University of Southern Queensland

Faculty of Engineering & Surveying

Automatic Roller Shell Groover

A dissertation submitted by

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Abstract

Sugar, a vital resource, is one of the key products extracted from sugarcane. During the extraction of this product, the sugarcane is passed through a series of grooved rollers. This project is concerned with the automation of the manufacture of these rollers.

After reviewing the various methods that could be used to cut a series of grooves into the roller shell, the aim of the project was to develop a device or machine which will automate part of the manufacture of the roller shells. Specifically, the design was to meet the following requirements:

- Able to handle a typical sized roller and most if not all of the roller sizes used.
- Able to complete assigned operations at an equivalent production rate as current processes employed, or better.
- Able to sense roller position and status and then determine the appropriate course of action.
- Able to operated safely by non-technical personnel.

Rather than attempt to modify a traditional lathe, a novel approach was developed and pursued. This approach was to hold the roller stationary and rotate the cutting tool around the roller instead. Areas that are covered in this document include: traditional machining methods; non-traditional machining methods; sensing methods; control methods; ergonomics; machining and power calculations; and stress analysis.

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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Michael Hugo

Q10217040

Signature

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Contents

List of Figures

List of Tables

Nomenclature

Acronyms

AWJC	Abrasive Water Jet Cutting
ECM	Electro-Chemical Machining
LBM	Laser Beam Machining
PAC	Plasma Arc Cutting

Mathematical

d	Diameter
E	Modulus of Elasticity
g	Gravity
I	Moment of Inertia
L	Length
P	Pressure
r	Radius
y	vertical deflection

Chapter 1

Introduction

Sugar, a vital part of everyday life, is a key ingredient in a majority of foods. In Australia, refined sugar is primarily produced from the crushing of sugarcane. The harvested sugarcane is fed into a series of crushing rollers and the juice is extracted for processing and refinement. These rollers vary in their dimensions and are typically manufactured from certain grades of metal, the exact composition of which is confidential. Like all moving metal machinery parts however, these rollers are subject to wear-and-tear and require periodic repair or replacement.

Crushing rollers are composed of two parts, a shaft and a shell, and the combined weight of which can be as high as 40 T. Both components are made out of similar grades of metal and cast as two separate pieces, machined to suit each other, and then the shell is mounted on the shaft. As shown in Appendix C below, the roller shell is grooved and these grooves are what actually crushes the cane while the the shaft supports the shell and transmits the driving rotation to the shell.

The grooving of the roller shell is currently cut into the shell using a lathe. While some automation of this process currently exists, it is still a time consuming and labor intensive process. It involves positioning the roller within the lathe, checking the size of the roller shell, monitoring the cutting of the grooves, measuring the cut profile, and changing the cutting tool when it is worn. This process is the focus of this project, namely the automation of the cutting a groove in the shell or a sugar mill roller.

Chapter 2

Background

As mentioned above, rollers are used to extract juice from sugarcane in order to produce sugar. Each roller is of course unique on the micro scale, yet overall, each roller is machined as close as possible to a specific macroscopic pattern. That is, there are several common features of all rollers that occur within certain specific ranges and with their own patterns. While it is the combination of these ranges and features that make each roller unique, by allowing for all possible combinations it is possible for all rollers to be considered alike and thus be catered for in a manufacturing machine.

Rollers can expect to have up to 20mm of wear per year and can last 3-5 years depending on treatment and usage. Typically they are replaced after 10% of main shell diameter is worn away (i.e. 600mm dia will be replaced at 540mm dia).

Some of the features that may or may not be included in the final roller, depending upon the requirements of the customer, are:

- Hard-facing
- Shell Arcing
- Juice Rings
- Juice Grooves

Additionally when a roller is sent to the foundry for repair, the repair may include repairing and/or resizing the shaft journals.

These features are outlined in the following section.

2.1 Roller Features

2.1.1 Hard-facing

Hard metal placed on outside of the shell, reducing the wear of the shell and the groove profile. This in turn extends the life of the roller, but is offset by the cost of producing and machining the hard-facing.

2.1.2 Shell Arcing

After the shell has had the grooves cut in it, some customers require a bead of metal to be welded to the tip of the resultant teeth, and partway down the sides of the teeth. These beads are designed to help the shell grip the cane as it is being crushed due to the increased surface area of the teeth. It is important that the arcing be of a high quality, and that there be no 'splatter' from the welds elsewhere on the tooth profile. The amount of splatter is dependant on many variables, one of which is the orientation of the welding head relative to the workpiece and that of 'down'.

One of the "features" of the automatic arcing machine used at the foundry is the fact that the welding head is oriented correctly and then held in position while the workpiece rotates. As the core concept in this project is holding the workpiece stationary, the arcing of shells was dropped from the design. However, if at some latter date, this project is to include arcing, it should be possible to quickly modify the design of the clamps, and add compensation for the rotation of the shell in the controlling computer programs.

2.1.3 Juice Grooves

Juice Grooves are one feature of the sugar cane roller that can vary between rollers. A juice groove is an additional groove at the base of the tooth profiles that aids in the collection and extraction of juice. The juice grooves are perpendicular to the longitudinal axis of the roller, and can be up to 75mm in depth and 16mm in width.

2.1.4 Juice Rings

Juice rings are bolted onto the end of the shell and are an aid in channeling the extracted juices away from the grooves. These juices are then transported to collection ducts to be moved to the juice-pans for holding.

2.2 Manufacture and Repair Process

2.2.1 Manufacture

The manufacturing process for a roller begins when the order for one is placed with the foundry, usually by a mill. These orders can be received up to eighteen months in advance, or could be part of a larger project that the foundry is completing for a client - e.g. for a client who has requested the foundry to design and build a sugar mill, of which the roller is automatically considered a part thereof.

The very first step of the manufacturing process that takes place once the order has been placed takes place, not on the foundry floor, but in the design office. Every mill has its own unique set of characteristics of its rollers. While all rollers were designed and constructed within certain constraints, it is extremely rare for any two mills to have the exact same combination of roller characteristics i.e. roller length and radius, teeth angle, groove pitch, etc. Thus, the design office uses a selection of engineers and drafters to detail the exact design of the roller and its shell to suit the requirements of the client, while also detailing the precise steps to be taken on the foundry's factory floor to produce the roller and shell to the appropriate standard of quality control and

Figure 2.1: Blank shells with center bored out.

assurance.

Once the design reaches the factory floor, there are two distinct processing trees that are followed that, while separate, must still coincide at some point.

The first processing tree is that for the manufacture of the outer shell. The dimensions of the shell are sent to the molding center, where carpenters are employed to build the molds. The casting shop uses these molds to cast the blank shell. The blank shell, in basic terms, consists of a single cylinder, as shown in Figure 2.1. The blank shell has outer dimensions which exceed the required dimensions by a significant factor whilst still by a minimized amount in other words, so that there is plenty of material to work with for cutting the grooves in case the unexpected occurs, whilst still ensuring that there is minimal wastage of materials. Once this blank shell is cast and cooled, a boring machine is applied to the shell's cylinder to remove an internal cylinder along the central axis of the shell, the dimensions of which are those of the appropriate section

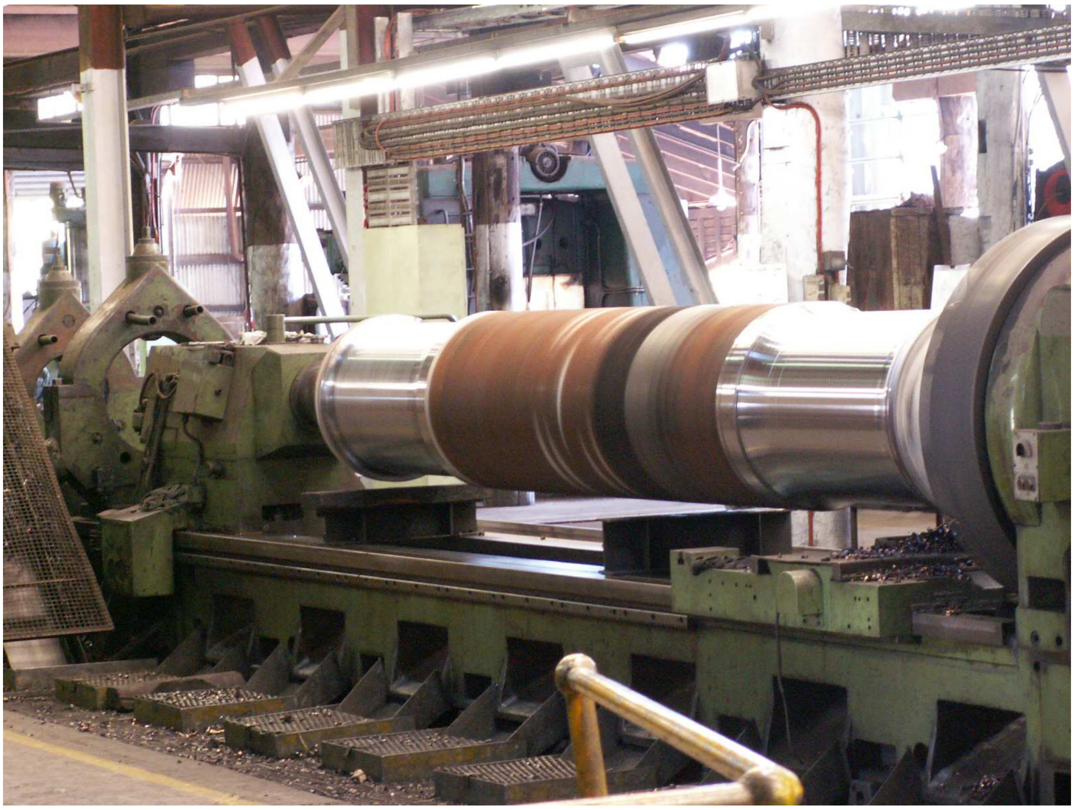

Figure 2.2: Shaft being machined to size

of the roller shaft to within a tolerance of 0.1mm. The shell cylinder thus becomes as a large metal tube. It is at this point that it must now meet up with the other process tree.

The second processing tree is that of the roller shaft, a relatively complicated design that, when placed with its central axis vertical, consists of a series of cylinders stacked on top of each other. Following a similar process as for the shell, a suitable mold (slightly larger than the final dimensions) for the shaft is constructed and then sent to the cast shop. Once the shaft has been cast and then cooled, it is machined to size to suit the client's requirements, as shown in Figure 2.2. Due to the nature of casting, it cannot be absolutely guaranteed that the result is truly circular as it may present an oval-bodied nature to a certain degree, and the central axes of its components may not be as tightly aligned as required. Thus, the cast shaft is placed into a lathe and then machined down to suit the design's requirements and tolerances. Once this machining is finished, the process tree for the roller is complete.

Figure 2.3: Furnace used to heat shells - not in use

These two process are now combined into a single process tree.

This combined process tree has the initial step of inserting the shaft into the roller's shell. As the shaft and shell are designed to have an interference fit, the shell must be heated in a gas fired furnace, shown in Figure 2.3, so that the shell might expand to allow its shaft to be inserted. Once this expansion has occurred to a suitable degree, the shaft is removed from the furnace. At this point, the roller shaft is inserted into the bored hole along the center of the shell and the shell then allowed to cool. Once initial contact is made between the shell and its shaft, the entire roller is moved into the open air to cool naturally. When complete, this step results in the roller literally being locked into place within the shell, as is characteristic of an interference fit.

The next step in the combined process tree is where the grooves / teeth are cut into the shell, and also where the arcing is performed if the client has requested it. This has already been described above, and is depicted in Figure 2.4.

All that remains, at this point, in the process tree are the finishing touches. This includes such things as painting, drilling holes where required to prepare the roller to be inserted in its mill, placing the foundry stamp on the finished article, etc. This completes the final process tree for the manufacturing of the roller.

The roller can then be delivered to its client and the job is complete.

Figure 2.4: About to commence cutting the grooves in a shell

Figure 2.5: Two completed rollers. The rear roller has arcing, the front one does not.

2.2.2 Repair

As with the manufacturing process, the repair process begins when the order for a roller's repair is placed with the foundry. However, after that point, the process differs from when a new roller is constructed.

Officially, the repair process begins when the roller is delivered to the foundry for work to completed on it. This is the point where the design office enters into the process, as the engineers test the condition of all roller components in order to determine precisely what work needs to be completed on the roller. The relevant drawings and designs for this work are then completed and sent to the foundy's factory floor to accompany the roller.

From there, the old shell is removed from the shaft and the material of the shell recovered, if it is at all possible. If the shaft should require repair, it is completed as described below in the following sub-section whilst it is without a shell.

At this point, the repair tree incorporates a process tree, namely that of the manufacture of a new shell. A newly blank shell is molded and cast, and the center of the shell is removed via a boring machine to suit the dimensions of the accompanying roller.

This newly blank shell is combined with the old roller shaft (repaired as needed), and the process tree followed from this point on is identical to the combined process tree discussed previously.

2.2.3 Shaft Welding/Repair

As noted above, this may occur as part of the shell repair process. These situations arise when the wear-and-tear of the roller shaft has caused cracks to appear as well as faults in the metal that bring the shaft outside its specifications.

This is a process whereby metal is welded onto the shaft in the form of a continuous bead. This increases the diameter of the shaft at the weld location. The shaft is them machined to the required dimensions to within parts of 1mm. Due to the time taken for the welding process (including preheating the shaft, welding, welding on top of welds as needed, cool down, etc.) it is typically restricted to where the bearings are mounted on the shaft. These surfaces are typically machined to a high-grade finish and precision.

Chapter 3

Traditional Cutting Processes

There are many ways in which the grooving details can be machined onto the outside surface of the roller shell. Each method has various benefits and problems, and have different speeds at which they can produce the final, desired result.

Traditionally, when grooves need to be cut on a curved surface, the method used is like that used in a lathe. Indeed, the lathe is what is currently in use at the Bundaberg Foundry to cut the grooving detail onto the outside surface of the shell.

