In fact, the output waveform should be a noisy version of the autocorrelation function. To implement this technique the matched filter signal must be known, but in this application the billet impact signals were considered too dissimilar.

Another approach was to use a filter signal sample of a characteristic signal, for example 1.5 kHz from the DFT of Figure 6.10. This approach resulted in an output waveform similar to an autocorrelation function, with peaks corresponding to the two central values being higher than the surrounding oscillations. This method would have been more appropriate in applications where the target signal is more identifiable with fewer oscillations, and as can be seen here the extra computing did not provide any outstanding results. Also the high noise content in the pass-band of the input signal was transmitted which is reinforced by the output signal and thus impeded successful detection of the impact signals.

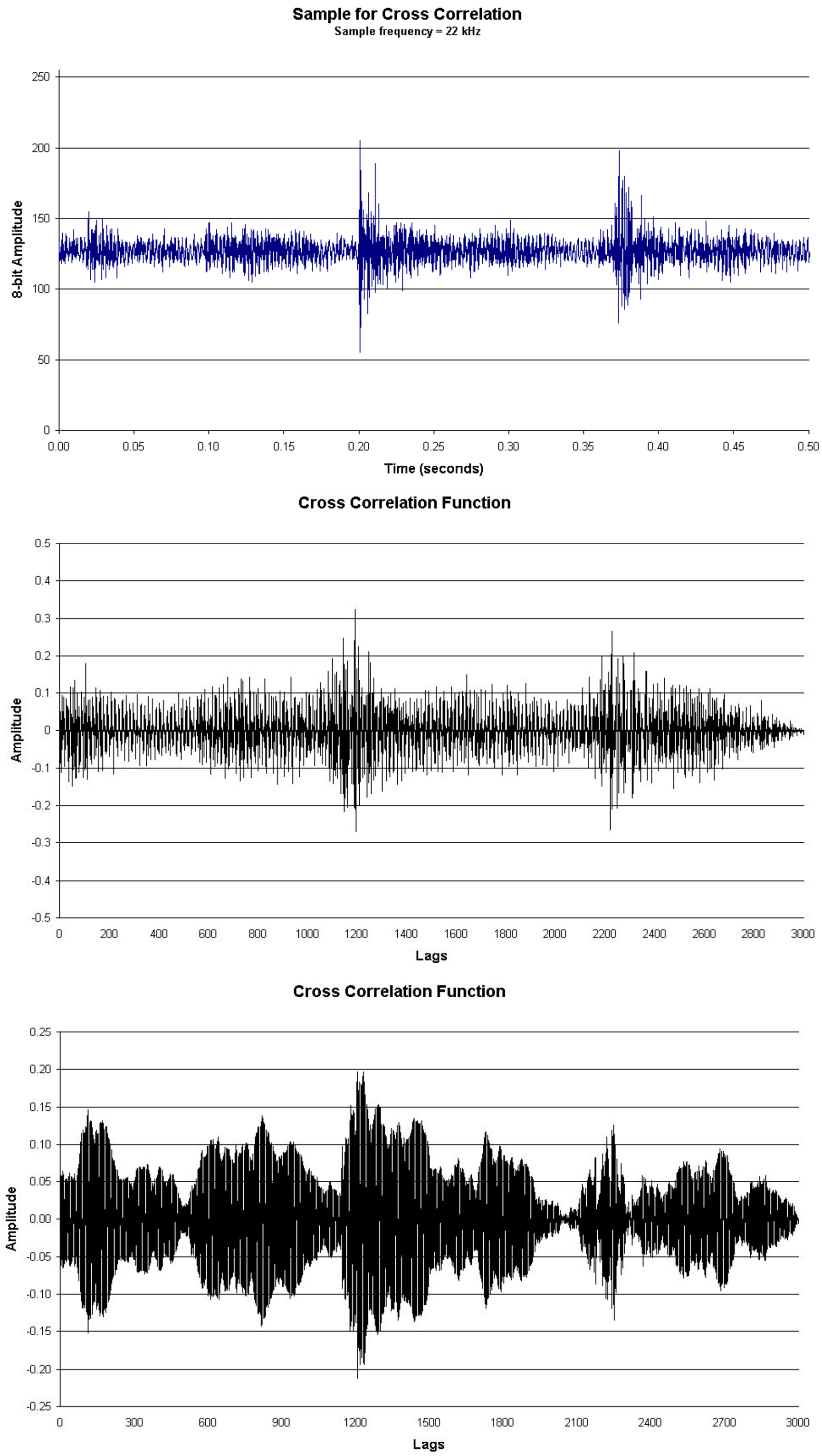


Figure 6.13: Cross-correlation functions of test sample (top), with single impact signal (middle) and a generated 1.5 kHz sinusoid

6.4.4 Moving Average Filter

The moving average is the most common filter in digital signal processing, because of its simplicity (Smith 1997). Despite this, the moving average filter is optimal for reducing random noise while retaining a sharp step response, which is ideal for time-domain encoded signals.

The moving average filter may be implemented as an explicit convolution of the input signal with a rectangular pulse of unity area. The filter pulse may be either averaged on one side, or symmetrically, the only difference being that one side implementation introduces a delay to the output signal.

A much faster algorithm was the moving average filter by recursion, which was a more implicit form of convolution.

$$y[i] = y[i-1] + x[i+p] - x[i-q]$$

where x[] is the input signal
y[] is the output signal
M is the (odd) number of points in the moving average
p = (M – 1) / 2
q = p + 1

This method uses both the input signal and previously calculated output values, and for this reason the equation is recursive. This filter is unlike other recursive filters because while these generally have an infinite impulse response (IIR) composed of sinusoids and exponentials, the impulse response of the moving average is a rectangular pulse (finite impulse response FIR).

The execution speed of this algorithm can be appreciated for a few reasons: regardless of the filter length only two computations are required per point; the only operations required per iteration are a simple addition and subtraction; and integer data types can be implemented because the samples were recorded with an 8-bit resolution. However, a cyclic buffer to hold the samples was required for this algorithm.

Figure 6.14 shows a typical output from a moving average filter applied to the test sample. In this case, the test waveform was down-sampled to decrease the computation time. The higher sampling rate was not integral with the moving average filter because the trends of the recorded signal would be similar, irrespective of the sampling frequency.

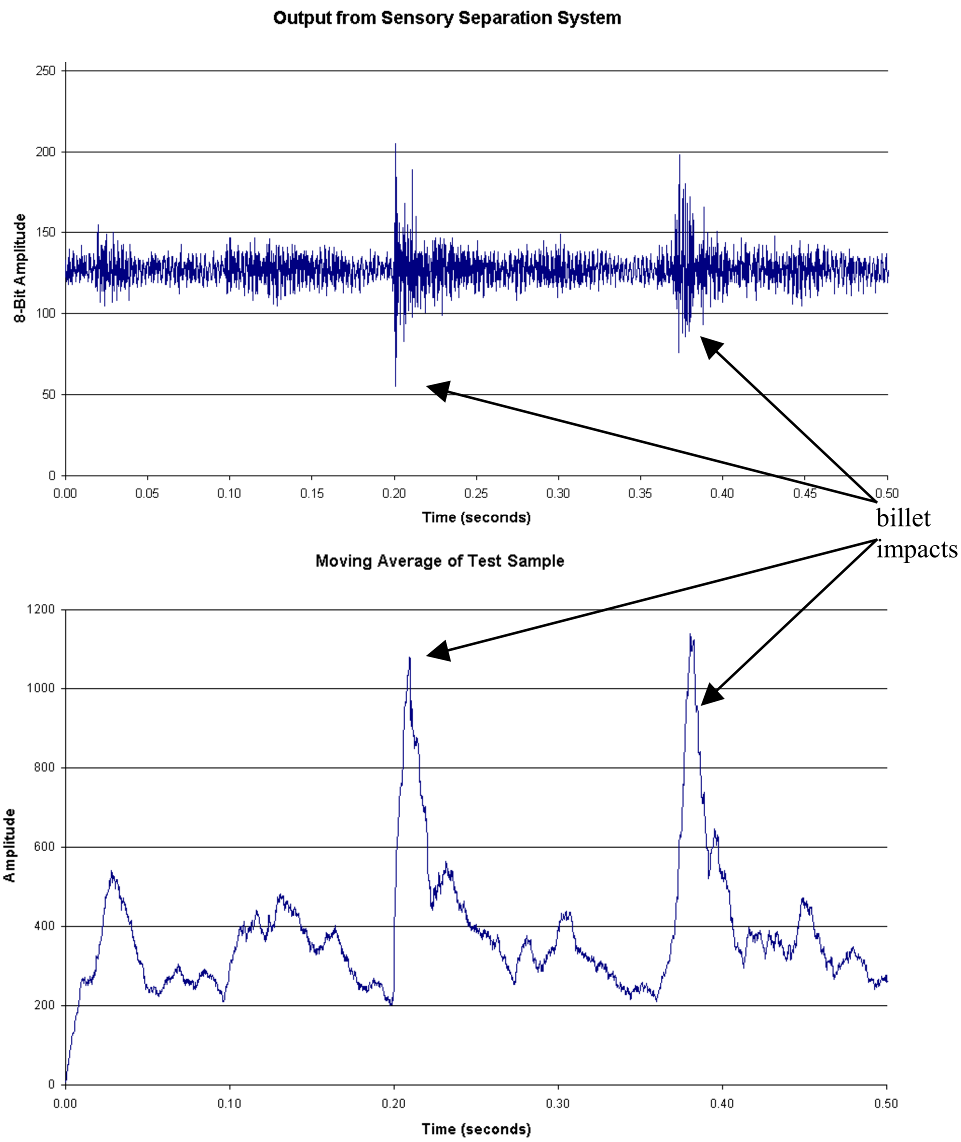


Figure 6.14: Moving average filter (M = 61) (below) applied to test sample (above)

The application of this filter was analogous to demodulating AM signals: the input signal was firstly rectified, and then the moving average filter was applied to the signal, which was equivalent to a low-pass filter in analogue terms. By implementing this variation in the algorithm, the output waveform was simplified to a trend line that followed the amplitude peaks. This effectively alleviated the high oscillatory nature of the input signal.

This output signal from the moving average filter indicates that an indeterminate input signal may be deconvolved with a relatively simple and time-efficient algorithm. The moving average filter is the optimal solution for this problem, providing the lowest noise possible for a given edge sharpness.

6.4.5 Frequency Filter

This type of filter separates signals based on their frequency spectra (Smith 1997). Some input signals have spectrum characteristics where at some frequencies there is mostly signal, while at others there is mostly noise. It follows that the frequencies that contain a large amount of useful signal should pass through the filter, while the noisy frequencies should be blocked. Once such implementation of this idea is the Wiener filter that then also considers the relative powers of signal and gain at each frequency to maximise the filter gain. In the case of the returned signal from the sensory separation system, the FFT of Figure 6.10 has already established that the frequencies of the billet impact signals were characteristic; however there was a high noise content across the spectrum and thus this implementation was considered inappropriate.

6.5 Implementation of Real-Time Filters

Various methods of extracting a useful measure of billet impact in any time period from the recorded signal of the sensory separation system have been discussed. However, to implement any of these techniques in actuality, many important practical factors must be considered and addressed. The filter must be capable of analysing an input signal in real-time with an acceptable level of performance, but also needs to be robust enough to manage subtle variations, and not be completely determined by the characteristics of the returned signal.

All of the discussed filtering techniques, except moving average, must be carried out by convolution, making them extremely slow to execute. It is for this reason that the moving average filter was considered to be the optimal digital filter for this application.

6.5.1 Digital Filtering

The implementation of a moving average algorithm to automatically detect the cane billet impact signals from the input signal was ideal for this application principally because of its reasonable performance levels with minimal computing requirements.

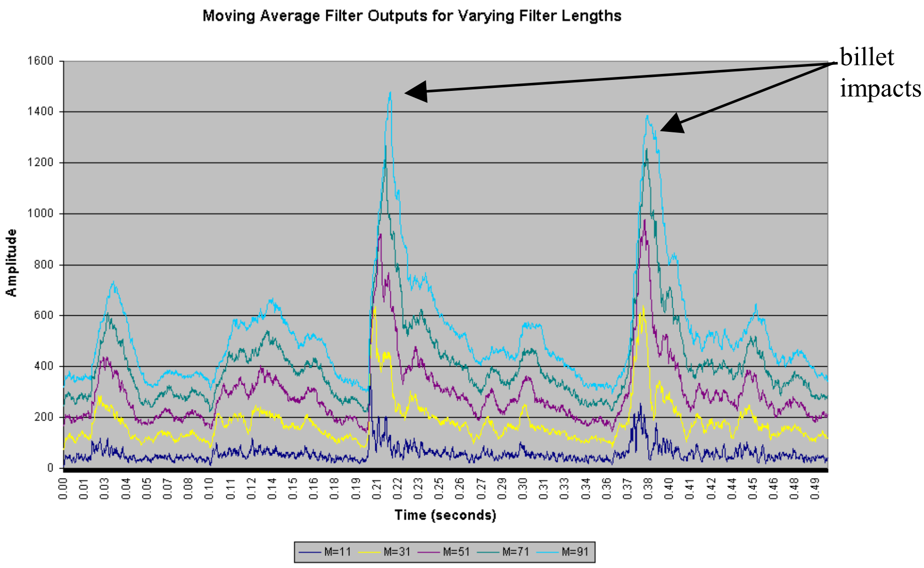


Figure 6.15: Outputs from moving average filters of varying window size applied to test sample

Of course once the filtering technique was finalised, fine-tuning of the system was required to optimise performance for a reasonable response time. Figure 6.15 indicates the effects on the output response when the test sample input signal was applied to moving average filters with differing windows sizes. It can be seen that as the number of points in the filter window increased the noise level was attenuated, however the edges to the impact signals became less sharp.