3.1 Historical background

The fundamental principle behind a lathe has been known since before the time period commonly referred to as the Middle Ages. Initially, lathes were used to shape wood. The first record of a device that was a type of a lathe was to accurately shape metal by European clockmakers in the early Middle Ages. However, development of metal-cutting lathes was limited due to economical constraints and limitation to available energy supplies. Stephenson (1997) states that the first major study of metal-cutting was in 1798 and was in relation to cannon boring using machine tools, a practice that started in Italy in 1540. By 1850, English tool builders had perfected the design of lathes. However, due to an export ban by the English government, the machine tool industry has been dominated by American companies.

Since that time, there has been a continuous advancement in the implementation and optimization of the fundamental principles behind metal-cutting lathes. One of the more notable advancements was the work done by Frederick W. Taylor. His research (from 1880 to 1905) was instrumental in the development of the famous tool life equations that bear his name, and the understanding about the effects of tool temperatures on the tools. Another major advancement came about in 1900, when the switch was made from using steam engines to rotate the lathe to using electricity instead.

3.2 Fundamental Principles

The fundamental principle of a lathe is illustrated by its typical arrangement in Figure 3.1, where the piece of material to be shaped is mounted between two supports. The support that drives the workpiece and spins it is called the head stock, while the other support is called the tailstock. The actual portion of the headstock that rotates the workpiece is called the spindle. The cutting tool itself is mounted on its own support and this, in turn, is typically mounted on a translating carriage or turret. As can be seen in the aforementioned figure, the workpiece itself remains relatively stationary, its only motion being rotational around the central axis of the final shape. The tool, on the other hand, has linear longitudinal and lateral movement, but no rotational moment. The tool is steadily pressed against the workpiece so that the tool's cutting edge carves the required shape into the workpiece as that workpiece rotates.

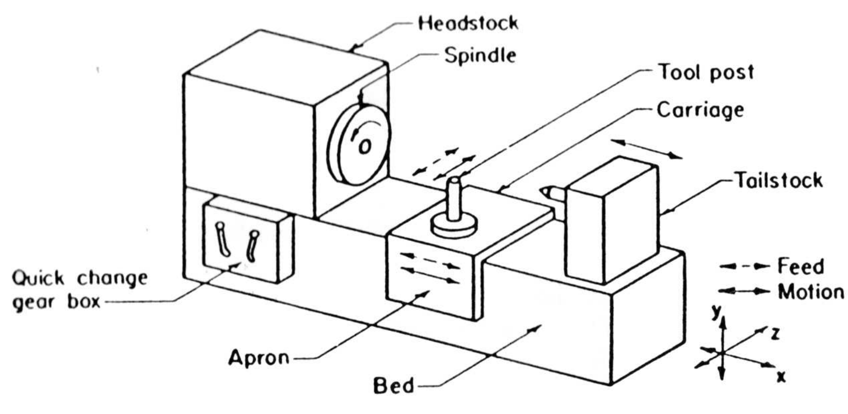

Figure 3.1: Principle components and motions of a lathe. Source: Stephenson, D. (1997)

3.3 Analysis

Much work has been carried out in the area of analyzing the mechanics, physics, and mathematics behind machining metal with a lathe. There are many variables, each of which can influence the other variables to varying degrees. Below is a brief outline of some of the core mathematics behind lathe operation.

One of the main variables that is optimized is that of tool life, as expressed by Taylor's equation. Taylor's equation relates the tool life T in minutes to the cutting speed V through an empirical tool life constant C_t by:

$$VT^n = C_t \tag{3.1}$$

where empirical constant C_t as well as the exponent n depend on tool material, workpiece material, and cutting conditions.

The order in which cutting conditions are determined is first the cutting depth d, then the feed rate f_r, then the cutting speed V (rotational speed of the workpiece itself). Note that these variables are determined in order of increasing impact.

The cutting depth, d, or the amount of material removed from the workpiece surface each cut, is:

$$d = \frac{D_1 - D_2}{2} \tag{3.2}$$

The feed rate is actually the tool advancement per revolution along its cutting path, or how fast the tool is moving along the workpiece with each workpiece rotation. Its specified in either mm/min (f_r) or mm/rev (f), which are actually related through the spindle's rotational speed (rpm) by:

$$f_r = f \times N \tag{3.3}$$

The time required to cut a length L in the feed direction is thus:

$$t_m = \frac{L}{f_r} \tag{3.4}$$

The cutting speed V is affected by the rotational speed of the spindle N, and the initial and final workpiece diameters, D_1 and D_2, by:

$$V = \pi \times N \times \frac{D_1 + D_2}{2} \tag{3.5}$$

$$\cong \pi \times N \times D_1 \tag{3.6}$$

From these variables, we can find the level of the material removal rate per unit time, Q, which is given by the product of the feed rate, cutting speed, and depth of cut, i.e.

$$Q = V \times f \times d \tag{3.7}$$

By combining equations 3.1 to 3.7 and knowing the optimal time the tool should last, it is possible to these equations and empirical data tables to relate this optimal tool life back to the cutting conditions involved, and from there to such things as the material removal rate, and on to the cutting forces, etc.

Chapter 4

Non-Traditional Cutting Processes

There are several other types of non-traditional processes that could be used to form the grooves in the roller. Many books have been written on these methods, which go into much greater depth then is possible here. The methods that will be mentioned below are by no means the only alternative methods available; they are merely the more popular and better documented methods. The alternative methods considered were: Abrasive Water-Jet Cutting (AWJC), Electro-Chemical Machining (ECM), Laser Beam Machining (LBM), and Plasma Arc Cutting (PAC)

However, there are several major limitations and detractors that prevent these processes from being used. Some of these limitations and detractors are outlined below, along with a brief summary of the process.

4.1 Abrasive Water-Jet Cutting

- **Description**

(*Machining* 1999) states:

> *"Abrasive water-jet cutting has been used to cut through 50 mm (2 in.) thick steel plate, leaving a smooth, clean edge that requires no further processing, such as grinding (Ref 34). The abrasive water-jet cuts straight and contour edges without heat; this eliminates thermal distortion and localized microstructural change."*

- **For**

One advantage of AWJC stated by (*Machining* 1999) is that AWJC "*cuts straight and contour edges without heat; this eliminates thermal distortion and localized microstructural change.*"

AWJC also tends to leave the workpiece with smooth and clean edges which require no further machining operations.

- **Against**

According to the research materials available at the time of compiling, AWJC is only suitable for plane sheets of metal, where the cutting nozzle is perpendicular to the work-piece, and the cuts are through cuts. If the cutting nozzle is at an angle to the work-piece, part of the cutting force is deflected, reducing the efficiency of the process.

Additionally, the process uses significant quantities of water, even with recycle systems in place. In view of the current crisis in Australia with a shortage of water, this is major detractor from using this method.

- **Conclusion**

Not Suitable.

4.2 Electro-Chemical Machining

- **Description**

  ECM is a process where the material is removed from the workpiece on the atomic level through the chemical decomposition reaction known as electrolysis. The workpiece is immersed in an electrolytic solution, and an electrical current is passed between the workpiece and a cathode shaped with the desired grooves.

- **For**

  ECM is able to produce a surface finish of between 0.3 μm and 5 μm, although this varies depending on current density, feed rate, gap dimensions, electrolyte composition, viscosity, temperature, flow, and the workpiece microstructure.

- **Against**

  As material is removed from the workpiece, the electrolytic solution will typically become diluted and a ‘sludge’ of waste materials will form which hinders the precise control of the process. This sludge needs to be removed from the solution, and the solution periodically replaced or clarified. Despite the extra costs involved in clarifying the solution, typically with a centrifuge, it is cheaper then the complete replacement even for the cheapest of electrolytic solutions.

  Additionally, due to the dimensions of the rollers that will need to be handled by this machining process, it would economically unfeasible considering the volume of electrolytic solution that would be required.

  The workpiece needs cleaning with either a ‘light’ acid or clean water or both immediately after machining is completed. This is to remove the residue electrolytic solution, and to maintain any achieved precision. This is both labor and material intensive. Although a vapor-blasting might limit the amount of water used, it is still an additional step in the machining process.

- **Conclusion**

  Not Suitable

4.3 Laser Beam Machining

- **Description**

  LBM is a process that utilizes a powerful laster to machine the material. The process works by first melting and then vaporizing a small area of the surface. The vaporized metal is then removed via a transport gas, typically oxygen.

- **For**

  One of the main advantages of the LBM process is that as the laser head does not come into contact with the material and hence does not wear out.

  Another advantage of the LBM over other methods is the readily available cutting medium (laser), particularly when compared to other processes. For instance, ECM, as detailed elsewhere, requires a continuous supply of electrolytic solution; similarly, AWJM also requires a near-constant supply of water.

  The very nature of the cutting medium means that, with careful control, the laser is able to handle fragile and delicate materials that other methods cannot touch. Also, the results are very accurate as the laser is able to machine very fine details into the workpiece.

- **Against**

  A problem frequently occurring with drilling is known as '*optical piping*,' which arises from the internal reflection of the laser light as the hole becomes progressively deeper. The light is increasingly reflected from the hole's walls until the angle of incidence at the foot of the hole is almost normal and most of the light is absorbed in that region. Not only does this reduce maximum hole depth achievable, but it also means that a straight hole is unattainable.

  Moreover, the high temperatures passed onto the workpiece by the laser disturbs the surface layers of its atomic structure and generate what is known as a Heat Affected Zone, or HAZ. This zone reduces the fatigue properties of the workpiece.

  Finally, generating the laser from the emitter uses high amounts of electricity, to the point that there is a power consumption on the order of 200W to 1kW to generate a laser suitable to cutting steel.

- **Conclusion**

  Not Suitable.

4.4 Plasma Arc Cutting

- **Description**

  Plasma, often called the fourth state of matter, is the state of a material where its gas has been heated to the point that its electrons have been striped from its atoms. This produces a substance that is ionized - electrically charged. (An example of this is the air within a bolt of lightning.)

  In PMC, a gas is introduced between a cathode and an electrode that have an electrical arc passing between them. This arc heats the gas to over 3000K, forming plasma which is then directed at the workpiece. This process is primarily used for cutting plate steel.

- **For**

  When used in turning applications, the head does not touch the workpiece.

- **Against**

  One of the main concerns with this process is the thermal stresses. Fine cracks can form if the workpiece is allowed to cool down too quickly, affecting the workpiece's chemical properties and its fatigue characteristics.

  Also, generating enough of a charge differential to create the necessary strength (energy) in the electrical arc that is capable of overcoming the forces keeping the electrons in an atom requires very high levels of energy. Thus, PAC has very high levels of power consumption.

  Moreover, due to its ionized nature (unstable nuclei) and the extreme heat generated, plasma cannot be directed without a very strong magnetic field. Moreover, the effect of particle physics mean that the plasma cannot be directed to a high level of certainty. In fact, other methods must be used to finish the machining in cases where tolerances better than 1.6mm are required.

- **Conclusion**

  Not Suitable.

4.5 Additional Methods

The methods mentioned above are by no means the only non-traditional methods that could be used to shape metal. There are many other methods that could be used, but were not considered in depth as to their suitability for this application. Primarily this was due to time constraints and the initial research which indicated that it would not be worthwhile pursuing them as valid alternative approaches.

The non-traditional methods that were not pursued after the initial stage of the background research are as follows:

- Chemical Machining
- Electron Beam Machining
- Ultrasonic Machining
- Photochemical Machining

This research was primarily conducted in "*Advanced Methods of Machining*" (McGeough 1988*a*) and "*Nontraditional Manufacturing Processes*" (Benedict 1987).

An in-depth consideration of these methods however, might reveal errors in the initial research material which lead to a false conclusion being drawn.

4.6 Results of Analysis

There are many alternative methods that can be used in the place of mechanical cutting. Upon analysis however, these non-traditional methods are not suitable for the application being examined. They are unable to generate sufficient levels of accuracy, too slow to generate results, consume to many resources, and/or are ineffective. Therefore, at this point in time for the application being considered, namely the grooving of sugarcane rollers, adapting the traditional method of mechanical cutting is considered a superior methodology and is by far the preferred option to having to adjust the demands of the application to suit the non-traditional methods.

Chapter 5

Applicable Standards

As with any machine, particularly one of this magnitude, there are various standards and guidelines that need to be adhered to. Thus when the concept outlined within this document is finalized into actual plans for the production of machine, a check to ensure that all appropriate standards have been met should be made. Some of the standards that could apply are listed below.

- AS 1114.1-1985

  Numerical control of machines - Data format for positioning, line motion and contouring control

- AS 1115-1985

  Numerical control of machines - Axis and motion nomenclature

- AS 2004-1977

  Dimensions of carbide tips and tipped tools

- AS 2939-1987

  Industrial robot systems - Safe design and usage

- AS 3877-1991

  Manipulating industrial robots - Vocabulary

- AS 3984-1991

  Manipulating industrial robots - Performance criteria and related test methods

- AS 3985.1-1991

  Manipulating industrial robots - Mechanical interfaces - Circular (form A)

- AS 3986-1991

  Manipulating industrial robots - Coordinate systems and motions

- AS 3987-1991

  Manipulating industrial robots - Presentation of characteristics equipment

There are several other standards that should be referred to in the final designing of the device. Standards such as in the area of Ergonomics for the location and design of the human interfaces, the safety standards for rotating machines, and so forth.

Chapter 6

Design Methodology

6.1 Methods Available

There are various design methods available that are well-known and proven to work with (and not against) the creative process, just as each methodology has equally known and proven pitfalls. The various methodologies can be classified by the descending levels of details to which they are applied, and may be listed as follows: General Project, Overall Design, Large Scale Design, and Small Scale Design.

In order to extract the most beneficial aspects of each methodology while avoiding as best as possible the pitfalls attached to using each one, the design methodology used for this project was a combination of these methodologies applied at various stages and levels. This was done in an attempt to extract the most beneficial aspects of the separate methodologies while trying to avoid the pitfalls that can arise for using them.

6.1.1 General Project

As a single body, the process of developing the design concept detailed herein was a progressive or incremental process. This document, for example, was generally written concurrently with the actual development of the concept. This was done to ensure that any changes in the design were documented in this document, before a final review and possible editing was carried out. The disadvantage to this method was that several large sections were rendered inaccurate, incomplete, and unnecessary due to the evolution of the concept, and thus had to be completely re-written or removed entirely as the project developed.

As a result of following this method, despite the rewriting of this document that occurred, the time spent on actually developing the concept was better managed and slightly increased than it would have been otherwise. This was due to the gradual documentation of previous results and that the conclusions from these results were readily available for review.

6.1.2 Overall Design

When considering the design stage of the project as a whole, i.e. on a grand or overall scale, it was decided that the ideal methodology to use would be what is called the *engineering design process*, as indicated in Figure 6.1. This method would allow the design to proceed in a logical manner, with clear targets or deadlines to be reached, while also drawing on the parts of the project already completed.

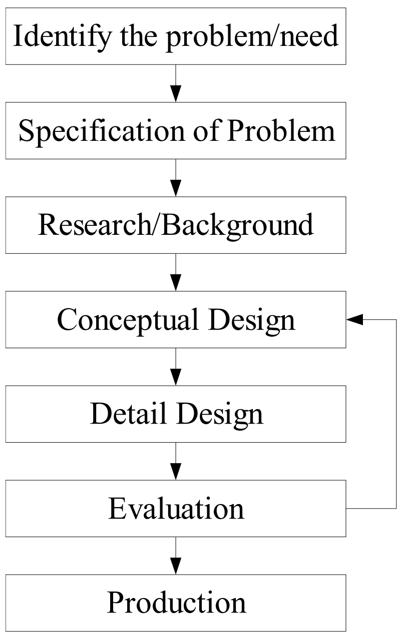

Figure 6.1: Engineering Design Process

6.1.3 Large Scale Design

The intended large-scale design methodology is to be a combination of a 'top-down' and then a 'bottom-up' approach. In the initial stages, this meant that the final design concept and desired device ('the top') was broken down into its various components or tasks. These parts or tasks (i.e. cutting the groove, etc.) were likewise broken down into various sub-tasks, and this process was repeated at all levels until the tasks to be completed can be divided no further. At this point, the various parts needed to complete each sub-task were then designed from the bottom upwards, progressively combined together (redesigning and modifying as needed), until the final device was produced.

6.1.4 Small Scale Design

After the final design was split into smaller sub-tasks, the small scale design methodology was used to actually design each of these sub-tasks. A modular design was used, whereby each of these sub-tasks formed a module which worked on a specific set of inputs to produce a specific output(s). It was decided to use a modular approach, whereby each of these sub-tasks formed a distinct module that worked on a specific set of inputs to generate specific output(s).

There are several advantages of taking this approach. If part of the device broke down or required maintenance, only the modules involved would need repair or replacement, rather than the entire machine. Additionally, by taking a modular approach, as technology improves or advances, obsolete modules can be upgraded without requiring businesses to replace the entire machine. It was also decided that, as far as possible, each module would be designed to be made out of 'off-the-shelf' components. All of this will no doubt reduce and optimise the cost of producing, maintaining, and updating the final machine.

6.2 Further Design Considerations

6.2.1 Experimental Data

Due to the final size and fundamental properties of cutting metal in a turning situation, producing a scale model in order to produce experimental data would not produce valid results. This is because the forces involved in cutting metal do not scale, in that to cut a certain type of metal, it will take the same amount of force per unit area of the cutting tool whether that cutting tool be large or small in size. Moreover, in providing the same level of force for the smaller tool, more pressure is placed on the tool than its size would be able to support, and that the size of the prototype could withstand.

An additional factor in this matter was that, given the resource constraints, it would also be too expensive at this stage to produce said prototype.

The obtaining of experimental data, particularly about the required levels of cutting forces involved, was further complicated by the tight manufacturing schedule that the foundry has to maintain. The lathes at the foundry are under continual operation as the factory works under tight production windows, and it was not possible to interrupt this window merely to place sensors on the lathes to gather data, nor did the resource constraints allow these sensors to be obtained.

These tight production windows are in place due to the size of the foundry business, as noted by Nancarrow (2006) in his article in January 7, 2006 edition of the *News-Mail*. In the sugar industry alone, this heavy engineering business provides spare parts and construction services to markets in Australia, islands in the Pacific, Asia, and South America. It also has up to twelve people traveling around the world for installation and services jobs. For instance, it is currently involved in the construction and installation of sugar mills in Thailand and Mauritius. Outside of its work in the sugar industry, this foundry has been involved in making equipment for businesses such as Queensland Nickel and the Bundaberg Distilling Company.

6.2.2 Automating the Process

It was suggested at one point that the entire operation of producing and/or repairing a roller would benefit from being automated. In other words, that the project focus on generating a *Flexible Manufacturing System* (FMS).

Flexible Manufacturing System (FMS)

The term "Flexible Manufacturing System" can be defined as a system where various inputs (typically data, programs, and raw materials) are then transformed, integrated, and/or processed to generate a definable output (typically a finished product, although it may also be data and/or materials). Extending this definition, the process of converting inputs into outputs by an FMS has minimal human intervention outside of starting and stopping the process. Moreover, a typical FMS system deals with high-level distributed data processing, automated flow of raw and processed materials, with computers integrated into the storage and handling systems.[1]

For instance, in the case of the production of a roller, an FMS would take the set of inputs, in this case the raw metals and the requirements of the design (dimensions, grooving, etc.), and then with minimal human intervention would produce the finished product, namely a completed roller that simply has to be packaged and delivered to the client. (The various steps that are required to convert the raw material into the final product were detailed in a previous chapter of this document.)

Within the FMS are various units, referred as cells or nodes, each of which may be thought of as an intelligent subsystem. The purpose of each cell is to complete steps in the manufacturing process, such as machining, welding, painting, cutting, inspection, assembly, etc. As such, each cell is typically a complete machine in its own right, designed and implemented to complete one or more steps in the manufacturing process that the FMS encompasses.

The advantage of such a modular system as the Flexible Manufacturing System is that

[1] (Ranky 1983)

it need not only be applied to machining systems, but also to other computer-integrated projects where the machining process is itself a part of the whole.

Is An FMS Possible?

While the proposition of generating such a system to automatically manufacture and/or repair a roller does have merit and would indeed have application in today's modern world, there are some concerns that had to be considered first.

Upon further investigation and consultation with the local supervisor, it was determined that to automate the entire process of manufacturing a roller (the current process being as described in an earlier chapter) would require designing and detailing a machine for each step. These steps include the construction of the mold, casting, boring a hole in the shell, machining both components as necessary, then heating the shell and inserting the shaft, and finally cutting the grooves. Machines would also be needed to place arcing on the grooves if required, to drill and tap holes in the shell, and also to cut and place juice rings as well as wear rings on the roller. There would also need to be facilities to place roller components in-to and out-of storage as needed. Moreover, to incorporate repairing a roller into this process would require additional machines to cut the shell off the shaft and to also salvage the materials (or deliver them to a workshop where this will happen) of the shell if this is possible, and then to use welding to increase the material of the shaft so that it can be re-machined.

As can be seen, there would be many cells needed to form a Flexible Manufacturing System suited to the manufacture and/or repair of a roller. Each cell is likely to require its own machine (if not multiple machines for some of them) for its set task to be completed, as well as the facilities to integrate as seamlessly as possible with other cells in the system.

Designing such a system in one year would require the resources of an expert team of engineers from various disciplines, if not multiple teams to complete the level of research, design, development, and testing that would be required. Moreover, even if the technology was already in existence and only had to be combined to form a final design implementation, an engineer with many years of experience with this particular industry called attention to the fact that it would be a multi-million dollar project before it could be completed. The costs would be so high not only because of the amount of engineers involved to complete the design in the required time-frame, but also because of the disruption this would cause to the local workforces even to bring the design up to the level of being ready to present for peer examination and approval. Additionally, these costs and disruptions would be of such a level that any factory floor that might be built from these design would need to operate for years to “break-even” in order to cover these design costs.

In short, designing such a Flexible Manufacturing System for this application is simply too large a task for one engineer with limited time and resources to complete with any degree of satisfaction in the results.

It was therefore a logical decision to focus this particular project on one part (cell) of the whole system, that only a portion of the manufacturing and repair process of a roller would be considered for automation. Namely, that the focus would be centered on designing a machine to machine the grooves into the roller (that is, into the shell while the shaft is in place).

It is thus hoped that, in the fullness of time, the final design considered herein might be used as a cell in a larger, automated process.

Chapter 7

Issues

7.1 Introduction

Despite the various design methodologies used, as outlined in chapter 6, or in some instances because of these methods, serval issues came to light that needed to be addressed. These issues covered a variety of areas, with varying degrees of impact. Some of the issues were able to be dismissed quickly as not being truly applicable, while others highlighted areas of major concern. These issues have been documented below.

7.1.1 Design Issues

- ***Required Cutting Force***

  Reason: In order to shape metal, particularly in the turning process, large forces are involved. These forces need to be generated somehow and also allowed for. If the forces are too large for the design of the machine, serious failures of both the machine and the workpiece could result.

  Is it a Problem? See Appendix B for calculations of the forces involved in turning the typical roller.

  Determination: Not a problem with the correct design and allowances made.

- ***Safety*** (See also Section 7.1.2 below)

  Reason: Safety is a major concern and factor in the design. If the machine is unsafe, it will not be used. Additionally, if the machine was found to be unsafe due to a design error, the designer would face the possibility of legal action against themselves.

  Is it a Problem? Yes.

  Determination: Incorporate multiple safeguards in the design, and use safe methods.

- ***Environmental***

  Reason: The machine is to be used in a foundry. Thus the environment that the machine will be used in is neither laboratory clean nor air-conditioned. The expected operating conditions are very hostile to machines and the machine will be expected to cope with the environment for multiple years with only simple maintenance.

  Is it a Problem? Yes. This will influence the design considerably.

  Determination: Design the machine to meet industry standards for the environment. Design for a hostile environment and make allowances. Armor wires, use angled rails to prevent swarf build-up, enclose electronics, etc. As far as possible, design to IP65 rating.[1]

- ***Shaft Deflection***

  Reason: All metal cylinders of sufficient length will deflect if supported only at each end, and will also experience some deflection in the middle when supported at both ends. This deflection is due to the cylinders own weight under the influence of gravity. Additionally, any forces imposed on the cylinder will alter the amount of deflection. Overall, the net deflection is proportional to the qualities of the metal, the length and the radius of the cylinder, and the forces that are being imposed upon it.

[1] According to (*Altronics Electronics Engineering Catalouge 2005/2006* 2005), an IP65 rating means the object is dust-proof and spray proof. Please consult the relevant Australian Standard for further details.

Is it a Problem? See Appendix B for details on the calculations of the deflection for a series of shafts with shells.

Determination: Not an issue.

7.1.2 Safety Issues

There are many safety issues involved in the project, some of which are avoidable, but others have to be addressed regardless of what approach may be used. However, the exact nature of the specific safety issues that are to be handled in the project depend largely on the final design or implementation of the concepts covered. Thus, safety is to be one of the key criteria used to evaluate any final design or implementation.

One such example of a safety issue that must be handled regardless of the final design and implementation is the issue of safely cutting the metal shell.

As brought out above (in Chapter 4) the method of producing the grooves in the roller will be following a process similar to the traditional processes currently used due to the limitations of the other (non-traditional) methods in this particular application. However even our chosen method is not without safety hazards, as brought out below, and several safety considerations need to considered. While most of these considerations were mainly identified in the event that an alternative method was used, they are still relevant to the design because the fundamental principles behind them are highly applicable.

- If the full traditional rotational method was used:
  - Prevent operators being injured by material that has been removed from the workpiece.
  - *Principle:* Workplace health and safety.
- If a chemical cutting agent was used:
  - Ensure workers are not exposed to any fumes or hazardous gases;
  - Ensure workers cannot come into contact with corrosive agents;

  - Ensure that chemical agent is completely removed from workpiece upon completion of cutting.
  - *Principle:* Handling of hazardous materials.

- If a 'high-power' cutting laser was used:
  - Ensure laser only activates when roller shell in machine and at the correct distance from the workpiece;
  - Ensure that the laser is at the correct power and cutting duration;
  - Ensure that workers cannot accidently place part of their body or other items in the laser beam;
  - Ensure workers cannot look directly into laser;
  - Ensure that there is a suitable guard behind workpiece to interrupt and absorb the laser beam;
  - Ensure that any reflections do not cause a hazard.
  - *Principles:* Ensuring correct use of machine and minimizing risk of injury when improperly usage or interfaced with; controlling the human element as much as possible.

- If a 'low-power' scanning laser was used:
  - Ensure laser only activates when roller shell in machine;
  - Ensure workers cannot look directly into laser;
  - Ensure that any reflections do not cause a hazard.
  - *Principle:* See previous section.

- Electrical concerns:
  - Electrical connections and components are not exposed, and that they are shielded where needed;
  - Ensure that there is a safety switch in the event of a short-circuit or failure;
  - Ensure that 'safe' voltages and currents are used as much as possible;
  - Ensure that there is sufficient isolation between modules, i.e. isolate the controls from the computer processor and from the motors.

Figure 7.1: Typical warning label to be used with laser equipment. Source: "AR-600 data sheet" from www.acuityresearch.com

- *Principles:* Safe use of resources and minimizing their wastage.