The data in Table 6.1 shows that there is negligible difference between either truncating or taking the absolute values of the input data about the DC level for the signal. The time (in seconds) for a selection of filter lengths is shown, and it can be seen that even the smaller windows yield good results with very small execution times.

Window (samples)	Absolute-value (seconds)	Truncated (seconds)
11	0.383	0.438
21	0.664	0.664
31	0.875	0.883
41	1.16	1.20
51	1.42	1.48
61	1.76	1.71
71	1.98	2.03
81	2.25	2.25
91	2.52	2.52
101	2.74	2.81

Table 6.1: Comparison of times for computations of oscillatory data

A compromise between the window size, output response and computation time had to be made, but from these results the optimum performance of this filtering technique can be easily verified.

6.5.2 Analogue Filtering

An alternative to introducing the developed digital time series in real-time to the measuring environment was to implement the moving average algorithm in analogue form.

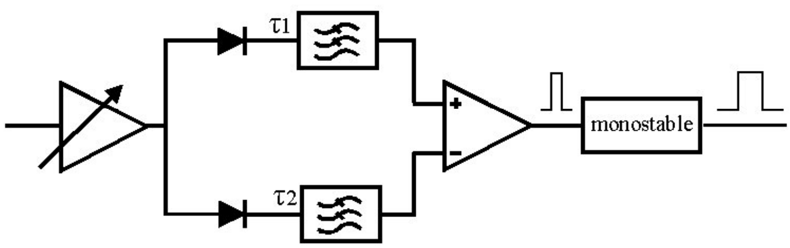


Figure 6.16: Block diagram of 'moving average' filtering

Figure 6.16 illustrates how this was achieved in practice. The input signal was buffered by a variable gain op-amp before the signal was split and truncated. The two signals were then passed to low-pass filter systems of differing time constants, t1 and t2, and the two developed signal envelopes were then compared against one another. The output of the comparator gave a logic high if the two input levels matched sufficiently, and the bandwidth of this output pulse was increased by the monostable.

This signal-conditioning module was constructed to interface with existing data collection hardware on a research sugar cane harvester. The constructed hardware detected billet impacts reasonably well, and this could be visually verified as in Figure 6.17.

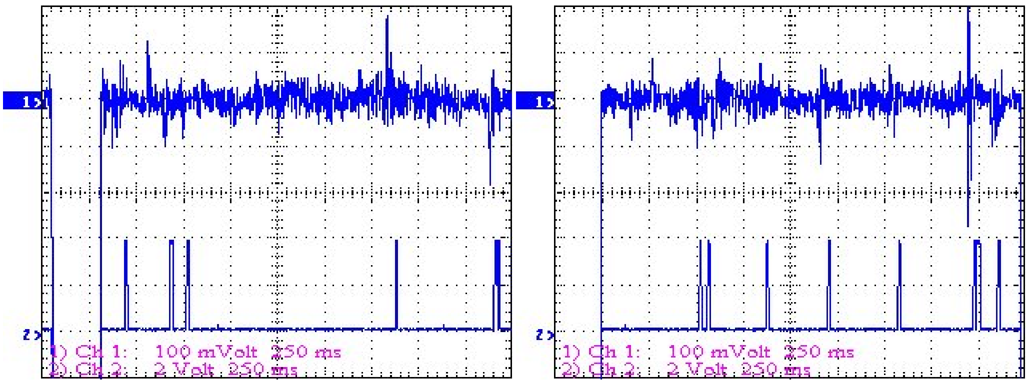


Figure 6.17: Output from oscilloscope with a test waveform as the top trace in each frame, and the TTL output from the analogue filtering (below)

The number of billet impacts could be determined easily by merely counting the number of peaks on the output channel. To further assess the system, field-testing was required.

6.6 Long Term Trials

The developed sensory separation system, and signal-conditioning module were fitted to an instrumented research sugar cane harvester for assessment under operating conditions. Figure 6.18 illustrates a sample of data that was collected from the developed detection during a harvest, and from this the correlation between cane loss and primary extractor fan speed can be seen. For this trial, the

fan speed was kept low for most of the time, and it is only at the initial period that the speed was increased (twice). It is clear that once the fan speed increased, the number of detected billet impacts also increased.
From the figure it can be seen that the system indicates only the extremes of cane loss, i.e. no loss or significant loss. It was assumed that these extremities occurred as a result of an over-sensitive signal-conditioning unit, as well as perhaps an inaccurate calibration of the unit in the field.

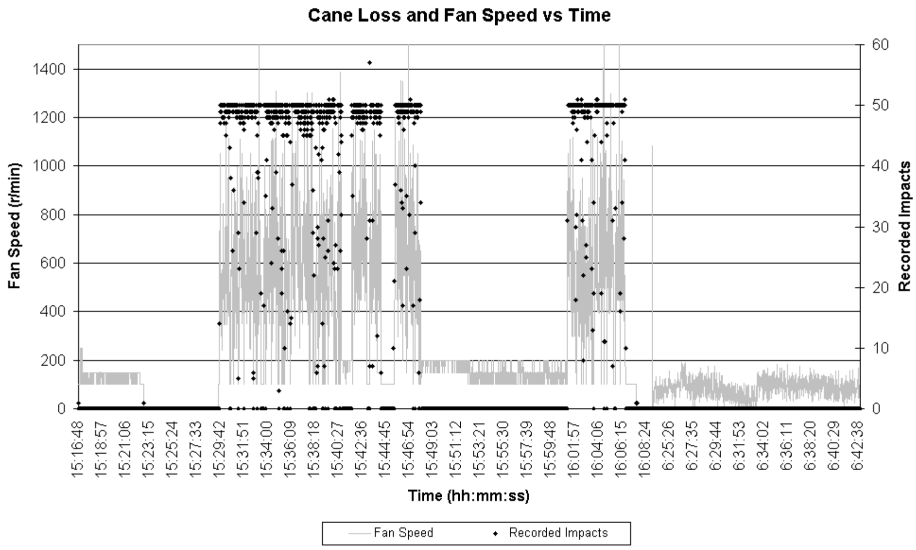


Figure 6.18: Sample result of sensory separation system with raw count of impacts

A clearer relationship between recorded impacts and fan speed is illustrated in Figure 6.19. In this figure the fan speed was sorted in ascending order with the corresponding impact count. A moving average trend-line was applied to provide more clarity by smoothing the raw data.

At this stage the output of the complete system is purely a measure of detected billet impacts on the blades of the primary extractor fan, which is an indication of cane loss. The developed signal conditioning algorithms consistently offer a high level (up to 80%) of accuracy from the input signal that was recorded from the sensory separation system.

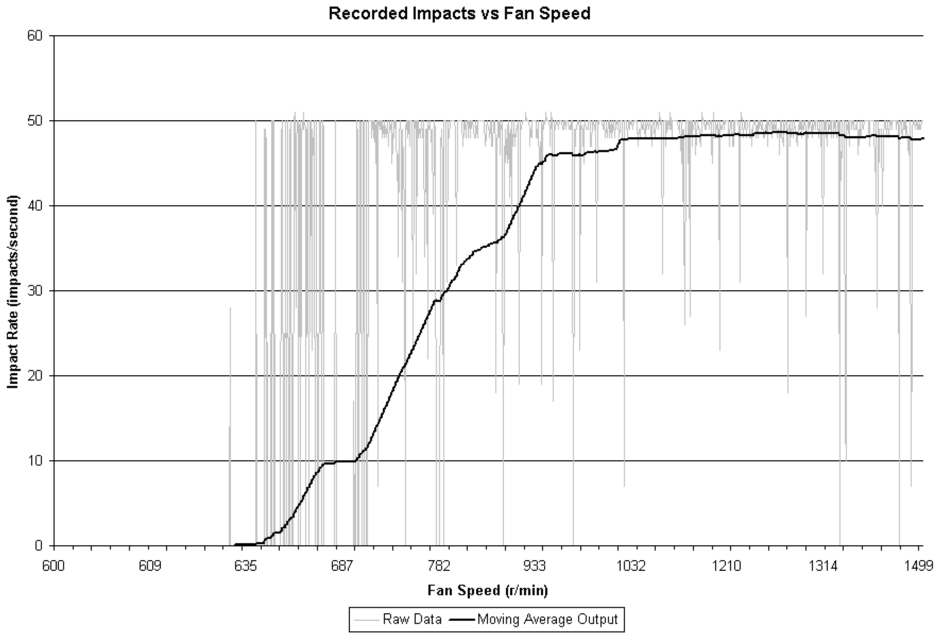


Figure 6.19: Relationship between recorded impacts and fan speed

6.7 Chapter Summary

This chapter demonstrated the returned data from the separation system at various stages during the development. Many design changes to the hardware were required even when the prototype had reached the field-testing stage because the differences between the simulated trials and the actual trails only became obvious then.

The returned data were analysed at many stages, firstly to establish the validity of the sensing concept, and then to assess the capabilities of each prototype. Once the data from the most reliable and successful system were recorded, the signal had to be conditioned to a more appropriate form. The expected outcome of the system was realised because cane loss was quantified from the returned signal. This in turn was to be provided in a suitable format to carefully monitor the operation of the sugar cane harvester.

Chapter 7

Sensory Topping System

7.1 Introduction

The preferred method in this area of the research was the direct measurement of sugar from the cutting interface between the topper and the cane stalk. Transducers for field use and laboratory chemical sensor methods were used to identify characteristics of interest. A novel version of the sensor that showed most promise was developed. This sensor is now at a stage where a sugar sample may be placed on its sensitive surface, and it produces a signal from which concentration can be calculated.

Figure 7.1: Harvester (left) with topper indicated, and a closer view

The topper is the first point of contact of the harvester with the cane stalk (Figure 7.1). Topping is an operation that occurs under extremely difficult conditions for the harvester operator. Continual monitoring and adjusting of the topper to an optimum height is often given very low priority and so it is not always performed efficiently. Investigations were conducted to determine the applicability of mechatronic tools in assisting the harvester operator's control of this function.

The topper of a harvester gathers, severs, and shreds the immature leafy material from the tops of the sugar stalks during the harvesting process.

Modern toppers are called ‘shredder toppers’ because of their ability to gather and shred the cane tops before discarding the waste back onto the field. Physically the topper is a large hydraulically powered, vertically rotating drum with many razor knives on the rotating drum and gathering walls.

The leafy upper part of the sugar cane stalk has very low sugar content compared with the stalk, and is consequently topped and dispersed back on to the cane field. A mature cane stalk is uniformly sugar-rich from the stalk down to the base of the plant. For cane to be accepted at the mill for processing, the stalk should ideally have been cut above the highest subterranean roots, and have been topped below the level of the growing point.

The topping height that gives the grower the greatest net return is the most desirable, and it is the stalk section (of up to 200mm) that separates the leafy top from the sugar-producing stalk, as shown in Figure 7.2 (B). This is difficult to identify visually, primarily because of the large amount of leafy material at the top of the stalk, but it is important to identify because over this space the sucrose content drops markedly. Currently it is the responsibility of the harvester operator to manually control the height at which the topper cuts the leaf from the stalk. The operator has no direct view of the actual cutting process because the back hood of the topper obstructs the view.

Cutting above or below the correct topping height yields equally unfavourable results. If the cut on the stalk is too high, a substantial quantity of leafy top is collected with the harvest, and this places greater demand on the cleaning system of the harvester. As a result the cane supplied to the mill is not as clean as it might be. If the stalk is cut too low, sugar-bearing stalk is wasted.