- Controls:
  - The controls are easy to see and use;
  - Ensure that the manual controls can override the automation at any time except to breach safety restraints;
  - Ensure the controls can not be accidentally activated during operation.
  - *Principle:* Interfacing with and controlling the human element.
- Other safety issues:
  - In an emergency, the machine stops in a safe manner;
  - Where-ever a worker is around the machine, there is an emergency stop within easy reach;
  - The machine can not be activated while in an unsafe situation, i.e. undergoing maintenance.
  - *Principle:* Operational safety.

Some of the above safety concerns cannot be fully minimized during the design stage, but require safe working habits on the part of the workers, i.e. not trying to bypass the failsafes, etc. During the development of the concept, various methods were found and explored that would cover all the issues mentioned above. However, as the design was only able to be taken to conceptual and not to the final design stage, these methods are not included in this document for the sake of clarity. Further consultation on these matters is recommended when this concept is sought be developed further.

The exact nature and specification of the safety implementations would be finalized during the actual design of the device, and would adhere to the guidelines specified by the relevant Australian and International standards as a base minimum. Some of these standards are mentioned in Chapter 5.

Chapter 8

Sensory Methods

8.1 Methods to sense/measure environment

There are many methods that can be used for the device to sense the location and dimensions of the roller shell to be machined. These basically can be defined as either requiring contact or non-contact methods. However, as the design brief stated that the location of the surface of the roller was to be determined with non-contact methods, only these methods were considered.

Non-contact methods include:

- Ultrasound
- Optical
- Magnetic

Each of these methods are explained in more detail below.

8.1.1 Ultrasound

Ultrasound is the term used for sound that has a higher frequency than audible sound, typically, above 20kHz. At these frequencies, sound waves tend to become highly directional, and can be thus used as a method of sensing the environment around a device. Ultrasonic 'sonar'-like devices are often used in mobile robotics (both at a hobby level and at an industrial level) as collision prevention mechanisms. Due to the much slower speed of sound propagation in air when compared to optical or radio methods, these 'ultrasonic sonar's are also able to directly measure distances, using time-of-flight methods rather than using triangulation methods. At sea level in calm air at 20°C, sound travels at approximately 334m/s. Also, due to the larger wavelength and wavefront of ultrasonic sound waves, small items like dust particles will not affect the accuracy of the sensors, whereas dust particles can disrupt optical sensors in sufficient concentrations. Most hobby built 'ultrasonic sonar' arrangements can resolve a distance to between 5-10mm. However, professional producers of ultrasonic distance measuring devices have claimed that they can achieve a 0.1% to 0.01% accuracy, i.e. 0.01mm at a distance of 100mm[1]. The downside to ultrasonic measuring devices is that they are fairly delicate, and prefer relatively vibration free work platforms.

8.1.2 Optical

Optical sensing methods are methods of detecting the surrounding environment using light. There are many different types of optical methods that may be used. For example there is visual sensing with a camera or similar, distance measurement via triangulation, and location determination via a beam breaking arrangement.

Visual scanning via camera basically mimics the function of the human eye and the visual processing abilities of the brain, to a limited extent. There has been much work done in this field of optical sensing, however it is not able to be used to measure the dimensions and shape of the roller being machined. The required resolution for that particular application is too great for this method, and the processing overhead would be too high. On the other hand, a camera could be used along with a steel rule to

[1](Opara 2005)

measure the position of the tool along the longitudinal axis of the machine.

Beam Breaking is possibly the simplest optical sensing method. It involves a transmitter and a receiver. The transmitter constantly sends a beam of light to the receiver, and when an object of sufficient size gets between the two, the beam is broken.

Distance measurement via triangulation is more difficult than a simple beam breaking approach, but is less vibration sensitive than a visual method, as multiple measurement if taken within a short enough window, can be averaged and the vibrational error mostly removed. This method can also produce a high resolution result. The light (typically a low powered laser) is reflected off a target and into a high resolution camera mounted a set distance and angle offset to the light source. The position of the reflection in the camera can then be used to quickly determine the position of the surface that the light reflected off.

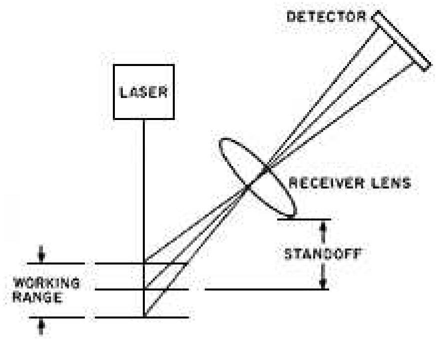

Figure 8.1: Laser Triangulation Principle. Source: Kennedy, W.(1998)

8.1.3 Magnetic

Another method that could be used for sensing the position of material are magnetic sensing, for example using Hall Effect Sensors. This works by detecting alterations in magnetic fields caused by the metal. The magnetic field typically is either generated by the sensor, or by passing a current through the metal. However, for this application, it is not feasible to use magnetic senors.

8.2 Methods chosen

After consideration of the above aspects, the following chooses were made:

- Ultrasound

  Due to their coarser resolution and its preference for a large, flat surface to reflect off, it was decided that if an ultrasonic sensor were to be used, it would not be to use an ultrasonic 'sonar' as a measuring device. Rather, it would be used as a safety device, particularly in detecting the presence of a shell.

- Optical

  The accuracy and resolution that can be obtained using this method of sensing means that it is almost ideal for this application. Thus, optical sensing should be used as the primary sensing method.

- Magnetic

  While magnetic detection method for metal does have its applications, this is not one of them. The mass of metal is too small, and the required precision too great for magnetic methods of detection to be used as the primary sensing system.

8.3 Other Sensors

Although sensing the location of the surface of the roller shell is one of the main requirements of the sensors used in the device, it is not the only item that needs to be monitored, measured, and suitable reactions made as a result.

However, it should be noted that as the design discussed in this document is only completed to a conceptual level, and not to a final specific design stage, only major details will be included. Moreover, the ever-changing "face" of technology means that any equipment or component suggested here may well be obsolete or deemed unsuitable by the time the machine is actually constructed. Thus, the exact components to be used and their specifications would be detailed during the transition from concept to working prototype and/or to final design.

That said, these additional sensors required and their purpose(s) are explained in the following chapters.

Chapter 9

Initial Designs Considered

Having specified and considered the issues involved with this project and the methods to be used to complete it, it is at this point that the concepts and designs to implement these ideas may be considered. The aim of this consideration is to produce a *conceptual design* of an automated shell grooving machine.

For the purposes of this thesis, 'conceptual' is here used in regard to its definition of "an elaborated concept." Hence, the main focus was determined to be on ways to implement the basic concept described in Section 9.1, in order to describe the major components and key elements such an implementation would require. Critical dimensions are given mainly as figures based on appraisals of existing roller designs and a consultation of the appropriate industrial standards (some of which are mentioned in Chapter 5).

For this reason, specific dimensions of each component and the complete and detailed design of the final machine has been viewed as outside this conceptual level of design. This is largely because the conceptual designs are yet to be fully approved and officially examined to determine whether the reasoning behind the designed can be found to be sound. Until that occurs, it would be foolhardy and wasteful to act on decisions that might yet be found to be faulty. The designs referred to in this chapter and in the following chapter are included in Appendix D.

One major decision that was made was to rest the entire design on a relatively simple principle, which will now be examined.

9.1 Core Principles

The basic design concept (pursued in various incarnations) is an alternative approach to the traditional method of cutting metal. As outlined above in Chapter 3, the principle behind this tradition is based on relative motion between the tool and the workpiece in a machine that we've come to refer to as a 'lathe.' This is usually accomplished by rotating the workpiece and holding the tool in a 'fixed' location. Any variation in the 'fixed' location is as minimal as possible, and is rather small compared to the continual and relatively fast rotation of the workpiece.

This is a method that is especially suited to relatively small objects needing to be machined to a certain shape. However, the drawback of this method becomes increasingly obvious as larger and larger pieces are considered. If the workpiece is of significant mass, a great deal of energy must be expended in order to rotate it, whereas a proportionally smaller amount of energy is used to move the tool. Moreover, a relatively large amount of energy is required to quickly overcome the extremely high inertia of a large workpiece in the event of safety emergency.

Considering that the extreme worst case scenario is a roller of up to 40T, the energy required to rotate the roller greatly outweighs the amount of energy that would be needed to instead rotate the tool, which might typically weigh only as much as 100kg (by itself), around a particular central or rotational axis or point.

Thus, it seemed a rather obvious and logical decision to switch the location of the rotational movement. That is, instead of rotating the workpiece and fixing the tool, it was decided to instead fix the workpiece in place and rotate the tool around the piece.

There were two design concepts that were partially developed before the final concept was developed. Due to their incomplete and partial nature, however, they will be considered relatively briefly.

9.2 Design Concept I

9.2.1 Features

The first design implementation was based on multiple long and thin worm gear like shafts which could be placed on an invisible ring concentric to the roller's perimeter, along which one or more large metal rings could be moved. In this design, each ring would support a particular tool to be rotated around the roller.

These complete rings might be considered to have three components, each component being a ring in itself. The outermost 'ring' is that through which the worm gears are run, through six shafts radially located in the ring, though not technically equally spaced around the ring. They would be equally spaced were there eight shafts instead of six (located at standard angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°), but it is as if the two shafts at 90° and 270° (along the vertical axis) are no longer present. The reasoning behind 'removing' the shaft at 90° was to facilitate the placing of the roller into the assembly through the top via a crane, and thus also for extraction of the roller. The bottom shaft, at 270°, was removed to preemptively prevent it being fouled by the swarf produced during machining operations.

Each ring assembly would derive its lateral movement and position from a single worm gear shaft on this 'outer'. The remaining five shafts for that particular ring assembly would be used to provide structural rigidity. This would be achieved by placing a fixed bearing on the 'drive' shaft while placing a bearing that is free to rotate on the remaining five shafts. Each ring assembly would be driven by a different shaft, allowing for up to six rings to be run simultaneously. Moreover, the worm gear shafts would perform a "double duty" by providing lateral positioning as well as support.

The 'middle' ring can be considered to be hollow, as it is designed to shield the mechanisms to rotate the 'inner' ring whilst simultaneously providing a "guide rail" for that inner ring to rotate on. This latter purpose of the middle ring is provided by using a lubricated "tongue-and-groove" fit to the inner ring. Thus, it is actually this 'inner' ring that rotates around the roller by sliding along the 'grooves' in the middle ring.

This entire system is guided by a drive assembly at one end of the six drive shafts, which contains a separate motor for each one of the shafts.

Each roller shaft is connected at each end to a lathe-type support which has been modified to hold the roller shaft stationary. The support at the drive-assembly end is fixed in place, while the support at the other end is able to be moved to accommodate various roller lengths.

9.2.2 Flaws

One of the most critical errors of judgement in this concept implementation was the lack of support provided for the worm drive shafts. Being long and relatively thin, asked to support multiple ring-and-tool assemblies, as well as having a gear profile cut onto its surface in the dimensions required, it would be impossible to prevent these drive shafts from bending in the middle of each run. Due to each shaft's unique physical characteristics, they would each bend by a slightly different amount and would thus change the gear profile. This would cause it to lock up in the bearing assembly and would rapidly lead to a cascading catastrophic failure.

The other main flaw is that there is no measure to ensure that the ring assembly does not buckle. Such an event would be caused by the assembly failing to maintain a normal orientation to the roller surface due to not advancing by identical amounts along all six shafts. This would be exacerbated by the thin-ness of these rings in the design. They were not made thick enough to prevent buckling, and attempts to make them thicker would only advance the failure of the shafts as discussed in the previously.

While there were other flaws, such as not being able to ensure the centerline of the roller is the same as the centerline of the device, these two main flaws were considered drastic enough for the design to be reconsidered and eventually abandoned.

9.3 Design Concept II

9.3.1 Features

The second conceptual implementation arose largely as a result of the flaws of the first. Where the first design was largely circular in nature, this design employed square frames and carriers to support the assembly in an effort to provide more support and rigidity.

The implementation, as conceived, used two grid like structures, tied together at either end to support and contain the cutting tool and arm. Each of these two structures are approximately 9380mm in length, stand 3150mm high, and are constructed out of 380 PFC [1]. This material was chosen to minimize the amount of material that had to be "custom made" through utilization of material that can readily be obtained with known dimensional standards. The structure consisted of 7 legs, equally spaced along the longitudinal axis (1500mm intervals), onto which 3 inward facing guide rails are mounted at 1100mm intervals from the top of the device. As mentioned previously, the two structures are tied together at the top of both ends by a "spacer," in order to maintain the rigid structure.

The outer framework and guide rails thus provide a basis for supporting the carrier frame. The vertical loading (weight) of the carrier frame is primarily carried on two separate guide rails on the floor which are positioned at 1100mm intervals from the center-line of the device. These are made also from 380 PFC[2]. The carrier frame has three wheels or rollers per guide rail mounted on it, in a manner that takes inspiration from roller coasters. This was intended to eliminate any possible (undesired) movement of the carrier frame other than the longitudinal travel along the length of the machine. Like the framework, the carrier itself is essentially square in nature, with a slot in the top for the ring assembly to be inserted.

[1] As per Australian Standard AS 4100, see Appendix F for datasheet extract from an Australian manufacturer

[2] An alternative mechanism to support the vertical loading was developed using two closely mounted 200 x 200 x 20EA which would tend to collect swarf was also developed.

It is this ring assembly onto which the cutting tool is mounted. The ring assembly, once locked into the carrier frame, is able to rotate the tool around the roller shell, thereby cutting the grooves. This assembly was made removable from the carrier in order to facilitate the use of different sized ring assemblies for different sized rollers. The motor that rotated the ring would be mounted on each of the ring assemblies. The ring assembly would be able to be inserted into the carrier frame via the same crane that would be used to load the roller with shell into the machine and then extract the final product again. This assembly would be inserted first, the carrier frame, driven by a shielded worm and groove assembly mounted at the center of the bottom of the carrier, would then be moved to one limit of its travel, the roller inserted, and then the ring moved back into place once the roller with shell was secured. This is possible because the upper limit to the size of the roller that the machine is designed to handle, as stated elsewhere in the design brief, is 7200mm.

9.3.2 Flaws

It is a well documented fact that changes in temperature will cause metal to expand or contract accordingly. It is also a given acknowledgement that every piece of metal has its own minute flaws in structure and composition, and that these are essentially random and unpredictable in nature and position. These two effects combine to produce the result that two lengths of metal, placed apart, cannot be guaranteed to both expand and contract to the precisely same amounts in the exact same direction and manner. Thus, it is more likely than not that each of the fourteen supports or legs as well as the eight guide rails will all react slightly differently to the heat generated through operation of the device as well as that from external environment factors. The environment this device is expected to operate in would be considered “highly hostile” in comparison to laboratory conditions.[3]

An additional flaw in this design is similar to one encountered in the initial design, namely that there is no real provision in place to ensure that the carrier advances

[3] The expected industrial environmental conditions to withstand include large temperature variations from 0°C to upwards of 40°C (on good days), vibration from other machines, dust, grease, paint, metal shavings (swarf) and metal dust, wear-and-tear through use, and also human error, to name a few.

equally along all rails at any one time.

9.4 Outcome

As has been already noted, both concept implementations were developed only partly before their flaws were discovered, usually during discussions with the local supervisor of this project. These flaws were considered so critical and intrinsic in nature that it was recommended for both implementations to be completely scrapped and a new method developed.

This 'new' method of implementing the core concept was the one that was chosen as being most suited to the final design, and as such is considered in the following chapter.

Chapter 10

Final Design

The design concept has only partially been compiled into a cohesive whole. At the time of writing, the concept was mostly completed to the concept stage, with a few details to included, finalized, or worked out how they matched the rest of the concepts. As such, a completed finalized conceptual drawing showing everything is not able to be included. Instead the various components of the concept shall be introduced and discussed. This is intended to demonstrate the completed concept as much as possible and to lay the foundation work for the concept to be finalized into a constructible machine.

10.1 Main Design Concept

This basic idea of the design, namely of keeping the roller still and rotating the tool, is the concept that was explored and developed for this conceptual machine. After several partial design iterations (see Chapter 9), the concept was developed to the stage shown below in Figure 10.1.

In contrast to all previous implementations, this design lacks an outer framework to support the ring assembly that is used to mount and rotate the tool. Instead, the carrier assembly itself has a base which is larger in width by a significant margin than the ring assembly and is moved along the roller as necessary. The roller is supported at either end, the design employing the sheer size and weight of the roller to keep it

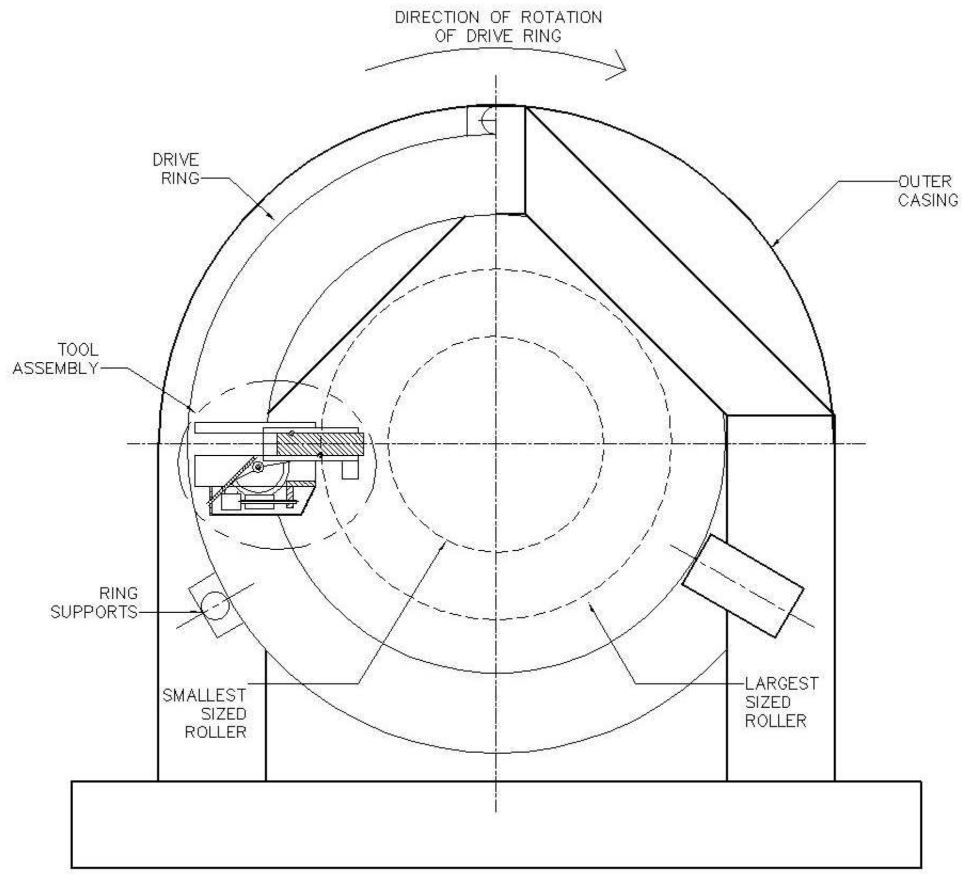

Figure 10.1: Design Concept

stationary.

The ring assembly has a main carrier ring mounted on either side of the tool (detailed in following sections). Unwanted vibrational movement is constrained through its size, as the ring assembly is estimated to weigh 3.5T. As before, the rings are turned by a separate motor, though this motor is mounted on the carrier in such a position and manner to also minimize vibrational error. Unlike previous methods, the actual ring assembly itself is only supported at three equidistant points separated by 120°. This thereby minimizes referencing errors. The base of the carrier travels along two slotted rails and the lateral movement is provided by a shielded worm and groove drive, similar to that used in existing lathes. One advantage of this design arising due to the outer casing and size of the support/carrier structure is that the risk of someone putting a hand between the tool and the workpiece is almost impossible, thereby maximizing safety.

10.1.1 Tool mounting

The method of mounting the cutting tool onto the machine can be technically classified as a '*swing arm*' style of design. However, as with the approach to a lathe above, the implementation of this swing arm design is again an unorthodox approach.

In automated device, the tool itself is already being controlled along two axes, namely, along the longitudinal axis of the workpiece and along the axis normal to the workpiece surface. Therefore, it should be only a slight increase in complexity to combine these two motions with a third motion which maintains the relative rotational motion between the tool and the workpiece. This was one of the core ideas behind the design concept.

Towards this end, the design incorporates a tool assembly that effectively 'orbits' the workpiece. The tool assembly itself is mounted on two adjacent rings to maintain rigidity. Due to the size of these rings, very little in the way of vibrational dampening is required to ensure tool accuracy. The size of these rings is also one of the main limitations of the machine in terms of the largest size roller it can machine.

Each of these rings can effectively be thought of as a very large gear cog that has been hollowed out to the diameter of at least a typical sugarcane roller. Due to the arrangement of the rings, they can be driven together from a single axle which transmits power via a gearbox from a suitably rated electric motor. This complete ring assembly would then be mounted on a frame to provide the relative linear motion of the tool parallel to the roller's central axis.

This circular nature of the method of mounting tool assemblies onto the machine allows for the possibility of various tools being mounted on one ring-pair. This increase in the number of identical cutting tools on the ring decreases the time taken to perform the required task without also requiring a proportional increase in the ring's rotational speed. For instance, two tools can be mounted on diametrically opposite each other on the ring assembly, one of which cuts a groove at half-depth while the second tool cuts the metal at full groove depth. Note, however, that more than three tools mounted on a ring assembly are expected to lead to diminishing returns as well as physical size limitations.

10.1.2 Welding

One of the initial actions that is was hoped that the device would accomplish was the combining of the shaft welding and shell arcing along with the machining one the one machine. Ideally, both types of operations would have been done simultaneously, on different parts of the roller. In fact, the stationary workpiece was an attempt to cater for the different rotational speed required by the welding process than that required by the machining process.

However, it was quickly realized that the welding process had a 'sweet' spot, relative to the pull of gravity, which would allow for quick welding with no splatter where it was not wanted. Some orientations of the welding tool would be guaranteed to produce problems, with the weld moving before the metal fully cools and solidified, excessive 'splatter', and/or the welding matter damaging the welding tool. The way to avoid this would be to have the welding head fixed in the 'sweet' spot, and the workpiece then rotate along its axis. However this would negate the advantages gained by having the workpiece held stationary while the tools orbited it. Thus, this optional feature was dropped from the concept, at this stage.

The design, however, is such that if this feature were to be required in the future, any modifications should be relatively simple to implement, namely: a suitable drive motor (with controller) to turn the shaft, a sensor of some sort to detect the rotation of the shaft, and sufficient modifications to the controlling software to compensate for the additional rotation of the workpiece.

10.1.3 Other Features

Another feature of the design is the ability to place multiple rings on the device, each with the appropriate cutting tools. Assuming of course that the automation of the machine can handle the additional operations, this leads to the possibility of carrying out multiple tool operations on the roller at the one time by operating a number of rings simultaneously. This would lead to multiple reductions in the time to complete one roller.

10.1.4 Pros and Cons

The advantages of this concept may be summarized as follows:

- Overall it's more energy efficient to move the tool and supporting members (expected to be no more than 4T in total) than to move the large roller (min. 2T up to 40T, average size of 13T)
- Easier to safely stop rotation of tool than rotation of roller in case of an emergency
- 'Fixed' loading on motor which as a result make it easier to tailor motor to design - smaller motor needed or able to work faster
- Able to work on multiple parts of roller at different rotation speeds
- Very high flexibility of use.

On the other hand, the disadvantages of the design are as follows:

- A lot more complex than the standard lathe;
- Larger than the standard lathe, and thus may not be a suitable fit for all its possible implementations and/or usages;
- The difficulty of obtaining data and sending instructions to and from rotating instruments and sensors;
- Increased likelihood of swarf adversely affecting operations, depending on the tool's location.

10.2 Electronics

10.2.1 Mechanical tool-life sensing

A strain gauge is a small electronic device that is used to measure strains in a material. It is comprises typically of a length of fine wire arranged in such a manner that when it is subject to a strain, the length of the wire increases. As the length increases, following Ohm's law, the resistance also changes. One disadvantage of most modern day strain gauges it that they are only sensitive to strain exerted along a single axis. Thus in order to monitor two dimensional strains in a material, multiple strain gauges are needed. The ideal situation would be would be for three strain gauges mounted in such a manner that their sensing axes are at a 45° angle to each other.

Despite the arrangement of the wires, the resultant change in resistance is only negligible. As such it will need to be amplified to measurable levels. This is typically done in a Wheatstone bridge arrangement. A small resistance change in a normally balanced Wheatstone bridge creates a significantly larger change in voltage, amplifying the minute resistance change in the strain gauge into a measurable voltage. The other option is a dedicated unit specifically designed for the measuring of strain gauge resistance, for example one of the many Data Acquisition Systems produced by National Instruments.

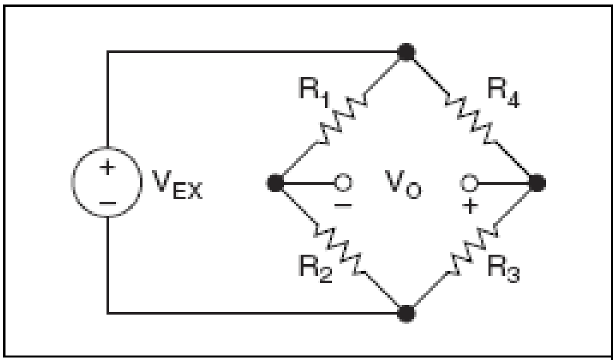

Figure 10.2: Wheatstone bridge. Source: National Instruments (2003)

The strain gauge is coupled with a model stored in the computer of the expected tool-life under various conditions,

But why is a strain gauge needed? As the tool cuts the metal, a force is exerted on the tool tip, leading to stress. These stresses, are related to the strain that the tool is experiencing. These stresses and strains are then transferred to the tool holder where they can be measured. As the tool wears, the cutting force needed, and thus the stress and strain produced, increases. Thus by measuring the strain in the tool holder, it should be possible to monitor the condition of the tool. This is done by as set of strain gauges, along with the principles developed by Mohr, to resolve the strains to a set frame of reference. When coupled with a computer which knows the material being cut, the depth of the cut, and the various other variables, and is able to calculate the expected cutting forces for the specified operations, the ability to monitor tool wear increases. Combining the strain gauge with the computer in this way allows the computer to continually compare the condition of the tool against the ideal model and thus instantly make the appropriate decision to automatically implement a tool change as necessary.

10.2.2 Optical sensors

The main method of detecting the location of the surface of the roller workpiece is via optical sensors. In particular, these sensors are classified as 'laser triangulation sensors.' The principle behind these is explained previously.

A survey of available sensors on the market currently revealed several likely candidates which could be used in this application. The best candidate of all these was the AccuRange600 (AR600) available from Acuity Research. This particular sensor can measure distances over 100mm span and is accurate to within 0.1% of that span. This meets the design criteria of being able to measure the roller diameter to within 0.1mm.

Telephone consultation with a representative of Acuity Research (Sam Bhasin on 29 August 2005 at 1:15PM) confirmed that the sensor can handle the vibrational stresses that would be applied to it, although there is a need to average several successive measures at first to identify and eliminate vibrational error, and that the sensor is precalibrated as well as self-correcting. Moreover, that this sensor uses diffuse reflection from the incident surface in its detection of distances, it is also able to handle measuring distances to uncut (matte) and freshly cut (reflective) surfaces. Also, this particular sensor has an output that is readily compatible with any potential automation or data acquisition system - such as the RS323 interface.

A data sheet for this sensor has been included in the Appendix **??**. The cost of this sensor was approximately A$5000.00 at the time of the discussion.