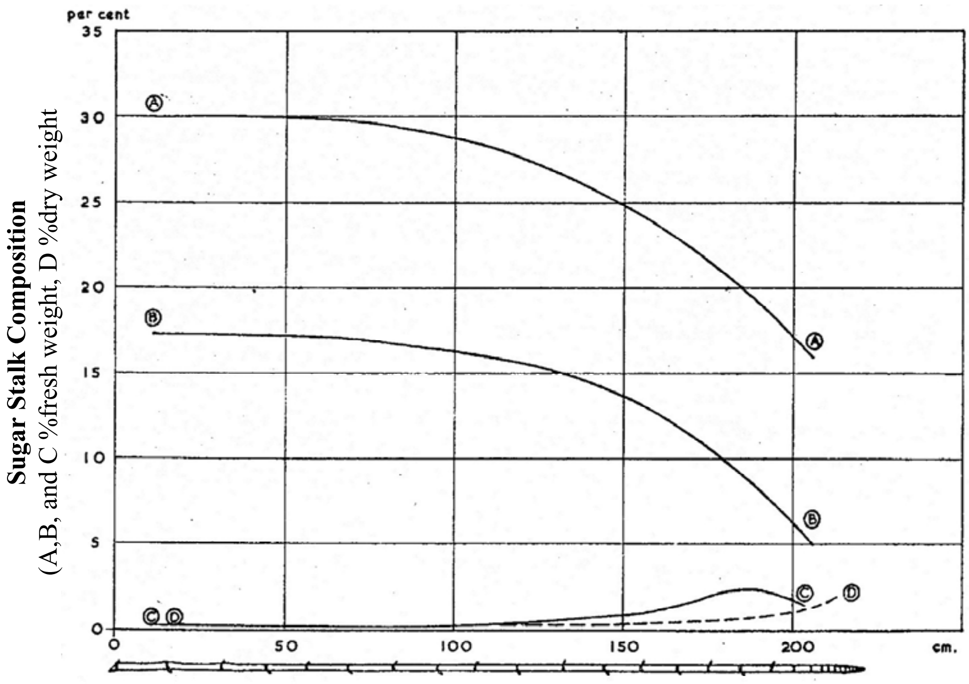


Figure 7.2: Composition of a ripening sugar cane stalk (Barnes 1964)

(A) Dry matter; (B) Sucrose; (C) Reducing sugars; (D) Nitrogen

7.2 Determination of Optimum Topping Height

Of the four principal regions of the sugar cane stalk: flower (or arrow), top (or leaf), stalk, and root system, it is only the stalk of the cane plant that contains a significant amount of sugar. To obtain an accurate and reliable measure of optimum cutting height in real time, it is proposed to introduce a mechatronic sensor to identify a characteristic property of the cane stalk to indicate the correct cutting height. In this case, 'real time' would constitute a measurement time of at least one second to ensure minimal lag time between the measurement of the cutting height and the application of feedback.

Before any instrumentation was attempted, a detailed study was undertaken to better understand the principle output of the sugar growing process, sucrose.

7.2.1 Properties of Sucrose

Sucrose is found in the juices of fruits and vegetables, and in honey, and the commercial sources are from beet and cane (Guthrie & Honeyman 1974);

sucrose is commonly known as sugar, and is the most common carbohydrate compound.

Sucrose is a pure disaccharide, resulting from the condensation of one molecule of each monosaccharide sugar glucose and fructose. Of the disaccharides, only sucrose and lactose are found abundantly in nature, and these are both considered to be sweet tasting, crystalline and soluble in water.

Carbohydrate	Relative Sweetness*
Glucose	74
Sucrose	100
Fructose	173

*Sucrose is assigned an arbitrary value of 100

Table 7.1: Relative sweetness of sucrose and its reducing sugars (eds. Pigman et al. 1970)

The sucrose molecule, α-D-glucopyranosyl-β-D-fructofuranoside, is shown in Figure 7.3. The empirical formula is $C_{12}H_{22}O_{11}$.

Acid hydrolysis of sucrose breaks the disaccharide sucrose into its constituent reducing sugars, and is usually performed at high temperatures to accelerate the process. The same hydrolysis is achieved by the enzyme invertase that is found in yeast, plants and animal digestive systems.

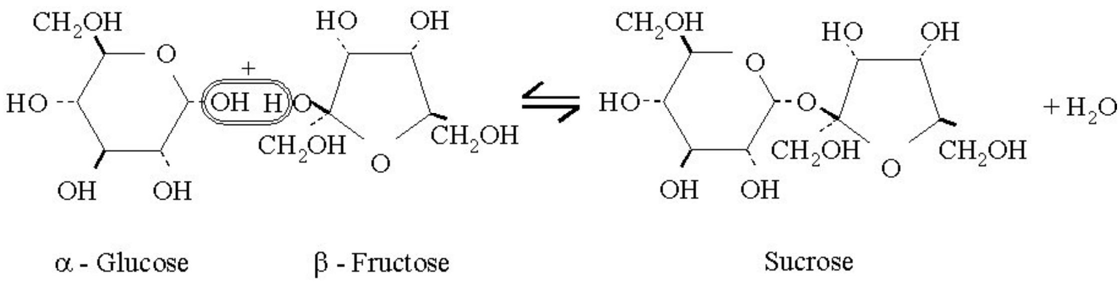


Figure 7.3: Chemical structure of sucrose (Bloomfield 1987)

Hydrolysis converts sucrose ($[\alpha]_D$ +66°) into an equimolar mixture of D-glucose ($[\alpha]_D$ +52°) and D-fructose ($[\alpha]_D$ -92°), and because of the high negative rotation of fructose, the final mixture has a net negative, or counter-clockwise, rotation (laevorotatory, $[\alpha]_D$ -20°).

For this reason, hydrolysis of sucrose is sometimes called the ‘inversion’ and the D-glucose, D-fructose mixture is known as ‘invert sugar’ (Guthrie & Honeyman 1974).

Sugar cane is harvested at a stage of maturity when maximum synthesis of sucrose has occurred. To minimise the hydrolysis of sucrose by the invertase in the plant, the sucrose must be extracted as rapidly as possible after harvesting (eds. Pigman et al 1970).

Sugar demonstrates many interesting properties at different concentrations. However, analysis of sucrose is generally only possible once the juice is extracted and is in a suitable form for the applicable sensor. Clearly obtaining a measurement of sucrose in real-time on the cane harvester is a challenging problem.

7.2.2 Measuring Environment

Before any measurement technique was attempted or even considered, a familiarity with the measuring environment was required. To achieve this, a miniature CCD camera was fitted inside a metal box (Figure 7.4) onto the topper in two alternate positions to collect video data.

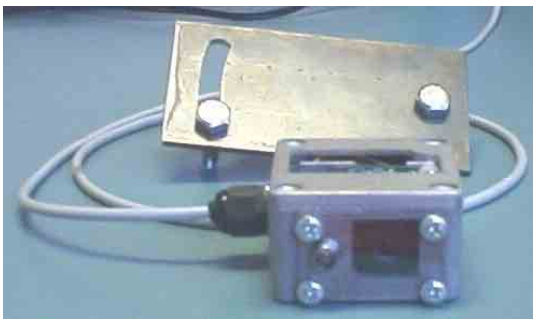


Figure 7.4: Manufactured camera box and adjustable mounting bracket

The box had a small aperture in one side for viewing, and this was covered with a small transparent sheet to protect the camera lens. The bracket was manufactured so that one end could be rotated about the other to simplify installation in the field. Figure 7.5 illustrates the camera box mounted on a harvester topper in the two arbitrary positions.

Figure 7.5: Manufactured camera box mounted on topper in two indicated positions: (a) at cutting interface, and (b) back of hood*

The output composite video signal from the camera was returned to the harvester cabin, and it was recorded on a DC video recorder. The video signal was also monitored by a portable DC television, and this was possible by modulating the video signal on the VCR and then tuning the television to the correct channel.

Figure 7.5 (a) illustrates the first position from which footage was collected. This view was of the initial cutting interface between the topper and the cane stalk, which at this stage of the harvesting process is still in the ground and generally upright. The lowest cutting point on the stalk is level with the bottom row of blades mounted on the topper drum. The video footage collected from this position did not yield much detail because of the large quantity of leafy pre-topped cane stalks entering the toppers.

The second position of the camera (Figure 7.5 (b)) allowed a view down at the tops of the freshly topped cane stalks before they were knocked down and fed into the mouth of the harvester. A sample of this footage is shown in Figure 7.6. This figure illustrates a sample of activity when harvesting a very light patch of sugar cane, and some topped cane stalks can be seen standing upright, and also some trash being dispersed.

* Video footage is accessible by 'clicking' on the figures in the dissertation CDROM

Figure 7.6: View from camera mounted in position (b) onto tops of freshly topped stalks

The video footage showed cane stalks slightly bowed by the topper drum returning to their upright positions and 'banging' against the back hood. This hood also tended to gather the tops of the stalks because of its slightly arced shape. The stalks were then pushed aside to allow the topper hood to pass over.

The data collected from the video was most useful because it allowed for a more precise understanding of the logistics of the topping process. This information was used in the developmental stages of the chosen sensing technique, and once a prototype sensor was constructed this footage also assisted with its mounting.

7.2.3 Preliminary Laboratory Testing

Another step in developing familiarity with the measuring environment was a detailed analysis of sucrose's chemical behaviour in a laboratory. The results of these investigations will be presented as part of the detection system alternatives in the next section.

7.3 Detection System Alternatives

Traditionally, the grower conducts static measurements of sugar concentration in the field with a handheld refractometer. More accurate measurements are later conducted at the sugar mill using polarimetry and spectroscopy. These methods are the most popular because of their simplicity and accuracy. As yet however, no device exists to reliably measure sugar concentration in real time that may be applied to the harvesting process.

For any one the following technologies to be applied on a sugar cane harvester, a robust and inexpensive system has to be implemented rather than sophisticated ‘off the shelf’ instruments to survive the particularly unfavourable measuring environment. Also the implementation of some of the more traditional sensors as part of the topping process is impractical because of the methods in which they operate.

7.3.1 Refractometry

A refractometer measures the refractive index (RI) of a liquid sample. The RI of a material is usually expressed in terms of air as a standard (Brown & Liptak 1995). There are two forms of process refractometer currently used in industry; one is based on measurement of changes in refraction angle, and one based on observation of the critical angle. The former measures refractive index relative to a sample, and the latter is an absolute measurement.

The critical angle refractometer is the most widely used instrument for measurement of refractive index. When light passes from one material into another where the index of refraction is lower, the critical angle (θc) is the incident angle that results in an angle of refraction of at least 90°, as shown in Figure 7.7. At this point there is no refracted light at all, and total internal reflection occurs.

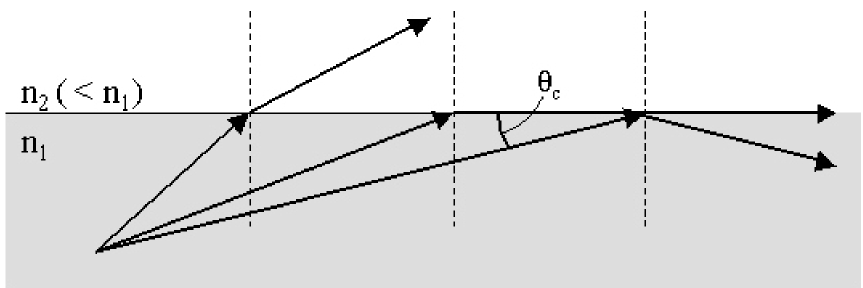


Figure 7.7: Critical angle for light transmitted between two media

Traditional Abbe desktop refractometers operate on this principle, and laboratory tests were performed to verify that changes in concentration of a sugar solution affect the index of refraction of the substance. The results can be seen in Figure 7.8.

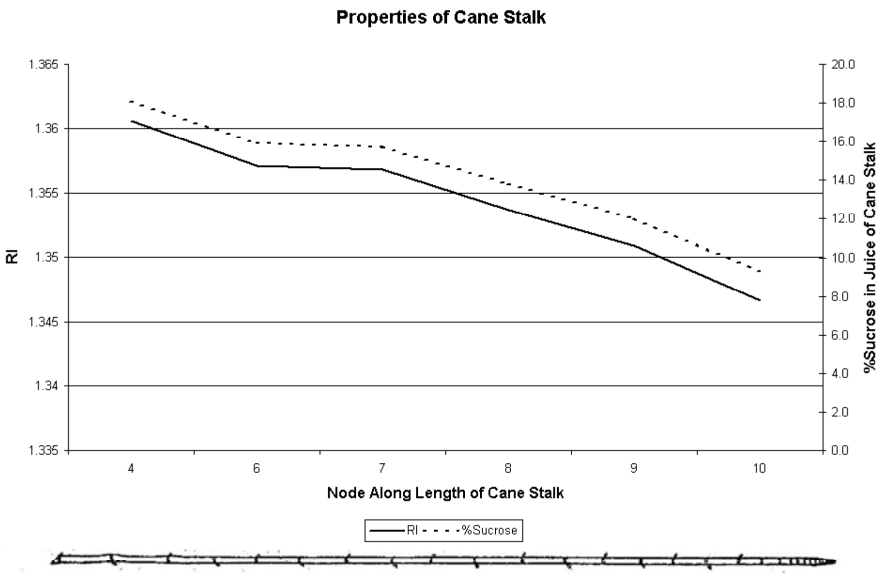


Figure 7.8: Values of sucrose and refractive index, RI, measured along the length of cane stalks

Some industries that are users of refractometers, such as the sugar industry, prefer to use their own units instead of index of refraction. They prefer to use the %Brix scale, which is a weight percent of sugar concentration, corresponding to the number of grams of sugar contained in 100 grams of solution.