On the other hand, there was also the AR200 sensor, also from Acuity Research. However, this sensor has half the span (50mm) in return for being half the price of the AR600. This reduction in accuracy makes this sensor inappropriate, as the minimum distance it needed to be able to measure was 75mm.

10.2.3 Decision Making

The final device is to automate several tasks together at the one time. As such, it is implied that some sort of computing power will be used. Given the amount of sensors and data that is generated, for each particular tool assembly and driving ring, the processor needs to be able to handle large amounts of information quickly and effectively. Thus the computer that it is suggested to be used is not a “simple” processor such as one of the PIC series. Rather, a full sized industrial computer similar to one of the modern desktop computers should be used. This is due to there begin larger amounts of flexibility in a processor of this magnitude, it is able to process the volumes of data quickly, and the controlling programs can be modified quickly.

Moreover, it is expected that at some point the machine's flexibility of use will be exploited. The size of the tool can be increased from a single point tool, to a multi-point tool. Additionally, multiple tools can be mounted on each ring, and multiple rings can be used. Also the size of the ring, within certain bounds, can be scaled up or down, depending on the size requirements for the application. All that would be required to ensure the computer processor can handle these adaptations would be relatively simple software patches and/or upgrades. That this is a successful methodology is vindicated by the Linux open source system, which has been updated and expanded in pace with available technology.

10.2.4 Component Communication

Data is to be communicated around the machine via a series of Bluetooth devices. Bluetooth actually describes the wireless networking standard used and not the actual devices themselves. Thus there are many possible sources of Bluetooth enabled devices. As mentioned previously, due to being a conceptual design only, specifying suppliers and exact components to be used has been considered to be outside the scope of this document.

Bluetooth transmits and receives data between two to eight enabled devices on the 2.4GHz ISM[1] frequency band, as long as these devices are within 32ft (about 9.75m) of each other. This frequency band is unlicensed, thus ensuring that it is relatively cheep to use in as much as there are no licensing fees charged on either a one-off or periodic basis. The system uses a selection of frequencies within the band, each called a channel. The specifications call for the devices to selectively hop between these 79 channels 1600 times per second in a pseudo random manner.[2] This is done to avoid problems with noise, and interference with other devices and other technology using the

[1]ISM stands for Industrial, Scientific and Medical

[2]According to approximate calculations, assuming one channel has equal chance of being selected as any other, the channel will be "occupied" for roughly 50ms per second, though not necessarily in consecutive increments.

same frequency band. Only devices that are connected to each other are synchronized to hop to the same frequencies at the same time. Moreover, if bits are lost on one channel, they can be resent on another.

Thus, the Bluetooth system can overcome noise and interference easily, even from other Bluetooth units, despite being low powered (usually by battery in most applications). Each set of 2-8 units that are communicating together form a piconet, and only the ones within a piconet are synchronized in their frequency hopping. Thus it is possible to have multiple piconets working together within the same area without significant degradation of bandwidth or signal strength.

Thus it was decided upon that the various pieces of data would be transferred to and from the controllers, motors, sensors, and alike via Bluetooth devices. This would also facilitate monitoring of these signals and future expansion if needed.

However, this approach will require the conversion of various analog signals into their digital equivalents on as close as possible to a real-time basis in order for the system to be able to immediately respond to any changes in the workpiece, the machine itself, and it's environment.

Note that other methods considered were:

- Physical connections via an electrical contact on a ring.
  - Problems: wear, interference, signal noise, safety
- Optical transmission i.e. via infrared.
  - Problems: moving parts, too easy to interrupt light beam, not practical
- UHF radio or similar (433MHz)
  - Problems: Possible licensing issues, easily interfered with at power levels involved (i.e. passing trucks, noisy equipment, etc)

10.2.5 Additional electronic items and comments

There are many other electronic systems that would need to be designed and specified for the device to become fully operational. For example, the motor to rotate the drive ring would require a suitable controller, as would the motor used to position the tool arm and the motor to rotate the the kicker gear inside the tool changer. Electrical power to these latter two motors, along with the sensors mounted on the rotating sections would need to be transmitted to them in a reliable manner. One of the most likely solutions to this is to use a induction system similar to the MOVITRANS[3] with the inductor mounted in a loop surrounding the ring assembly.

The lateral position of the carrier assembly would be monitored via various methods, and is one of the key areas which impact on the precision of the final device. One suggested method was to use a camera mounted on the carrier which was focused on a stationary graduated scale coupled with image recognition technology. Another approach would be to used an off-the-shelf sensor called Sealed Incremental Linear Encoder such as available from Heidenhain, some of which have a accuracy of $\pm 3\mu$m.

10.3 Mechanical Design

10.3.1 Tool changing

Why is a tool changer needed? A tool changer is needed due to the short life span of the machining tool. The life of the machining tool is directly related to several variables, which was analyzed in Chapter 3.

For instance, take the relative rotational speed at with the workpiece passes past the tool. Obviously the deeper and faster the tool cuts, the quicker the task can be completed. However this incurs the penalty of greatly shortening the tool life of the machining tool. The tools usable ‘life’ can be as short as 15 minutes. Conversely a slower speed and shallower cuts tends to increase tool life, but also increase the time take for

[3]MOVITRANS is a registered trademark of SEW- EURODRIVE

the cutting tasks to be completed. As one of the research sources stated, if the tool life is larger than 2 hours, then the tool is not being used effectively and needs to be modified. When compared to the 60 hours required to properly machine a roller, it is expected that several tools will be used for each roller.

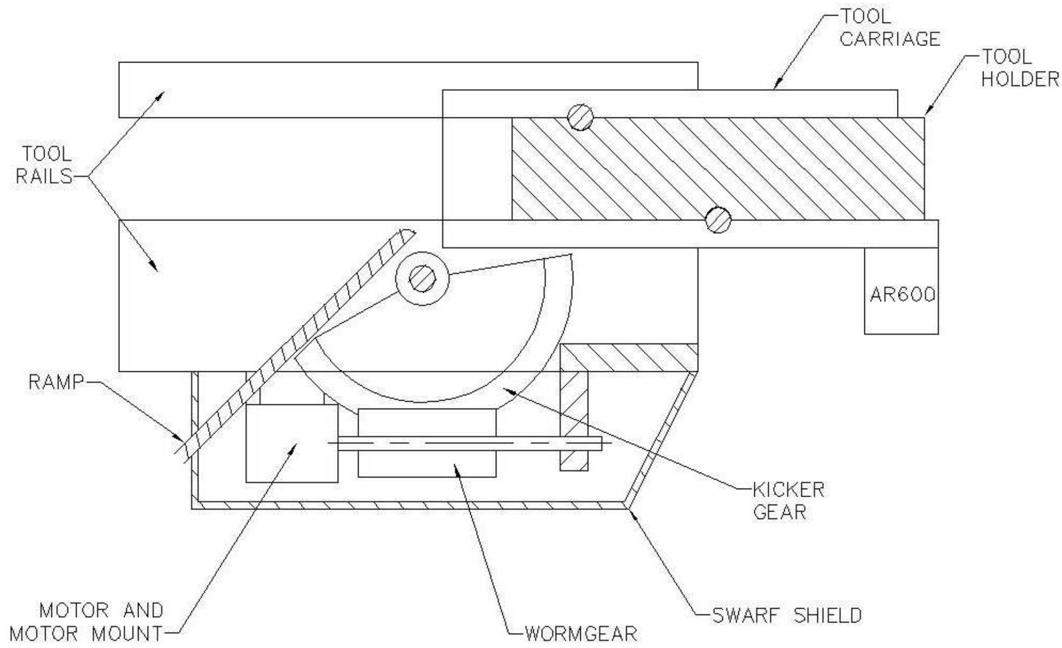

Figure 10.3: Tool Assembly - Side sectional view

When the tool needs to be replaced, the carriage return to the 'tool change' position. An internal gear of the assembly then rotates and pushes the holder so that it pivots on a central pin and slides out of the chute. The next tool is simply pushed up onto this central pin, the arrangement of the internal pins and the force exerted on the tool under normal operations locking the new tool into place without any further adjustments being necessary.

10.3.2 Recognizing the tool

No single tool is able to do one complete job. This is because the tools wear, and that in a typical roller machining operation many different types of cuts to various different depths are needed. Thus the machine needs to be able to identify which tool is in the tool holder and where the cutting edge of it is.

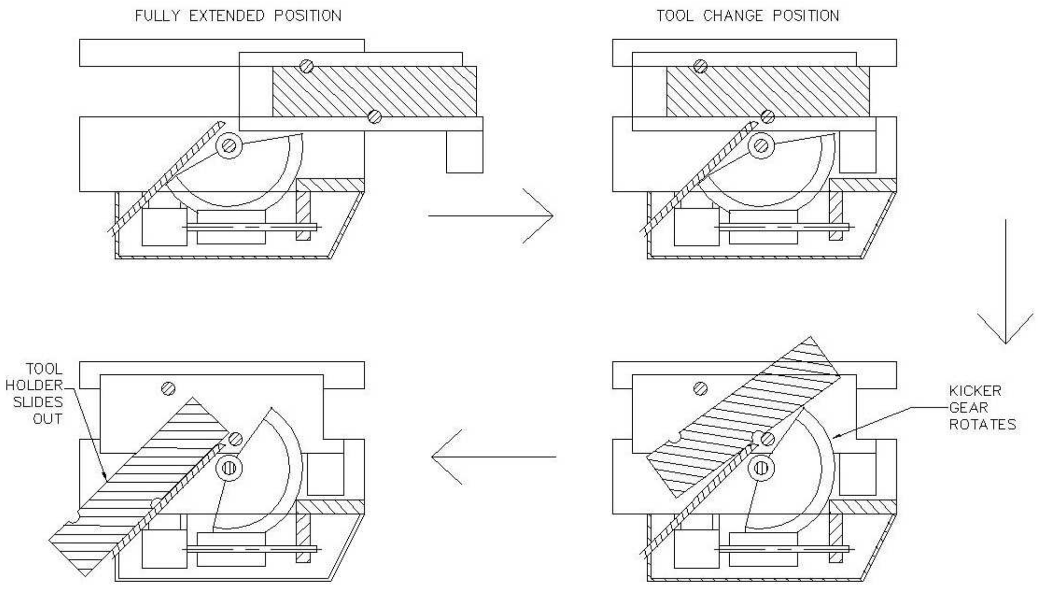

Figure 10.4: Process of removing the tool

There are several ways in which the machine could identify which tool is being used at that time. One way is for the upper surface of the tool to have a barcode printed on it, and the machine read this barcode each time a tool is loaded. This has the problem of the barcode not always being legible, and trying to mount a reader in the loading mechanism.

Another method, and the method that was pursued, is to have the tool holder tell the machine which tool it is holding. This is done by the human who loads the tools into the tool holder in readiness for them to be loaded by the machine. A series of contacts are positioned on the side of the tool holder, and when loaded and locked into position, marry up to a similar set of contacts on the tool platform. These contacts (6-8) are configured to provide a certain binary code, which the main computer then uses to find the type of tool and the location of the cutting edge from a database in its memory. Due to the posilock[4] characteristics, the self locating properties of the tool holder, and the size and positioning of the contacts, the tool holder contacts are ensured that they will always locate the correct contacts on the tool platform and will always have a good connection with them. Additionally, due to their location, it is extremely improbable

[4] A system where a component will find its own proper location and then lock into place, even as it wears.

that swarf or similar contaminates would be able to cause interference with time.

10.4 Some safety concerns

There are many safety features incorporated in this design. For example, mounted on the main operator panel is to be a large emergency stop switch. When this switch is pushed, it latches shut and disconnects the power to the main drive motors and applies a short across the terminals, thus applying an electric braking action. This is also monitored by the computer, and it will recognize that the device is now in an emergency stop event, and will stop disconnect all power to the unit.

Due to the construction of the device, the swarf is mostly contained within the machine. Also, a 'light curtain' or similar safety device should be mounted on the device, which when it detects a sufficiently large enough intrusion into the work area, cease all movement, sound an alert on the control panel, and then wait for the operator to signal that it is cleared to continue operations.

Another area that monitoring is needed is that of the tool status. It is expected that with the correct optimization of the cutting speed and the cutting depth, that the tool will be replaced long before it reaches break point. Thus, if the tool suddenly breaks, the device would detect this as a sudden change in the cutting force measured by the strain gauges and the deflection of the tool holder. There would also likely be a large variation in the reading between the two monitoring methods. Thus when the controlling computer detects that the cutting force is outside the operational window, it should stop cutting, return the tool assembly to the change location, and signal the operator. One aspect that the operator would have to my a decision on was whether the tool break has damaged the workpiece and whether it is still feasible to continue with the job.

All of the above safety mechanisms do require input from an operator in order for the error to be cleared. This is due to the serious nature of the hazard involved, or the higher risk of inadvertent damage to the machine.

One inherent safety feature, according to the design as currently implemented, is that all the rotational parts are shielded behind casings, or extremely difficult (to the point of physically impossible for an average sized individual) to reach without deliberately attempting to do so, or tripping any of the other safety measures mentioned above.

Chapter 11

Conclusions

11.1 Achievement of Project Objectives

Various approaches to machining metal were analyzed as to suitableness. The result of this analysis was that the traditional method, if somewhat adapted to this application, was most suitable.

Based on this analysis, an alternative approach to the traditional lathe-based machining approach was developed to conceptual stage. The issues involved in implementing this alternative design concept was also explored, particularly in the area of safety concerns. However, due to various constraints, the solutions developed to these concerns could not be included in this document. Further consultation on these matters is recommended.

As noted, the main advantage of the developed design concept is its expansiveness. The size of the tool can be increased from a single point tool, to a multi-point tool. Additionally, multiple tools can be mounted on each ring, and multiple rings can be used. Also the size of the ring, within certain bounds, can be scaled up or down, depending on the size requirements for the application.

11.2 Further Work

There are, however, several items that need to be addressed, before the device can be taken to the final design or prototyping stages. These include, but are not limited to, the following tasks:

- Design of the holding rack for used and unused tools for the tool changer.
- Design of a suitable ring and tool-changing assembly for use on the end faces of the shell.
- A swarf collection and removal system suitable for the concept, to be applied to each ring assembly.
- Complete mathematical analysis, in particular of vibrational dampening.
- Implement safety measures.
- Complete costing.

Additionally, areas where the design concept outlined herein could be expanded to include are:

- Multiple ring assemblies, doing multiple cuts at different speeds.
- A ring dedicated to operations at the end of the shell, such as machining it to size, drilling holes, etc.
- A smaller ring assembly for machining the bearing journals while the shell is being grooved.

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Appendix A

Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

ENG4111/2 Research Project

PROJECT SPECIFICATION

FOR: Michael John HUGO
TOPIC: Automation of Sugarcane Crushing Roller Shell Groove Cutting
SUPERVISORS: John Billingsley, University of Southern Queensland
ASSOCIATE SUPERVISOR: Enio Troiani, Bundaberg Foundry Engineers Ltd.
PROJECT SPONSORSHIP: Bundaberg Foundry Engineers Ltd.
PROJECT AIM: This project aims to automate the process of cutting grooves of a specified profile into sugarcane roller shells.

CONFIDENTIALITY: ***This document and any attachments are confidential and intended solely for the person or persons involved in this project. This document is not for general distribution.***
This project and any drawings, procedures, specifications, technical information or similar contained therein is not to be used or circulated without the written consent of the copyright holders.

PROGRAMME: **Issue A, 21st March 2005**

1. Research existing traditional and non-traditional machining methods, and critically comment on their suitability for producing grooves in roller shells.
2. Research methods that can be used to detect the location of a roller shell within a specified region, i.e. within the bounds of a machine.
3. Develop a scheme for the detection of the position of the roller when placed in the machine and during any machining operations on the roller shell.
4. Design and develop a method of cutting the grooves into the roller shell, based on data inputed by a non-technical skilled labourer, and positioning data from the detection process mentioned above.
    - Monitors tool wear, changing tools as needed
    - Able to be overridden by above mentioned user for manual operations
    - Have provisions made for completion of additional roller shell operation, i.e. drilling, machining of end faces.
    - Block diagram of program/s for any processing units used
5. Incorporate safety mechanisms into any designs.
6. Simulate or model the final design.

As time permits...

7. Include automation of some or all of the additional roller shell operations that are preformed as part of their production.
8. Provide specific programming for the processors used.
9. Provide approximate costing details.
10. Include detailed plans for the construction of the final machine.

AGREED:

____________________ Student   ____________________ Supervisor

___/___/___   ___/___/___

Appendix B

Mathematics

Overall	Largest	Average	Smallest
Shaft Length (mm)	6270		
Shaft Weight (T)	26.1		
Shell Weight (T)	18.39		

Table B.1: Dimensions of the sample rollers used

B.1 Introduction to this Appendix

As with all engineering projects which involve designing objects, significant amounts of mathematics is used. Rather than obstruct the flow of the above report, all the mathematical calculations mentioned in the report are included below. This information is provided to support the figures stated in the report above.

B.2 Design Issue Calculations

B.2.1 Shaft Deflection

Due to the complex shape of the shafts involved, approximate the shaft with a single-radius shaft of the same length, with the same mass, under the same loading.

Assumptions

- Use 'weasel' tonne, i.e. 1000 kg = 1 T.
- Use gravity (g) as 1kg = 9.81 N.
- Use density (ρ) of 7860 kg/m ^{3}
- Use Modulus of Elasticity (E) of 207 GPa

Equations and Definitions

$$Mass = Volume \times density$$

$$Volume = Area \times length$$

$$Area = \pi r^2$$

$$\therefore r = \sqrt{\frac{Mass \div density}{\pi \times length}} \tag{B.1}$$

Moment of Inertia:

$$I = \frac{\pi d^4}{64} \tag{B.2}$$

Deflection at center of beam, fixed both ends, central load:

$$y = \frac{PL^3}{192EI} \tag{B.3}$$

Deflection at center of beam, fixed both ends, uniform load:

$$y = \frac{PL^3}{384EI} \tag{B.4}$$

Calculations

For the Largest or maximum shaft, using the formulae and definitions stated above.

Equivalent radius, using Equation (B.1).

$$r_{max} = \sqrt{\frac{(26.1) \times (1000) \div (7860)}{\pi \times (6720) \times (10^{-3})}}$$

$$r_{max} = \sqrt{\frac{26100 \div 7860}{\pi \times 6.72}}$$

$$r_{max} \approx 400 \text{ mm}$$

Moment of Inertia, using Equation (B.2).

$$I_{max} = \frac{\pi \times (800 \text{ mm})^4}{64}$$

$$= 0.20106 \text{ m}^4$$

To calculate total deflection, calculate the deflection from the shafts own weight and the deflection due to the weight of the shell separately and then combine. Deflection due to the shell's weight, using Equation (B.3).

$$\begin{aligned} P &= 18.39 \text{ T} \times 1000 \times 9.81 \text{ N} \\ &= 180344 \text{ N} \approx 180 \text{ kN} \\ y_{shell} &= \frac{180 \text{ kN} \times (6270 \text{ mm})^3}{192 \times (207 \text{ GPa}) \times (0.20106 \text{ m}^4)} \\ &= 0.005553 \text{ mm} \end{aligned}$$

Deflection due to the shaft's own weight, using Equation (B.4).

$$\begin{aligned} P &= 26.1 \text{ T} \times 1000 \times 9.81 \text{ N} \\ &= 256041 \text{ N} \approx 256 \text{ kN} \\ y_{shaft} &= \frac{256 \text{ kN} \times (6270 \text{ mm})^3}{384 \times (207 \text{ GPa}) \times (0.20106 \text{ m}^4)} \\ &= 0.007897 \text{ mm} \end{aligned}$$

B.2.2 Cutting Forces

Assumptions:

- Cutting tool material: Tool Steel
- Material being cut: Roller Iron equiviliant to K1040
- Material hardness: 220 BHN
- Depth of cut: 5mm
- Feed of cut: 1mm
- Tool lift desired: 180min

Based on information in (Oberg 2004).

$$
\begin{aligned}
\text{Speed} &= 85\text{fpm} \\
\text{Depth cutting factor} &= F_d = 0.93 \\
\text{Feed cutting factor} &= F_f = 0.6 \\
\text{Tool life factor} &= F_t = 0.61 \\
\text{Adjusted cutting speed} &= 85 \times F_d \times F_f \times F_t \\
&\approx 28.93\text{fpm}
\end{aligned}
$$

Converting this to metric yields: 0.147m/s

This value can now be used to determine the amount of force being exerted in the tool. This will allow for two calculations to be made, 1) the size of the motor required to drive the tool, 2) the stresses that the tool is subjected to.

B.2.3 Angle Encoder

The rotational position of the tool is to be known to the precision of 0.1. Thus there are 3600 possible values. One idea was using a barcode type system to measure the rotational position of the ring.

Assuming the "barcode" is mounted on the other surface of the ring.

$$
\begin{aligned}
\textit{Maximum possible size of barcode} &= \textit{radius} \times \sin(\textit{angular resolution}) \\
D_b &= r_r \times \sin 0.1^\circ \\
&= 2200 \text{ mm} \times \sin 0.1 \\
&= 4.18 \approx 4.2 \text{ mm}
\end{aligned}
$$

While it is possible to have an encoder using barcode-like coding scheme with a small enough form factor to fit under this limit, it is extremely difficult and not likely to be very practical in this application. Thus alternative methods for monitoring the rotational position would need to be employed.

However, this level of precision is not required for general operations. It is only required for the optional end rings, when drilling the holes in the roller shell. Under normal conditions, for the main, central cutting only ring, the level of precision could be reduced to approximately 1. This results in the following:

$$\begin{aligned} \textit{Maximum possible size of barcode} &= \textit{radius} \times \sin(\textit{angular resolution}) \\ D_b &= r_r \times \sin 1^\circ \\ &= 2200mm \times sin1 \\ &= 38.39 \approx 38.4mm \end{aligned}$$

This value is much easier to design an encoding system for.

Appendix C

Roller with Shell Examples

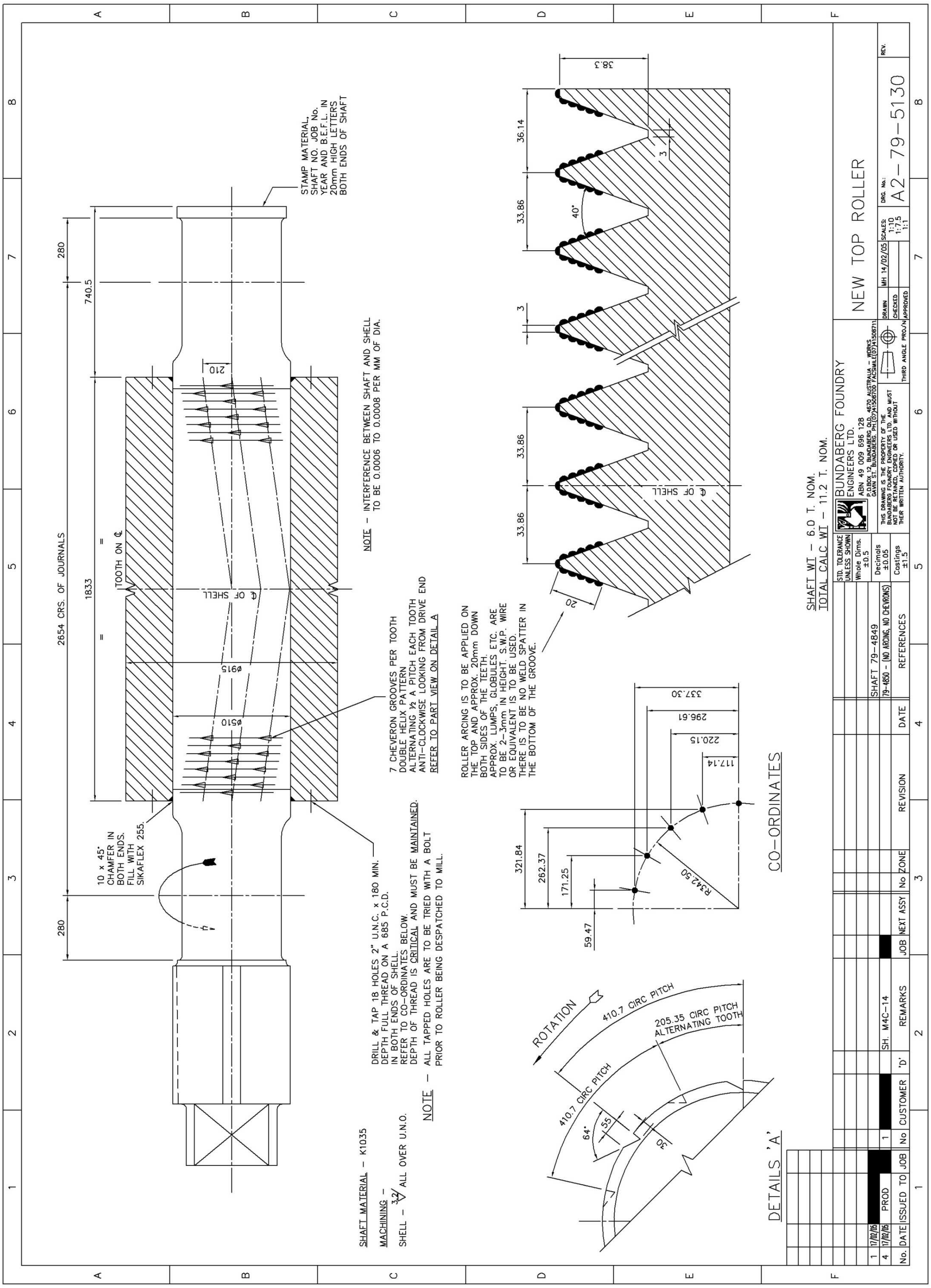


Figure C.1: Reduced copy of roller with shell drawing from Bundaberg Foundry Engineers Ltd.