7.3.2 Polarimetry

Optical activity is a measure of the ability of certain substances to rotate plane-polarised light (Skoog 1980). Polarimetric devices measure the optical rotatory power of a substance. Sucrose is an optically active material, which means plane-polarised light is rotated clockwise (dextrorotatory) when passing through the sugar solution. In terms of its invert sugars, sucrose is dextrose (i.e. a 'right-handed' variation of glucose) plus dextrorotary fructose. This can be seen more clearly in Figure 7.9.

$$C_{12}H_{22}O_{11} + H_2O \xrightarrow{acid} C_6H_{12}O_6 + C_6H_{12}O_6$$

Sucrose		Glucose	Fructose
$[\alpha]^{20}_{D} = +66.5°$		$+52.7°$	$-92.4°$

Figure 7.9: Inversion of sucrose

The most extensive use of optical rotation for quantitative analysis is in the sugar industry (Skoog 1980). If the only optically active constituent of a substance is sucrose, its concentration can be determined from a simple polarimetric analysis of an aqueous solution of the sample. The concentration is directly proportional to the measured rotation.

Polarimetry tests are performed by completely filling a sample tube with the substance, before plane-polarised monochromatic radiation passes through the tube and the angle of rotation from the sample is determined. The frequency of analysis via polarimetric means has led to the development of the saccharimeter, which is dedicated to sugar concentration measurements.

A number of laboratory tests were conducted to verify the use of polarimetry to determine sucrose concentration, and the results of one such test are shown in Figure 7.10.

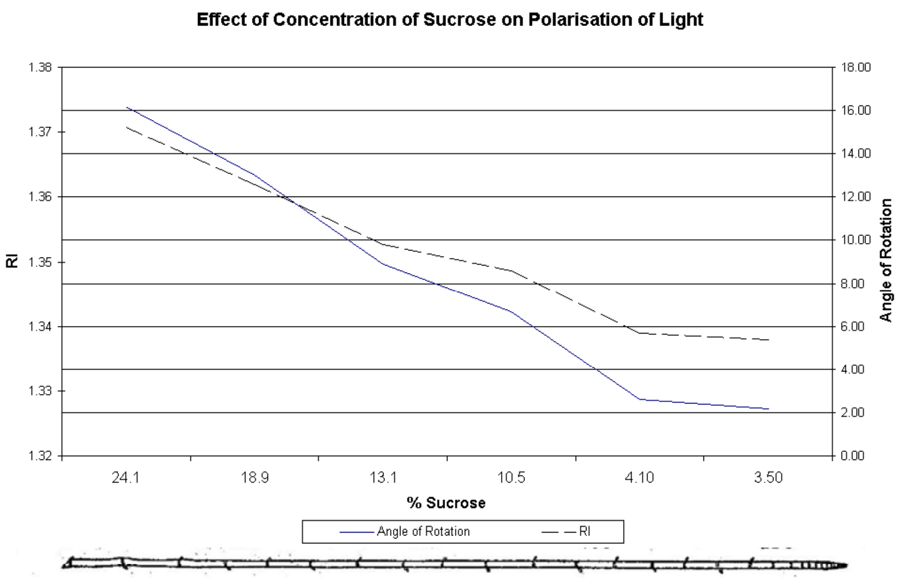


Figure 7.10: Values of rotation angle and RI against sucrose concentration measured along the length of cane stalks

Polarimetry has limitations because other optically active materials are present in the sugar cane juice from a stalk. The presence of the invert sugars may cause these and the sucrose to change forms depending on external conditions, and the measurement would vary accordingly. In this case, an alternate procedure may be required. Also the logistics of implementing polarimetry in the field may be extremely difficult and not robust to the high levels of contaminants.

7.3.3 Spectrum Analysis

There are many applications of spectroscopy in the analysis of agricultural products (Sverzut et al. 1987). In the past, near infrared (NIR) spectroscopy has become prominent for the measurement of parameters in other industries. Its use in the sugar industry has not been accepted until recent times, however it is now used in mills to quantify brix of the extracted sugar juice.

A prototype spectroscope was constructed to analyse absorbed wavelengths by a liquid sample using a diffraction grating to separate the different wavelengths of light. A simplified spectrometer (or spectroscope) is illustrated in Figure 7.11.

Light from a source passes through a narrow slit in the collimator. The slit is at the focal point of the lens, so parallel light falls on the grating. The viewing angle q corresponds to a diffraction point of a wavelength emitted by the source (Giancoli 1998).

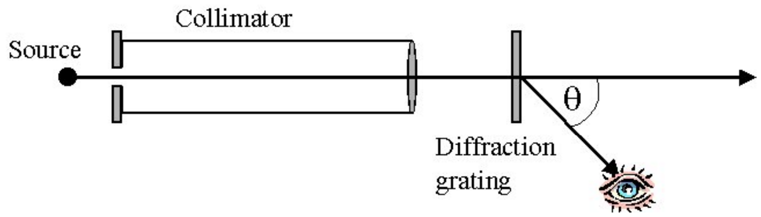


Figure 7.11: Operation of simple spectrometer

The spectrometer that was manufactured is shown in Figure 7.12. In this case the source light was a bulb with a filament that effectively emitted only a line of light (c.f. source light through slit). A cuvette was positioned in a direct line between source and detector to hold the aqueous sugar solution. The detection device is a Nintendo GameBoy camera that has a diffraction grating (1000 lines/mm) positioned in front of it. The camera and grating were fixed together, so that the angle of these relative to the incident light could be changed. All of these components were mounted in a steel box, and the interior of the box was painted flat black to absorb any extraneous light.

Figure 7.12: Spectrometer test rig with cuvette in position in box, and the collimator is in the foreground

Before the output waveforms were recorded, the detector and grating were adjusted until the maximum resolution of the detected light intensities in the spectrum was observed. The detected radiation was not only in the visible region of the electromagnetic spectrum, but also in the infrared. The input ‘soak’ time of the camera was adjusted so that it was not saturating, and the spectrum was centred on the detected output. By doing this, an alternate method of detection could be a linear array detector.

A sample of the output data is shown in Figure 7.13. The output is the relative light intensity cross-section through the middle of the observed spectrum.

From this figure it can be seen that the solutions have similar shapes peaking at the same absorbance wavelength. There is a discernable difference between the two sucrose concentrations, and this is most evident from the upper waveform that represents the differential reading. At the stage of these measurements, the horizontal axis was scaled in terms of pixels, but with further development this could be calibrated to wavelengths with known lights.

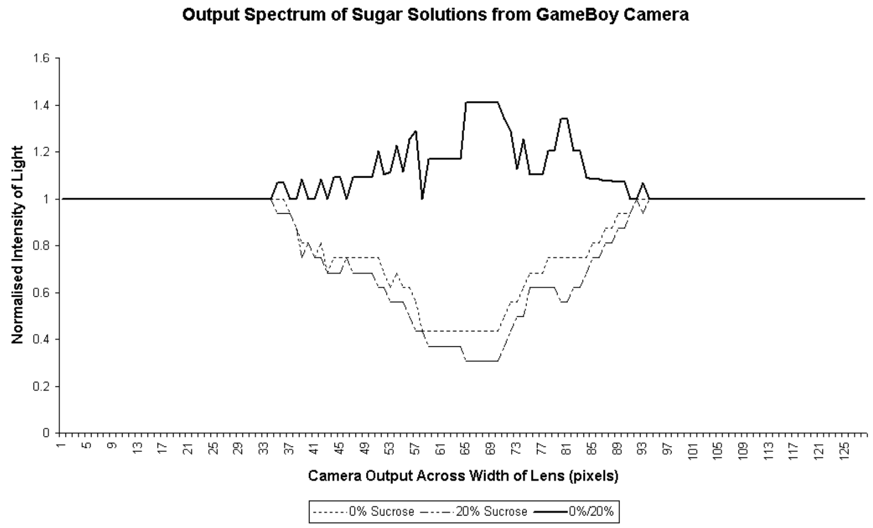


Figure 7.13: IR spectrum from GameBoy Camera

Other tests were conducted in the laboratory to determine other spectrum properties of sucrose that were dependent on concentration. Some fluorescence trials were conducted on a spectrofluorimeter, and the results of this are shown in Figure 7.14. From this figure it can be seen that sucrose does fluoresce when subjected to excitation radiation in the ultraviolet region. This particular wavelength has very high energy levels

The physical logistics of the measurement equipment and the difficulty of obtaining new sugar samples in real-time in the necessary form would make this form of detection for sucrose concentration in the topper application very difficult.

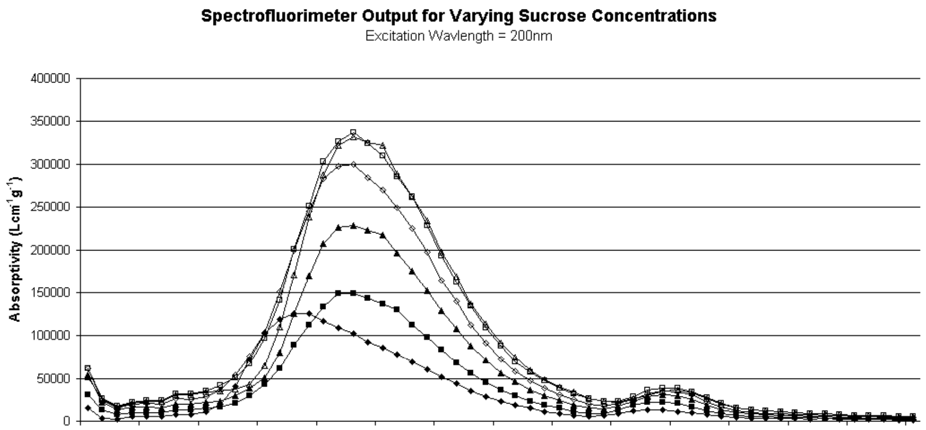


Figure 7.14: Spectrofluorimeter output

7.3.4 Acoustics

Another possible method to determine optimum cutting for sucrose content that was considered was the implementation of acoustic transducers to the topper to 'listen' to certain events during the harvesting process.

The first area of interest for this approach was the interface between the lowest row of cutting blades and the cane stalks as they were being topped. The theoretical basis for this placement was that the noise of a blade cutting a dense sugar-bearing cane stalk would sound substantially different from tops being cut.

Figure 7.15: Placement of transducers (indicated) on topper to collect acoustic information: (a) cutting interface, and (b) back of hood

A small electret microphone was installed in this position, and this is illustrated in Figure 7.15(a). An alternate position for microphone placement was on the back of the topper hood.

From the video footage that was collected (see Section 7.2.2) of the freshly topped cane stalks still in the ground, it was noticed that the stalks were firstly bent to be topped, and as they returned to an upright position they would impact against the back of the hood. This impact signal was considered to be a potential tool that could be used to determine topping height because of the increased density of the sugar-bearing stalk. A small electret piezoelectric transducer film was installed on the back of the hood, as illustrated in Figure 7.15(b).

Figure 7.16 illustrates a sample of the two signals recorded in stereo; note that the upper waveform has had a DC offset introduced for clarity. Aural assessment of these signals was not overly convincing, and it was determined that a more precise method of determining the cutting height would provide a higher level of confidence.

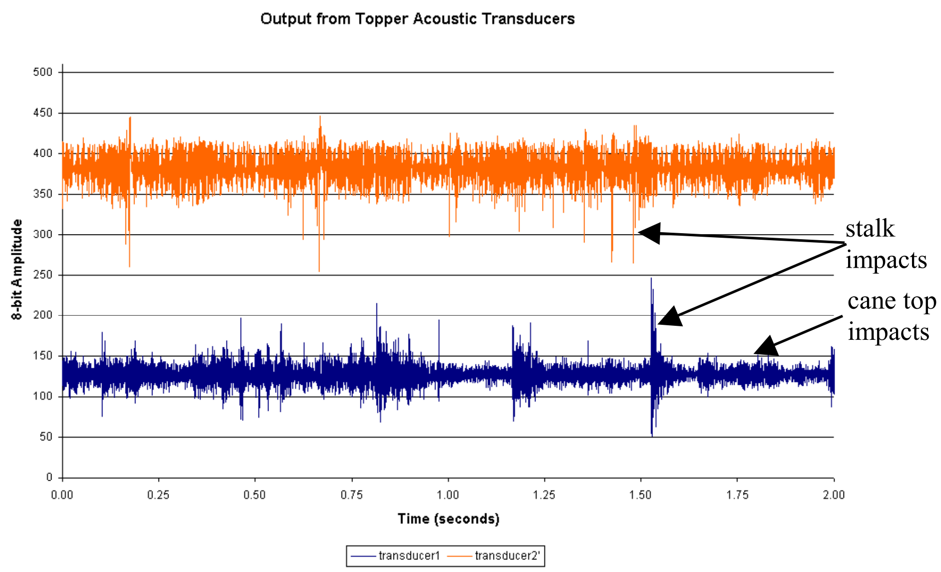


Figure 7.16: Sample of collected acoustic topper data from the cutting interface (top) and the back of the hood (bottom)*

7.3.5 Machine Vision

Another alternative to determine the optimum topping height from external indicators that was considered was machine vision through the implementation of a colour digital CCD camera. This installation could provide the raw colour signals of the detected input image, and subsequently a raw RGB (red-green-blue) signal that could be analysed. Figure 7.17 indicates a sample of cane stalk being topped and the green-brown transition near the top can be clearly seen.

This method was not considered further because of the huge quantity of cane stalks to be harvested, and the very low level of discrimination between rows, let alone stalks. Also a large proportion of the field to be harvested would be lodged

* Audio sample is accessible by 'clicking' on the figure in the dissertation CDROM

to varying degrees, and as a result the stalks would not be vertical, and this would complicate the detection process.

Figure 7.17: Topper removing leafy waste material from upper section of cane stalks

7.4 Development of Sensor Concept

The sensor that was deemed most appropriate for the topping system was the refractometer. A novel critical angle refractometer was constructed to be the active measuring device on the toppers of the sugar cane harvester. This sensor operates by detecting variations in the critical angle when different solutions are placed on its sensitive surface. The shift in critical angle is calibrated relative to a control liquid that is 'sucrose neutral'; in this case water was used.

The light source is focused to fall on the prism-sample interface with a variety of incident angles progressing across the width of the prism (Brown & Liptak, 1995). Some of the incident light will refract into the sample medium, but internal reflection will occur when the incident angles are greater than the critical angle. The exact point that the incident light changes from being refracted to total internal reflection is dependent on the refractive index properties of the solution placed on the sensitive surface of the prism.

Therefore, the density or concentration of the solution placed on the prism can be identified via the discontinuous change in reflectance of the incident light. As the refractive index of the sample changes, a larger, or smaller, portion of the incident light beam will be reflected internally and the width of the resultant beam on the third face of the prism will change. The amount of light reflected is easily identified visually on the third face of the prism by the distinct dim-bright transition line. The transition line appears instantly as the sample solution is placed on the sensitive surface of the refractometer.

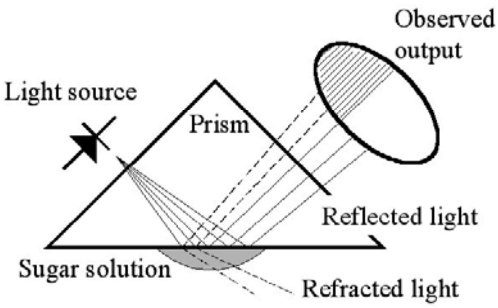


Figure 7.18: Simplistic view of critical angle refractometer

To remotely sense the amount of light internally reflected, an optical detection system has been implemented on the third face of the prism. The detection system was made up of a line scan camera chip that was placed in such a position that the full range of sugar concentrations expected in a stalk could be detected. The chip that was chosen was a TSL214 integrated opto-sensor* with a resolution of 64 linear pixels; this sensor is ideal for edge-detection applications. In addition, a colour filter was placed between the detector and the face of the prism to help eliminate other incident light that may enter the prism through the sensitive surface.

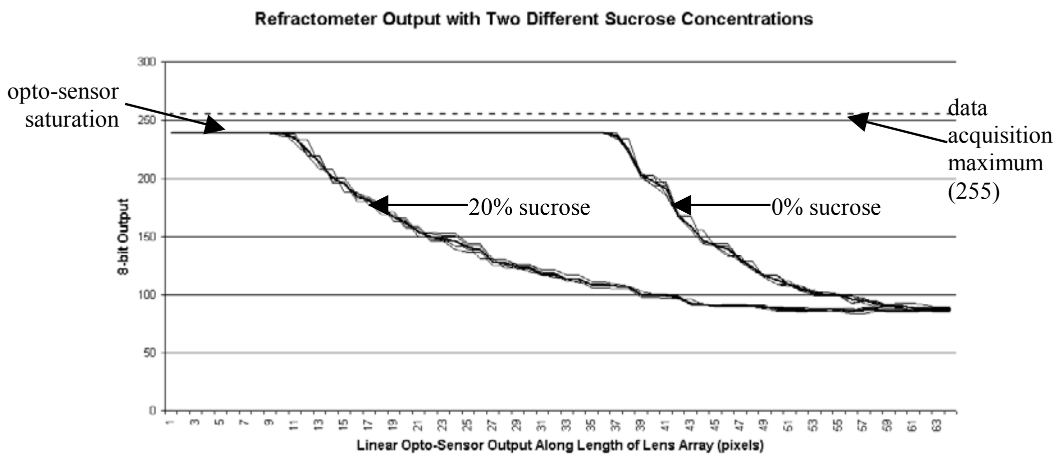


Figure 7.19: Sensor output from 20% sugar (left), and 0% sugar (right)

* Specification sheet is accessible by 'clicking' on the hyperlink in the dissertation CDROM

Preliminary trials and analyses in the laboratory have indicated a strong correlation between the output of this device and the traditional Abbe desktop refractometer.

7.5 Chapter Summary

The topper of the cane harvester is a difficult operation to control accurately, and as a result this function is often neglected. Numerous methods were considered potentially useful for determining the optimum topping height. These methods detected height from both internal and external indicators on the sugar cane stalk. One promising method to accurately and reliably measure sugar concentration at the top of cane stalks in real-time during the harvesting process has been described. This information could possibly be used to optimise the topping height of the cane by either automatically controlling the height of the topper operation, or by providing relevant information to the harvester operator.

The next step for the sensor was the transition to field-testing for further evaluation.

Chapter 8

Sensory Topping System Results

8.1 Introduction

A promising method to measure sugar concentration has been developed. Samples are taken from the tops of cane stalks, and an accurate and reliable measurement is provided in real time. However, the sensor to be used for feedback to optimise the topping height must be capable of surviving in the harsh environment of the cane field. Developing a robust method for preparing samples for the refractometer presented some problems.

Many prototype devices to assist the sampling method were attempted and other relevant issues have been considered. The configurations of prototype devices that were developed to measure sugar at the topping height during the harvesting process will be discussed.

Figure 8.1: Row of cane

The optimum topping height of the sugar cane stalks varies greatly across a field, and factors such as variety, age, season and environment influence the vertical distribution of recoverable sugar in stalks (Inman-Bamber & Wood, 1985).

Considering these factors, the variation in height across a whole field might be substantial, however the height variation of one stalk compared to its neighbours will be more gradual. To the harvester operator, following the subtle differences in the optimum topping heights with the topper may be a low priority, but this responsibility will be simplified with the application of the sensing mechanism in the field.

8.2 Laboratory Results for Novel Refractometer

At this stage, a simple critical-angle refractometer has been manufactured as the sensor element in this mechatronic system. The refractometer is illustrated in Figure 8.2. Appropriate methods of quantifying the sugar content of the sample on the refractometer were investigated for optimal results, including minimising computing requirements.

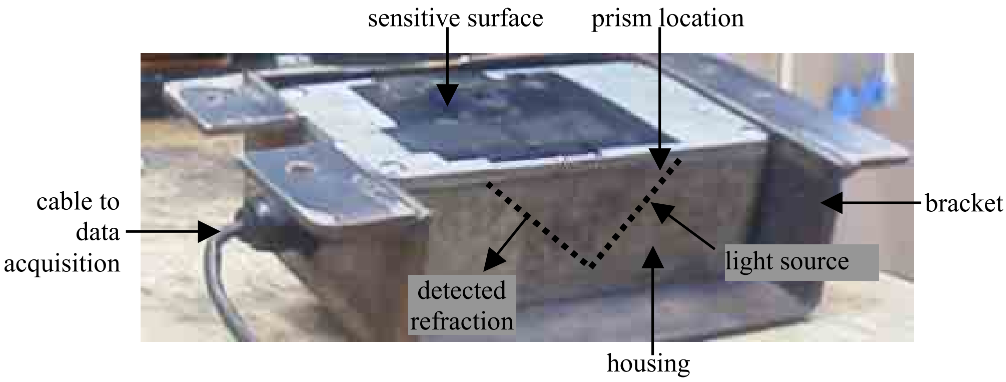


Figure 8.2: Simple critical-angle refractometer in housing

8.2.1 Signal Analysis

Figure 8.3 indicates two sample output waveforms from the refractometer. The two concentrations were prepared samples, and their measurements were verified by a commercial Abbe desktop refractometer. The figure indicates the definite light-dark transition point that indicates the ‘shift’ in the critical angle caused by the varying sample medium. The ‘light’ portion of the output was when the detecting pixels were saturated, and the sensitivity was adjustable. In this case an arbitrary value was set that was slightly less than maximum value for the 8-bit resolution of the A/D converter.

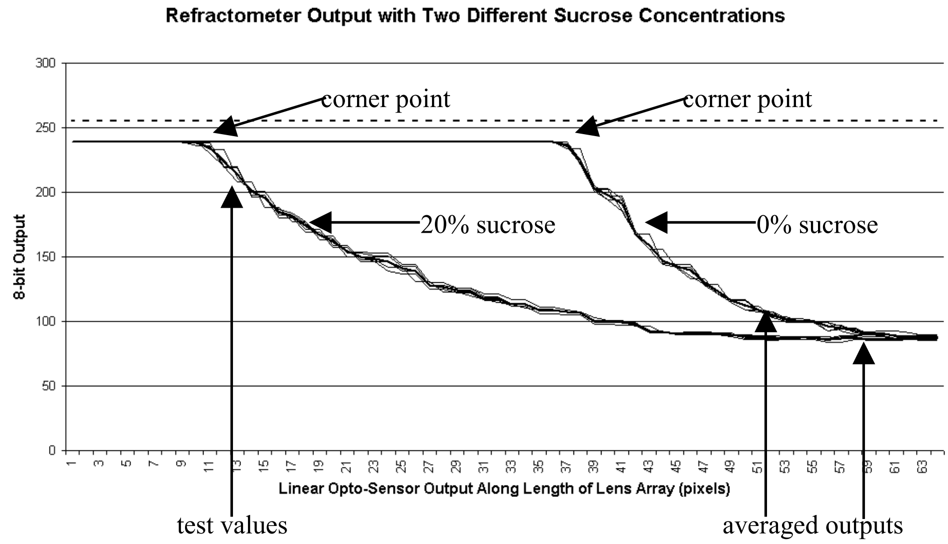


Figure 8.3: Refractometer output from two different sugar samples measured with traditional refractometer

It can also be seen there is a significant difference between the output waveforms associated with the two extremes of sugar. The corner points for each concentration were well defined, and the waveforms had reasonably fast roll-offs. There was an opportunity to apply various signal analysis techniques to the output signal of the refractometer to automatically compute the sugar concentration accurately.

The reaction time for the dim-light transition line to appear when different sugar samples were applied to the prism surface was less than one second, and this consumed time was in the interfacing of the linear array detector with the PC via the ADC. Therefore, to ensure that the system still operated in close to real time, the computation time of the sugar concentration via the signal analysis algorithm was minimised.

A direct reading of the corner point was clearly the simplest approach for the sugar measurement, however it was not deemed the most accurate method. A few computation alternatives were possible, and there was a trade-off between accuracy and execution time in each alternative.

The sugar concentration was measured from the -3dB point of the saturated 8-bit output (see Figure 8.4), and the pixel closest to this line's intersection with the roll-off of the sensor was calibrated with different sugar concentrations. This method was very simple, and eliminated the reading errors around the sometimes-unclear corner point.

Another possibility was overlaying a line of regression from the input data, and from this determining a 'virtual' corner point from the intersection of this line with the saturation line. The advantage of this method was the increase in resolution of the sensor because the virtual corner point may be in-between two adjacent pixels, and hence a more continuous range of concentration was possible.

Figure 8.4 demonstrates the implementation of these two example algorithms to the output waveforms presented earlier.

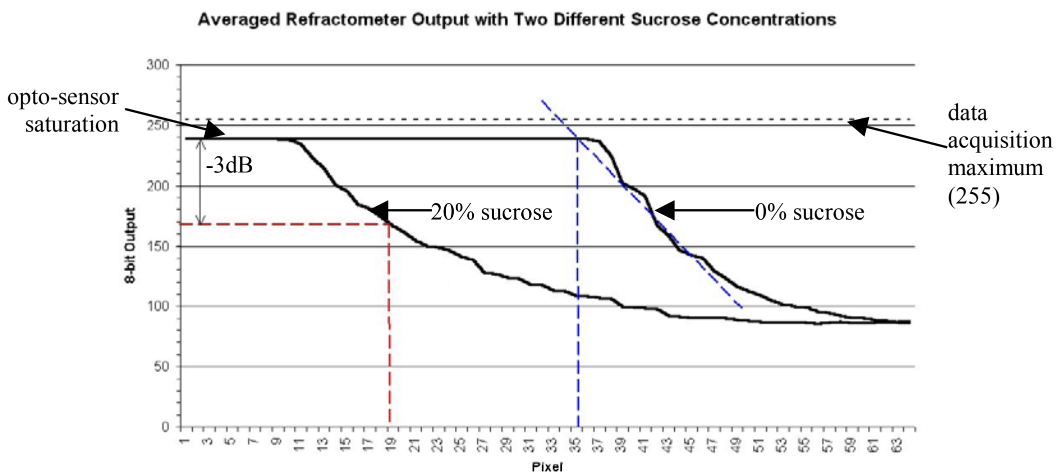


Figure 8.4: Sensor output from 20% sucrose (left), and 0% sucrose (right)

It can be seen when compared to the two samples presented earlier, that either method would be an efficient means of identifying sugar concentration.

8.3 Cane Field Trials

During laboratory trials, this sensor provided a very accurate measure of sugar samples that had been artificially created, as well as from a sugar cane stalk. The laboratory tests consisted of the sugar samples being extracted from a cane stalk and then placed on the sensitive surface of the refractometer. Once the refractometer had been constructed and calibrated to accurately discriminate between different concentrations of sugars, field trials were initiated.

8.3.1 First Concept

An effective method was required for measuring sugar concentration of the tops of the stalk in the field. The refractometer required sugar samples while the stalk was intact, because the stalks are chopped and the billets quickly mixed together. This meant the stalks should be sampled external to the harvester, but after the cane was topped.

Initial trials of the instrument required it to be mounted on the back of the topper shroud near the centre. The sensor was not mounted exactly in the middle to accommodate the lever movement of the topper when the height was adjusted.

Section 7.2.2 discussed the mounting of a camera in the topper to identify the processes, and it was from the video data returned from these experiments that the current concept was attempted. The position was chosen because footage showed the curved shape of the shroud effectively gathering the topped cane stalks as the cane was being harvested.

The concept aimed to take advantage of the curved geometry of the topper to feed cane towards the sensor, and the freshly 'topped' stalks would wipe across its sensitive surface. The residue that was left by this contact would be sampled by the refractometer, and an accurate sugar concentration could be determined. The surface was also assumed to be relatively self-cleansing because of the wiping action of the stalks. Figure 8.5 shows the addition of the refractometer behind the topper shroud.

Figure 8.5: Operator's view of refractometer (left), and instrument mounted on back of hood (right)

This concept was theoretically quite feasible, but in practice on an operating harvester was unsuccessful. It was found that under harvesting conditions, a large amount of trash and other waste leaf material was also forced underneath the shroud especially between the sensor and the cane stalks. This material prevented the freshly topped stalks from wiping across the sensor.

Also it was discovered that even if the trash did not hinder the measurements, the quantity of sample medium being deposited on the sensor was often insufficient to obtain a clear measurement. This was especially significant when the cane was harvested burnt, because the extreme heat of the fire dehydrates the stalk.

8.3.2 Second Concept

The major shortfall of the sensor was that without external (human) assistance raw sugar samples from a cane stalk could not be extracted and placed where they were required for measurement. The shredded tops of the cane stalks inhibited the refractometer from having sugar samples smeared across its sensitive surface, and there was insufficient sample for measurement. Once these points were established, it was decided to relocate the sensor from the topper mechanism to a position closer to the harvester.

Also, to ensure that there would be sufficient sample medium to measure, a mechanised crushing device was designed to squeeze the tops of the cane stalks.

The sampling concept for the squashing mechanism was to test the juice extracted at particular heights by the mechanism, starting high in the leafy tops and gradually lowering the topper until the transition section was detected.

The squashing mechanism was to be mounted on the topper arm. This was chosen because the height of the crushing was always then going to be proportional to the lowest cutting plane of the topper.

Static load frame tests were performed along the length of cane stalks to determine the force required to deform the cross-section. The load was incremented until an adequate amount of juice sample was extracted that would enable a measurement of sugar concentration. The amount of deformation required for this was up to approximately 30% deformation. The results of these trials are illustrated in Figure 8.6.

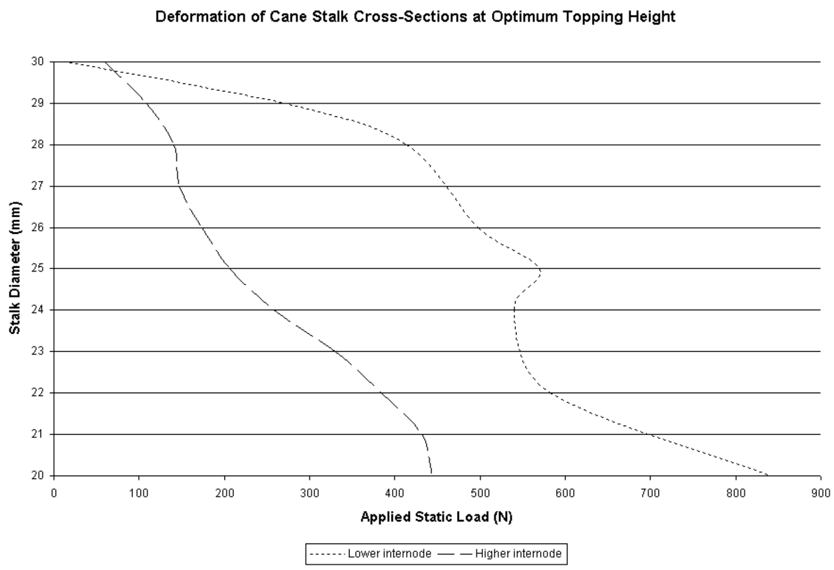


Figure 8.6: Results of deformed stalk cross-sections

The trials were conducted on the internode above and below the optimum topping height. As can be seen from the figure, the load required for the 30% deformation varied by up to 400 N over the transition section of the mature cane stalk: from approximately 800 N to 400 N respectively.

The squashing mechanism was designed to crush the soft tops and not the strong exterior of the mature cane stalks. This consideration allowed a conservative figure of 600 N to be chosen as the deformation force required for the ‘interesting’ section of stalk.

Alternate forms of mechanical device were available to be utilised for the squashing process, and a selection of these is shown in Figure 8.7. The principle design factor was that the device sampled the upper section of the topped cane stalks after the topper and before the throat of the harvester, and to ensure that this flow was not impeded.

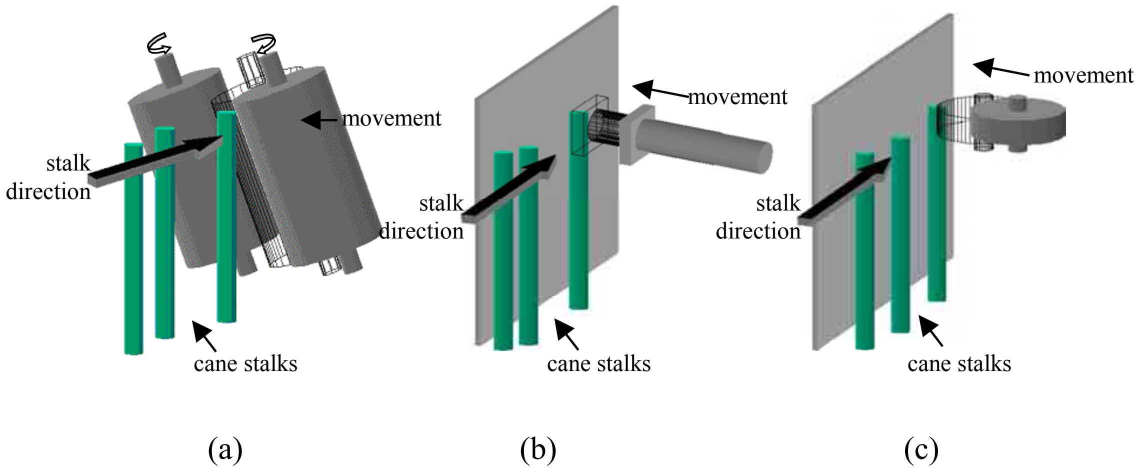


Figure 8.7: Squashing concepts to extract sufficient sugar sample: (a) spring-loaded rollers, (b) impact device, and (c) spring loaded roller

The forward ground speed of the mechanical harvester was up to 12 km/h, and this meant the contact time between the stalk and squashing device should be minimised. The techniques investigated included spring-loaded crushing wheels, impact devices, and a cam-driven crushing lever.

The cam-driven crushing lever was chosen for its ability to capture and crush stalks quickly and to create a juice flow for the refractometer, and this concept is illustrated in Figure 8.8.

To handle lodged cane the mechanism was required to have a wide opening that directed a selection of topped stalks into a narrower crushing area.

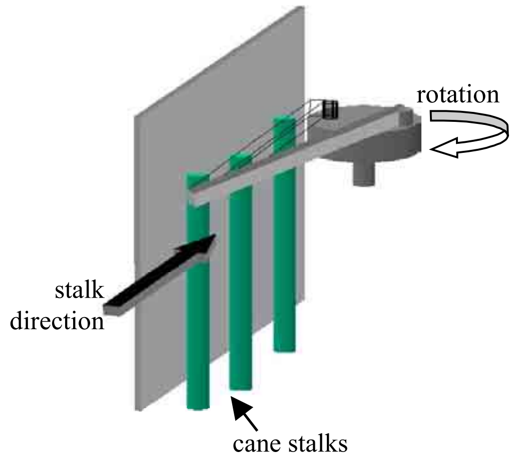


Figure 8.8: Cam-driven cane squashing mechanism

The crushing arm was a lever mounted on a cam that forced it to reciprocate cyclically. A heavy-duty DC motor provided the torque for the cam disc, and this disc was machined with many settings so that the throw of the lever arm could be adjusted to suit the diameter of the cane stalk variety being harvested.

Figure 8.9 illustrates the prototype squashing mechanism.

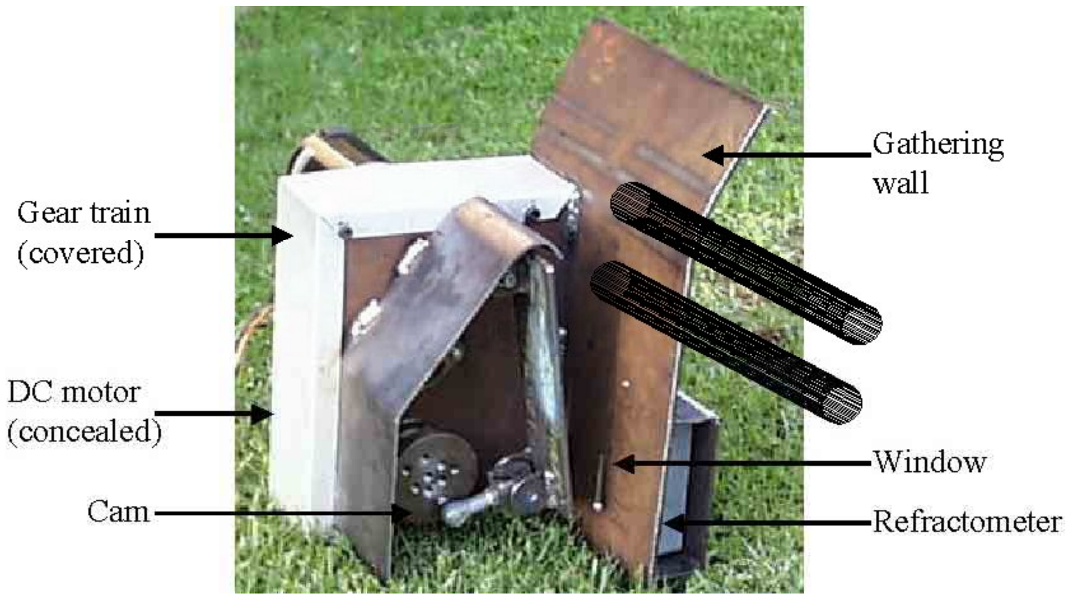


Figure 8.9: Prototype squashing mechanism with key elements indicated, and stalk orientation illustrated

The selected DC motor had inadequate torque to generate the required amount of force to deform the top section of stalks. The required torque was generated via a gear train to provide the necessary mechanical advantage. The ratio required was calculated to be up to 30:1 as shown below.

$$\text{Mechanical advantage} = \frac{\omega_{IN}}{\omega_{OUT}} = \frac{r_{OUT}}{r_{IN}} = \frac{\tau_{OUT}}{\tau_{IN}}$$

where ω is the angular velocity of the indicated gear
r is the radius of the indicated gear
τ is the torque at the nominated position
and the subscripts 'in' and 'out' represent the input and output stages of the gear train

A nominal radius of 25mm was selected for the gear, and in these calculations this is effectively the lever arm. From §8.3.2 it was determined that a force of 600 N was required to deform the top section of a cane stalk. These values give a required torque, τ_{OUT} of 15 Nm. The maximum torque available from the selected dc motor, τ_{IN}, was 0.576 Nm.

$$\frac{\omega_{IN}}{\omega_{OUT}} = \frac{r_{OUT}}{r_{IN}} = \frac{\tau_{OUT}}{\tau_{IN}} = \frac{15}{0.576} \approx 26 = \text{Required gear ratio}$$

Captured stalks were crushed between the lever and the stationary back wall. The periodic throw generated by the cam allows stalks to be captured, crushed and released in a relatively quick motion. The crushed stalk provided sufficient juice to flow down the back wall and onto the refractometer through a small window. The window has a sharp blade positioned near it that penetrated the stalk when being crushed. This blade allows a sufficient quantity of juice to flow. Also, the crushing arm had two rails attached to it to concentrate the crushing force on the cane stalk in an effort to maximise extracted sugar juice.

Figure 8.10: Squashing device from behind

Cane fields provide a hostile measuring environment, so the effect of impurities and other contaminants on the refractometer was reduced by regularly cleaning the sensitive surface with water. This process involved periodically 'flushing' down the juice track and the sensitive surface, which also allowed the sensor to be recalibrated at regular intervals.

Figure 8.11 shows the device mounted on the topper arm directly behind the topper. The mechanism has a throat wide enough to allow a sample of the freshly topped cane to be fed into the device and crushed.

It could be argued that the device would create extra loss for the grower because of the extra damage inflicted on the cane stalk, but it is envisaged that the monetary loss introduced because of this extra system will be negligible because of the low sugar concentration in the top crushed section.

Several attempts were made to test the prototype to gather data relating sugar content to topper height, but severe difficulties continued to hamper the success of these trials. It was decided to move trials back to the laboratory to continue the development of the sampling and measurement system, and by doing this some assessment of its performance would be possible.

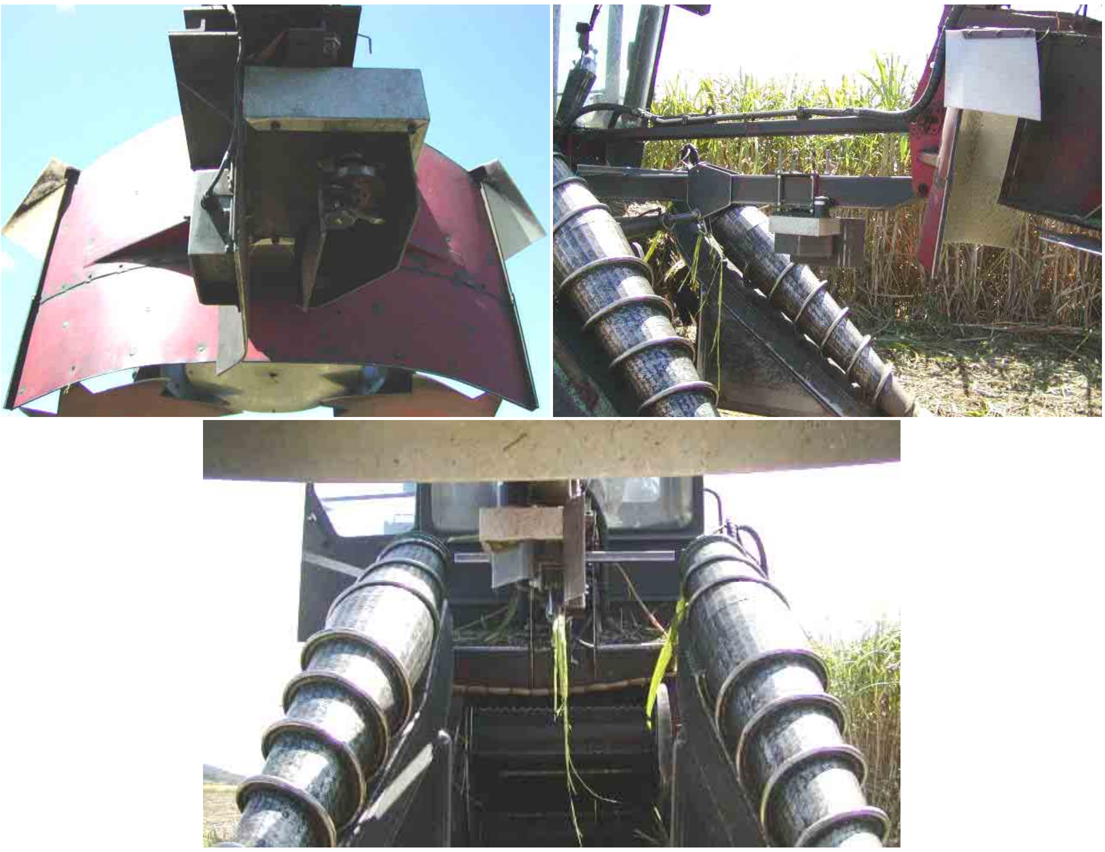


Figure 8.11: Crushing mechanism mounted on topper arm

8.4 Laboratory Testing

The squashing mechanism and refractometer were assembled for laboratory trials as indicated in Figure 8.12. These trials were conducted to simulate field results by using real stalks of sugar cane.

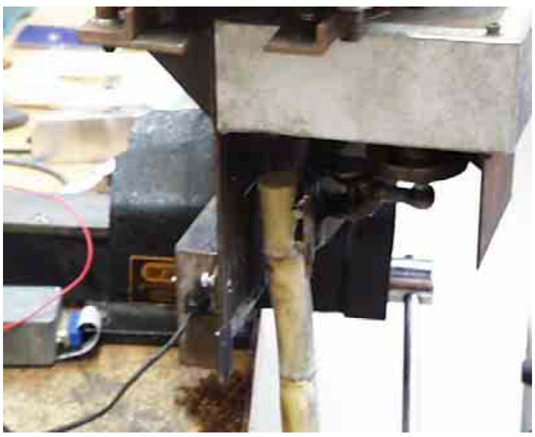


Figure 8.12: Squashing mechanism in laboratory crushing sugar cane stalk[*]

[*] Video footage is accessible by 'clicking' on the figure in the dissertation CDROM

A trial consisted of dividing the length of the stalk in the internodal spaces and then manually feeding the stalk section through the mechanism. Each stalk section was crushed and a flow of juice was identified, and this juice appeared on the sensor and a measurement of sugar concentration was taken. The sensor had been calibrated earlier by manually placing different concentrations of sucrose on the sensor. During the testing process, the refractometer was regularly flushed with water. This also allowed the refractometer to be periodically recalibrated with a 0% sucrose measurement.

The quantities recorded when performing these tests included, node number, vertical height of the stalk, and sugar concentration, and from these quantities a vertical distribution of sugar in a cane stalk could be plotted. A sample output waveform is indicated in Figure 8.13.

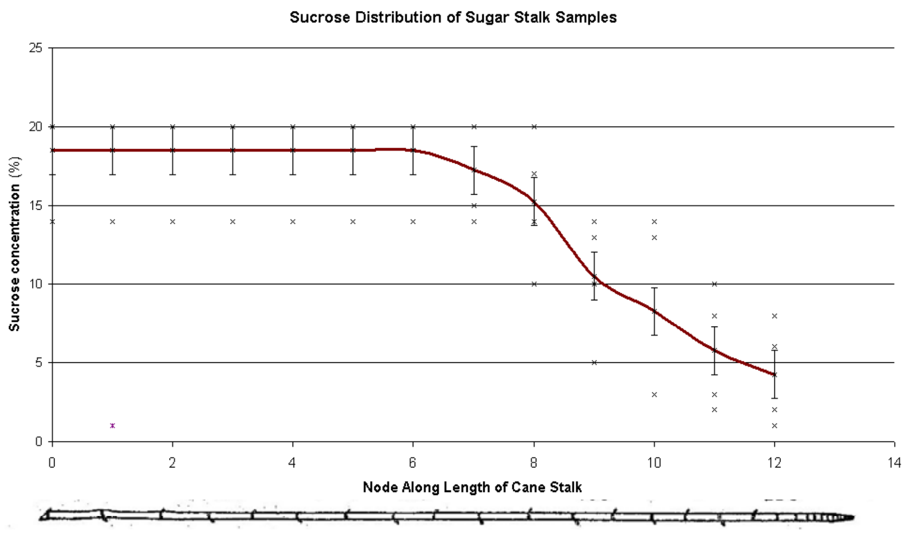


Figure 8.13: Distribution of sugar concentration from refractometer with samples from stalk (left) up to top (right). The samples were taken from different stalks

The trend that is evident in this distribution was expected from the available literature, as well as previous manual testing performed with a stalk sugar and a laboratory refractometer. The results indicated that the squashing concept performed to specification on the cane stalks.

8.5 Chapter Summary

A prototype mechanism was constructed to provide sufficient sugar juice sample to the developed refractometer. This device was designed to provide sufficient force to deform a small part of the rigid upper stalk. The resultant juice flow trickled over the sensitive face of the refractometer, and a measurement was obtained.

Substantial field trials were frustrated by limited results, however laboratory trials yielded promising results.

Chapter 9

Integrating the Systems

9.1 Introduction

Until now the chosen harvester functions have only been considered as measurement systems. The separation system and topper have been identified as requiring improvement, and appropriate signals relating to performance indicators of these systems have been collected. Transducer and signal conditioning modules have allowed the signals to be collected in useful forms.

The measurement systems can be considered to consist of three elements, and are summarised in Figure 9.1.

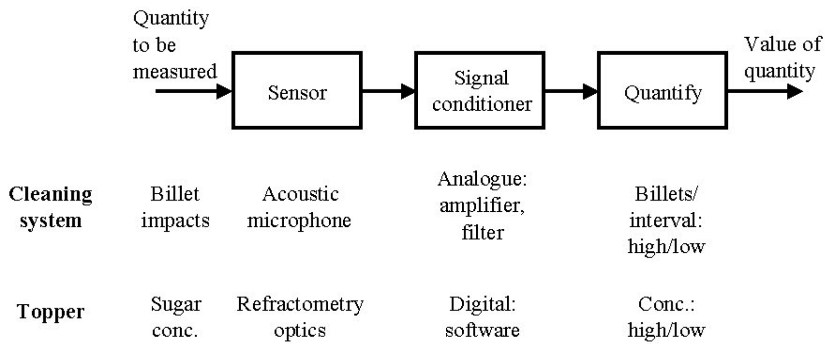


Figure 9.1: Measurement systems model

To provide the necessary assistance to simplify the operation of the mechanical harvester, the outputs from the measurement systems have to be used as the feedback element to create a closed-loop system for each of the considered harvester functions. Thus the measured quantities will provide indications of the adjustment required to maintain the output signals at the required levels.

In either of the identified cases, the cleaning system or topper, a compromise must be maintained. Careful control of the extractor fan speed is required to achieve a balance between excessive trash in the cane supply, and the ejection of cane billets. The height at which the topper cuts the cane stalk has a considerable effect on the quality of the product supplied to the mill. In both cases, the level of control affects the return to the grower.

9.2 Feedback Alternatives

There are numerous methods to provide feedback. Figure 9.2 illustrates the feedback loop applied to the general model of the measurement systems that have been developed.

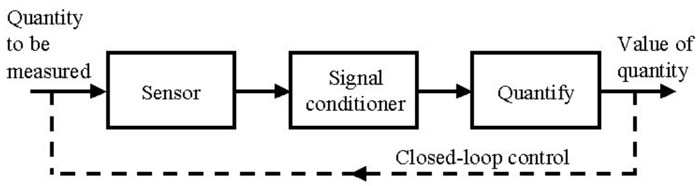


Figure 9.2: Feedback applied to measurement systems model

Automatic control algorithms may be implemented through microcontrollers, indicator devices could visually assist the operator, or possibly a combination of these two methods.

Whichever method is pursued, the desired outcome is to simplify the responsibilities of the harvester operator. To be most effective, the developed control systems will be integrated to form the basis of a more efficient sugar cane harvester.

9.2.1 Visual Indicators

In Chapter 2 the existence of a commercial cane loss monitor was established. This instrument was installed in the cabin of the mechanical harvester, and provided large digit displays for the numeric identification of operational parameters. These were:

1. Cane loss
2. Groundspeed (km/h), which was monitored via a magnetic sensor on a (non-driven) front wheel;
3. Extractor fan speed (revolutions/min)
4. Basecutter speed (revolutions/min)

The groundspeed information was also used to provide the cane loss indication directly on a loss/hectare basis rather than as a rate (loss/unit time).

No topper height performance indicator is currently available.

To implement a visual indication device for either the extractor fan speed or topper height, the physical ergonomics of the harvester cabin would have to be considered. It is a rather confined area, and excess cabin space is very limited.

Also the operator would still have to operate the harvester, while regularly monitoring the performance gauges. The proposed visual indication devices could be very similar for either function chosen for improvement (Figure 9.3).

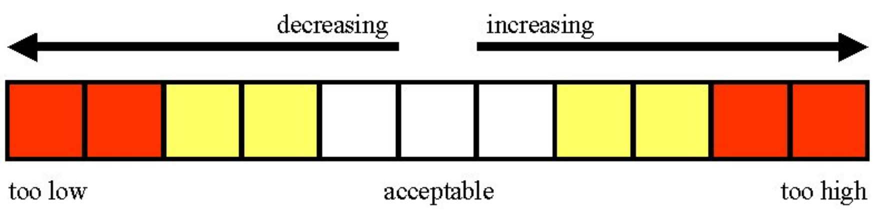


Figure 9.3: Visual indicator concept

The proposed indicator would be similar to LED bar graph arrays, with different colours to indicate extremities and urgency of attention.

9.2.2 Automatic Control

In practice hydraulic powering of machinery is prevalent, particularly in agriculture, because of its controllability and rather high power-to-weight ratio. It is most important for steering, drives and implement operation. Automatic control of the mechanical harvester's functions is certainly not a trivial exercise due to the many discontinuities and nonlinearities inherent in hydraulic systems. The control of the servomechanism that controls the hydraulic lift of the topper may be achieved by a microprocessor. The output from either measurement system would be directly coupled to an A/D channel, and the software necessary to drive the sensor, and record a sample could be easily implemented.

For automatic control, a decision-based system would need to be implemented, and one option could possibly be tracking trends and predicting the optimum fan speed/topper height. An alternative could be a nonlinear control algorithm, where the primary extractor fan speed is lowered until the cane loss reaches an unacceptable level, then the fan speed is lowered and the process is repeated. Similarly the topper would be lowered until the sugar concentration is too high, then the topper is 'backed off' or lifted, and once again the process is repeated. An important point to note is that if any method of automatic control is desired, some form of manual override should also be implemented if either function's operation becomes extreme.

Figure 9.4 illustrates three examples of a proposed nonlinear control algorithm. The random input data was simulated in software, and it typifies the trends that would be expected from either measurement system during the harvesting process. The three simulated cases were for varying standard deviations about the same mean.

The signal that illustrates the control algorithm linearly decays at a certain rate until this intersected the input measurement signal. Once this occurs, the output signal is quickly raised at a rate much greater than the decay, and the cycle repeats. The decay and rise times of the algorithm were arbitrary for this simulation, but these would be calibrated in practice.

Figure 9.4 demonstrates that this algorithm would work well in practice, and its adaptive nature would improve efficiencies of the chosen systems. Of course to implement this, or any algorithm, in practice, physical nonlinearities of the machinery such as function slew rates would have to be considered.

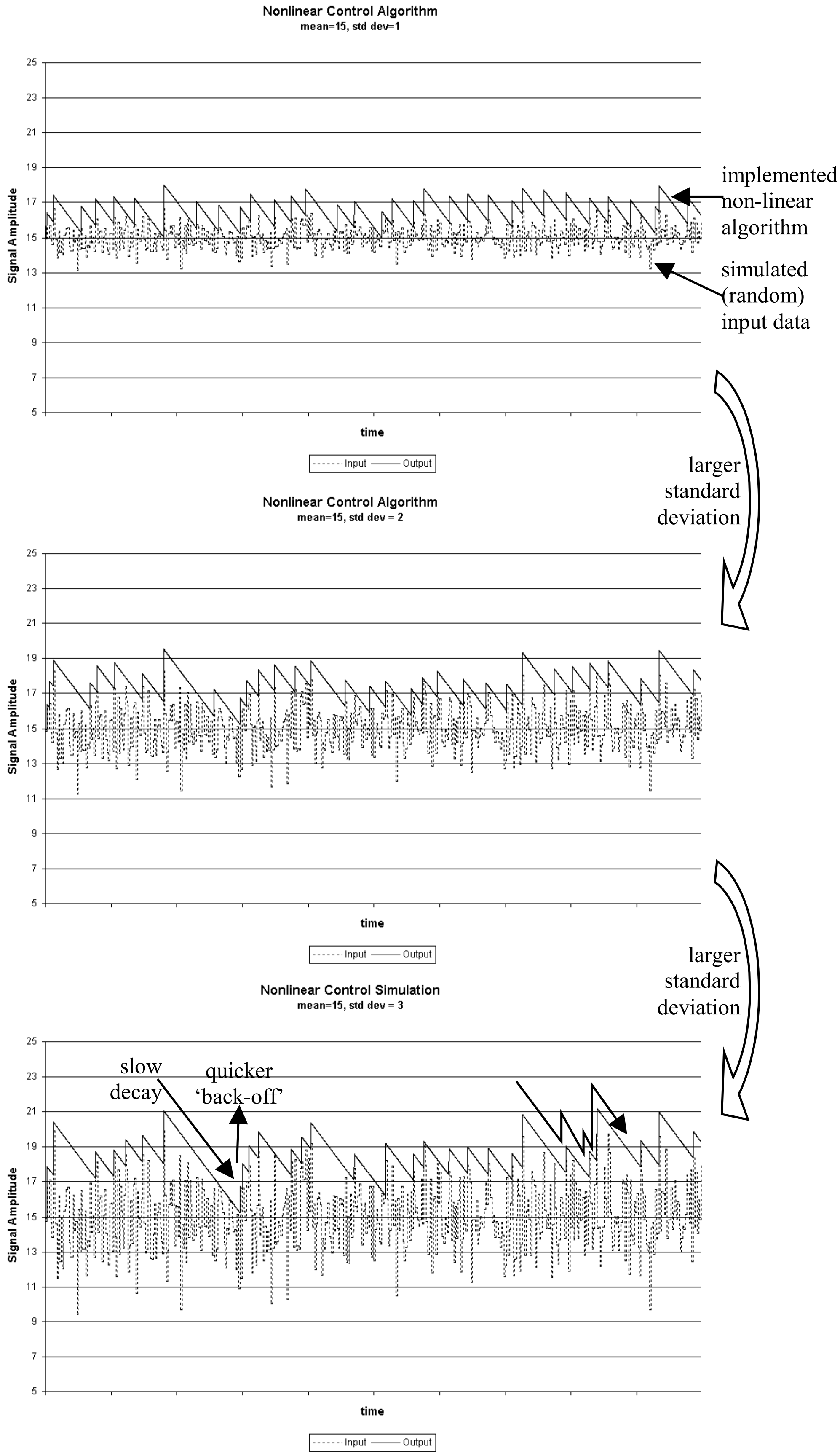


Figure 9.4: Implemented control algorithm on simulated data

9.2.3 Combination of Active and Passive Control

It is possible to combine the first two alternatives presented. The automatic control would be implemented, and the performance of the designated function would be monitored by the visual indication. If either function's operation becomes extreme, or erratic, when automatically controlled, manual override of the function would be enforced, and the indicator would monitor the operation once again.

9.3 Chapter Summary

Measurement sensors have been developed that have an electronic output suitable for interfacing to the eventual on-line control system. Consideration has been given to appropriate feedback strategies and the means of implementation, although opportunities for field tests have as yet been extremely limited.

Chapter 10

Conclusions and Recommendations

10.1 Conclusions

There are many areas where sugar cane harvesters seem to be particularly inefficient compared to agricultural machines in general. An in-depth study of two of the harvester's functions has been made and this dissertation has presented methods whereby their efficiency can be improved. It is important to maintain a generic view of the project to appreciate the objective of simplifying the arduous task of operating a mechanical harvester.

A project such as this requires familiarity with the machinery and its operating environment. To this end, considerable time was spent in the cane field, first to observe the variables that had to be measured and later to commission the resulting measurement and control systems. The time spent in the field led to the selection of two areas of interest, the topper control and the system that separated harvested billets from the trash to be discarded.

The first project was to provide a means of measuring the effectiveness of the primary separation system. A novel measuring system was developed in which the transducer was mounted at the point of contact between ejected billet and fan blade. A rotating signal interface was developed that was suitable for gathering signals returned from the transducer.

The returned signals were analysed and a technique was established to effectively extract the impact information in an accurate and reliable fashion. The signal was in a form that would be useful as a feedback parameter and cane loss was quantifiable.

The next harvester function to be investigated was the topper. Substantial efforts to identify suitable optimum height indicators were expended. These efforts resulted in the development of a novel chemical method that measured the sugar content of the cane stalk at the cutting interface. Developing a suitable method of sampling the stalk in the field created some problems, but these were overcome with the construction of a crushing mechanism that could be mounted to the topper arm. Results from the laboratory tests with the manufactured crushing mechanism and sensor gave promising indications that the proposed technique was suitable. The sugar cane stalk sugar concentration was quantified reliably and accurately, and this information would be useful as an indicator for the optimum topping height.

Ultimately it is the simplifying of the operation of the mechanical harvester that is most important. The logistics of implementing a closed-loop system to the identified harvester functions were discussed, and even the ergonomics for driver assistance were considered to simplify the demanding multifunction task. The developed systems form the basis of an improved harvesting process, and when integrated with other such systems, will improve the standing of Australia's sugar industry.

10.2 Recommendations

Experience gained in field-testing has indicated some modifications that would benefit any future implementations of this project.

Separation System

- Further development of the transducer and signal interface elements should be undertaken so the manufacturing of system components is less labour-intensive. It would be preferable if common components could be implemented rather than custom designs.
- Ideally the transducer would be embedded into the flange of the fan hub, with the leads completely internal to avoid the need for external shielding devices.
- An investigation of the introduction of digital signal processing algorithms to quantify cane loss is advisable. The small microcontroller required could also include the control system software, and this would provide a simple low-cost product.

- The user-control interface requires further investigation. Studies in the industry should be conducted to determine the most suitable control method.

Topper System

- The refractometer could be further developed so that it is less complex.
- Software to interface with the sensor could be developed to provide a more 'user-friendly' environment.
- Once the feedback information is available the most suitable control method should be investigated.

Field-testing conducted under harvesting conditions should focus on the following.

Separation System

- Substantial long-term field trials should be conducted to further assess the relevance of the developed advanced cane loss monitoring technique. This would need to be a broad study that covers the large range of variables that are experienced in the field environment, for example cane variety, harvesting conditions (e.g. burnt or green), and moisture content.
- The sensory separation system should be attempted on the range of primary extractor fans that are commercially available.

Topper System

- Further studies are required to ensure that there is a successful transition for this system from the laboratory to the field environment. This may require changes to the squashing mechanism and juice flow, or even a complete redesign of the concept(s).
- A real-time relationship between sugar content and height of the topper would be the ideal method, so trials to this end could be attempted.
- Perhaps real-time sugar measurements taken inside the harvester (e.g. the choppers) could be used in conjunction with GPS information to develop Brix maps, similar to current yield mapping systems. Although there are

other factors relating Brix to CCS, such maps could possibly be useful as an assessment of cane fields.

The complete redesign of the modern mechanical sugar cane harvester is not a practical consideration, especially if attempting to standardise – or optimise – the performances of all ‘traditional’ harvesters currently in service. The applications of some of the technologies that have been presented in this dissertation are beneficial for the retrofitting of harvesters in service, but also should be a consideration for the design of new harvesters.

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Appendix

Project Research Publications

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2. McCarthy, S.G., Billingsley, J., and Harris, H. 2001, 'Where the Sweetness Ends', Proceedings of the 8th IEEE International Conference on Mechatronics and Machine Vision in Practice, Hong Kong.

3. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, 'Development of an advanced cane loss monitoring system', Proceedings of the Australian Society of Sugar Cane Technologists, Cairns Queensland.

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5. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, 'Control of the Sugar Cane Harvester Topper', Proceedings of the 9th IEEE International Conference on Mechatronics and Machine Vision in Practice, Chiang Mai.

6. McCarthy, S.G., Billingsley, J., and Harris, H. 2002, 'A Sugar Cane Harvester System', Proceedings of the 2002 International Conference on Engineering in Agriculture, Wagga Wagga NSW.