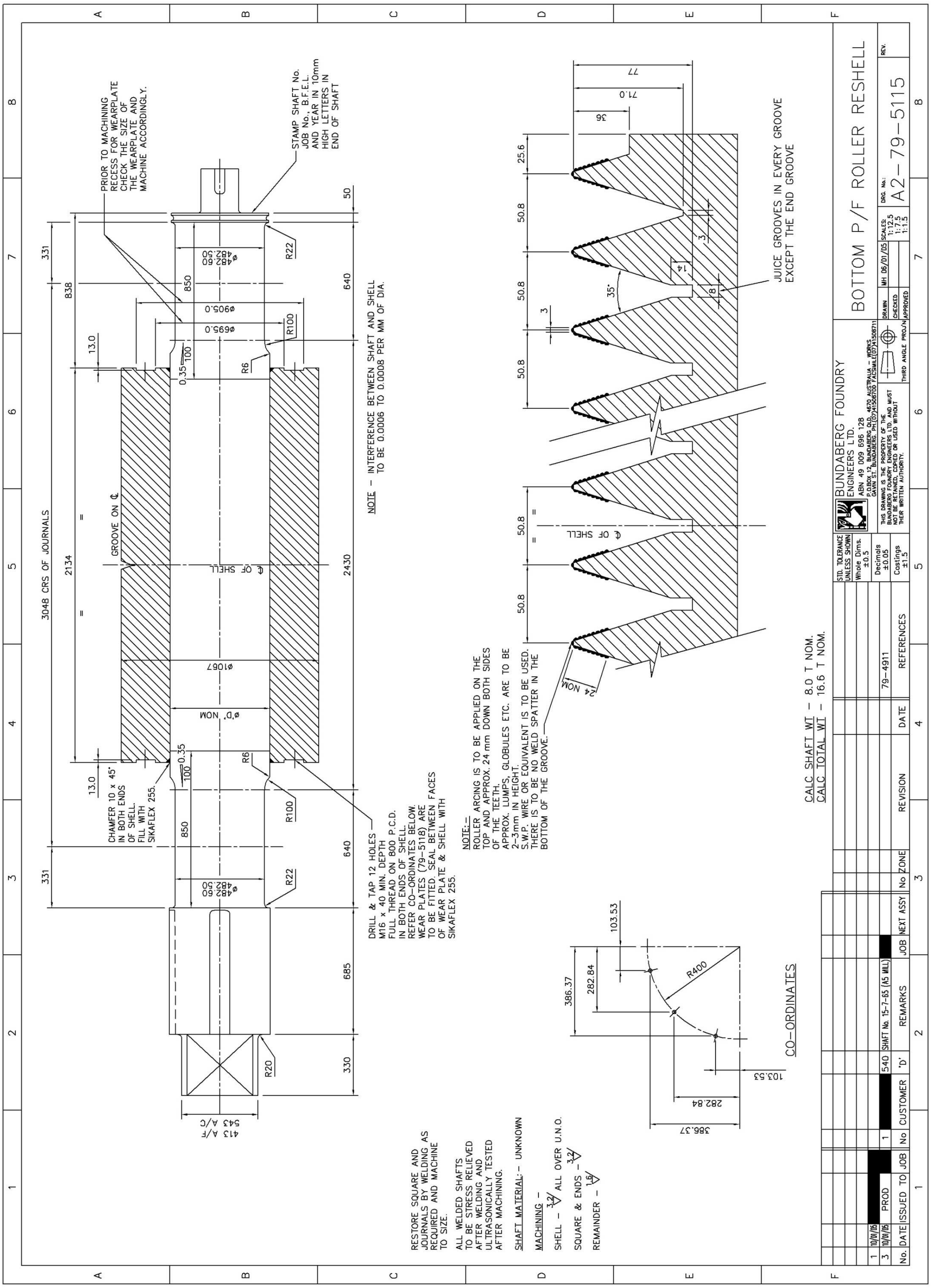


Figure C.2: Reduced copy of roller with shell drawing from Bundaberg Foundry Engineers Ltd.

Appendix D

Proposed and Final Conceptual Designs

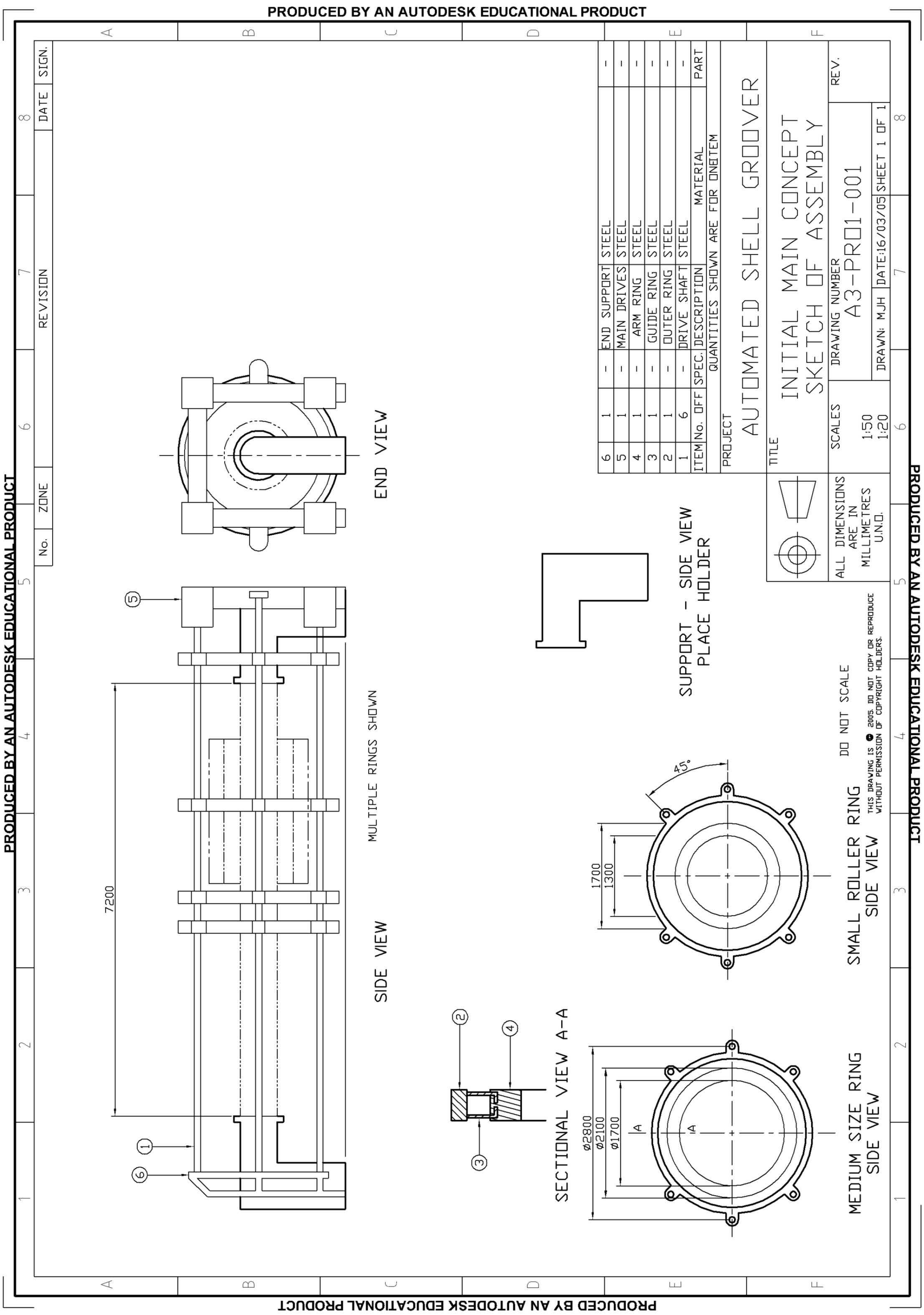


Figure D.1: Reduced copy of initial design proposal

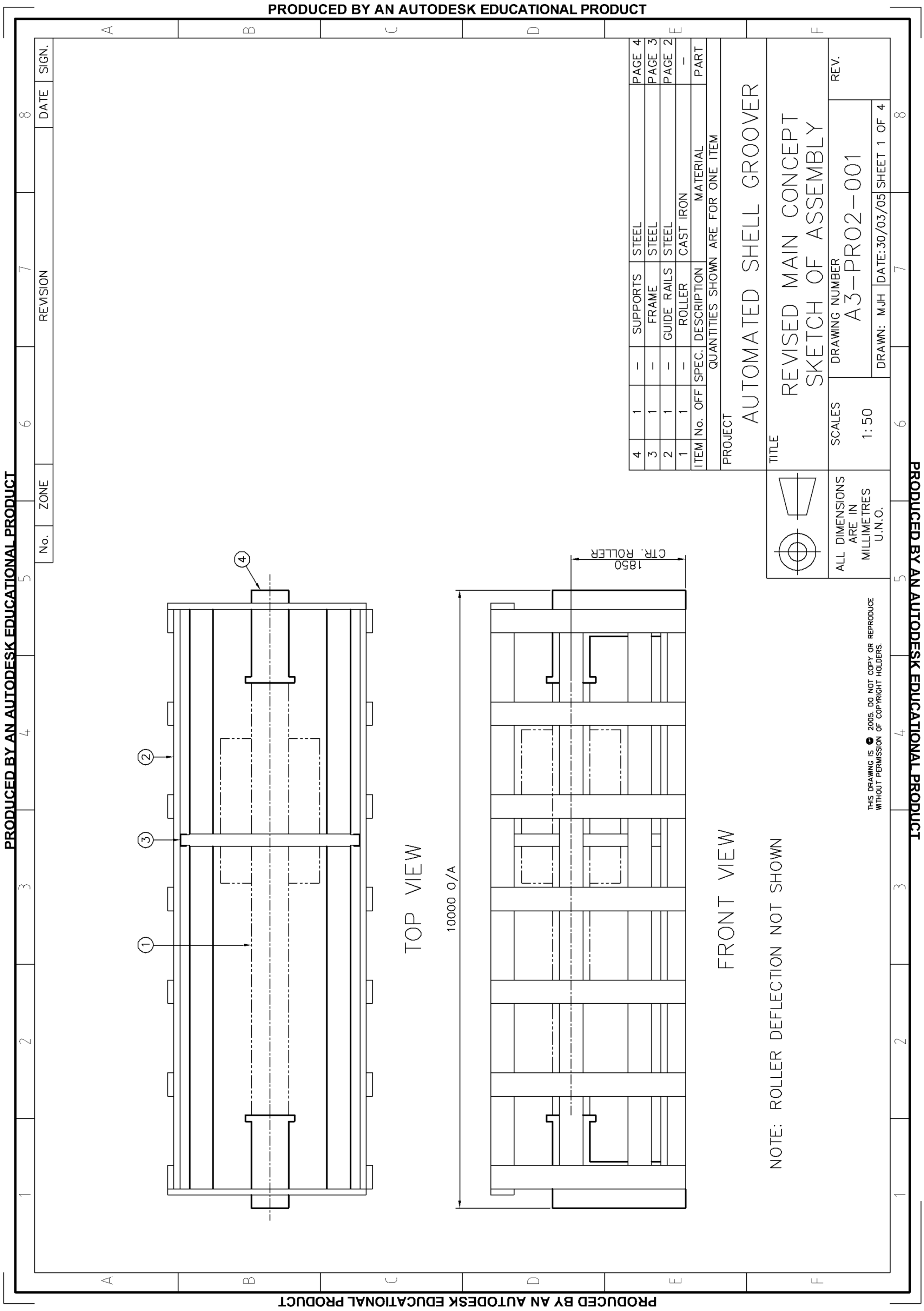


Figure D.2: Reduced copy of second design proposal, page 1/4

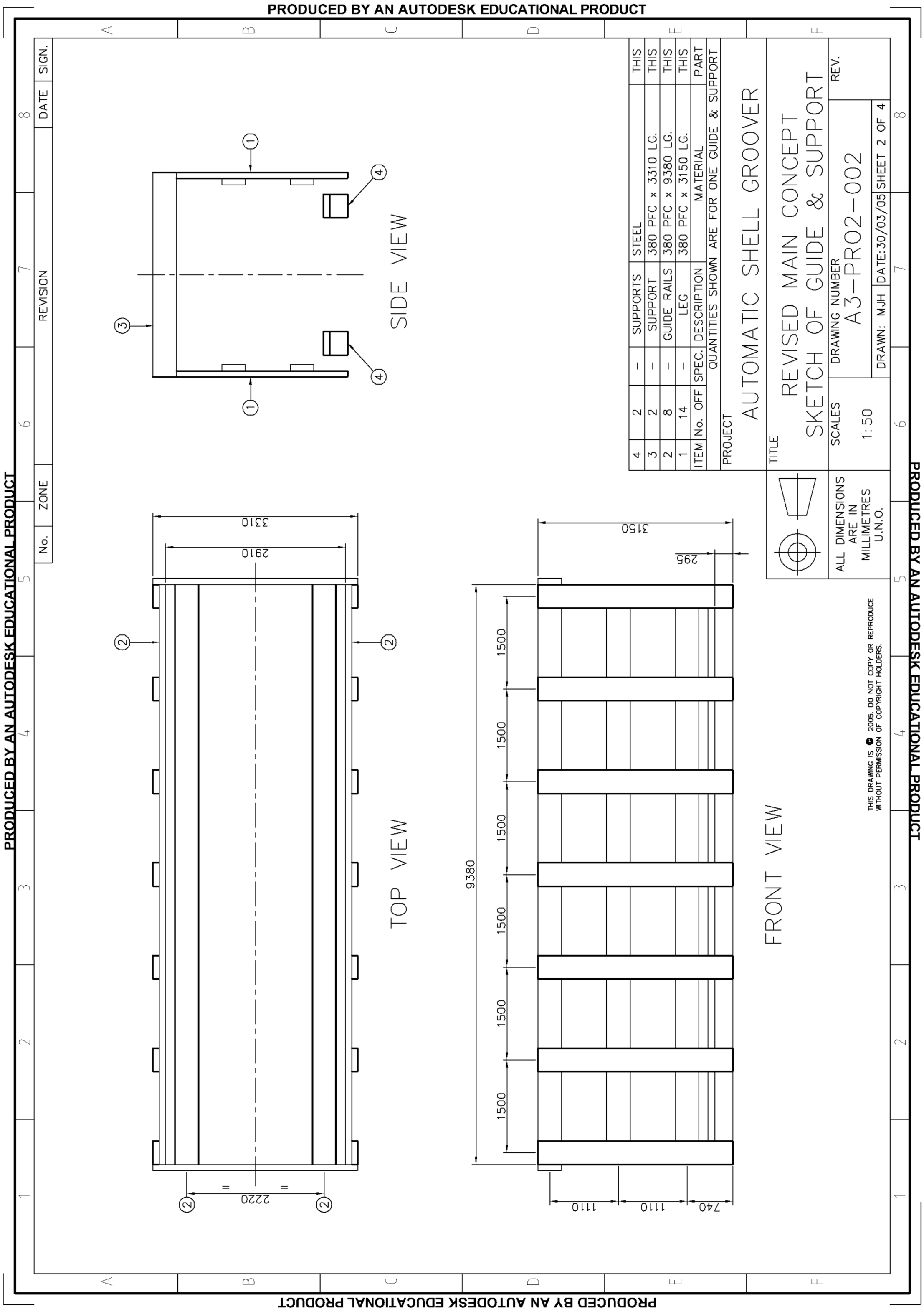


Figure D.3: Reduced copy of second design proposal, page 2/4

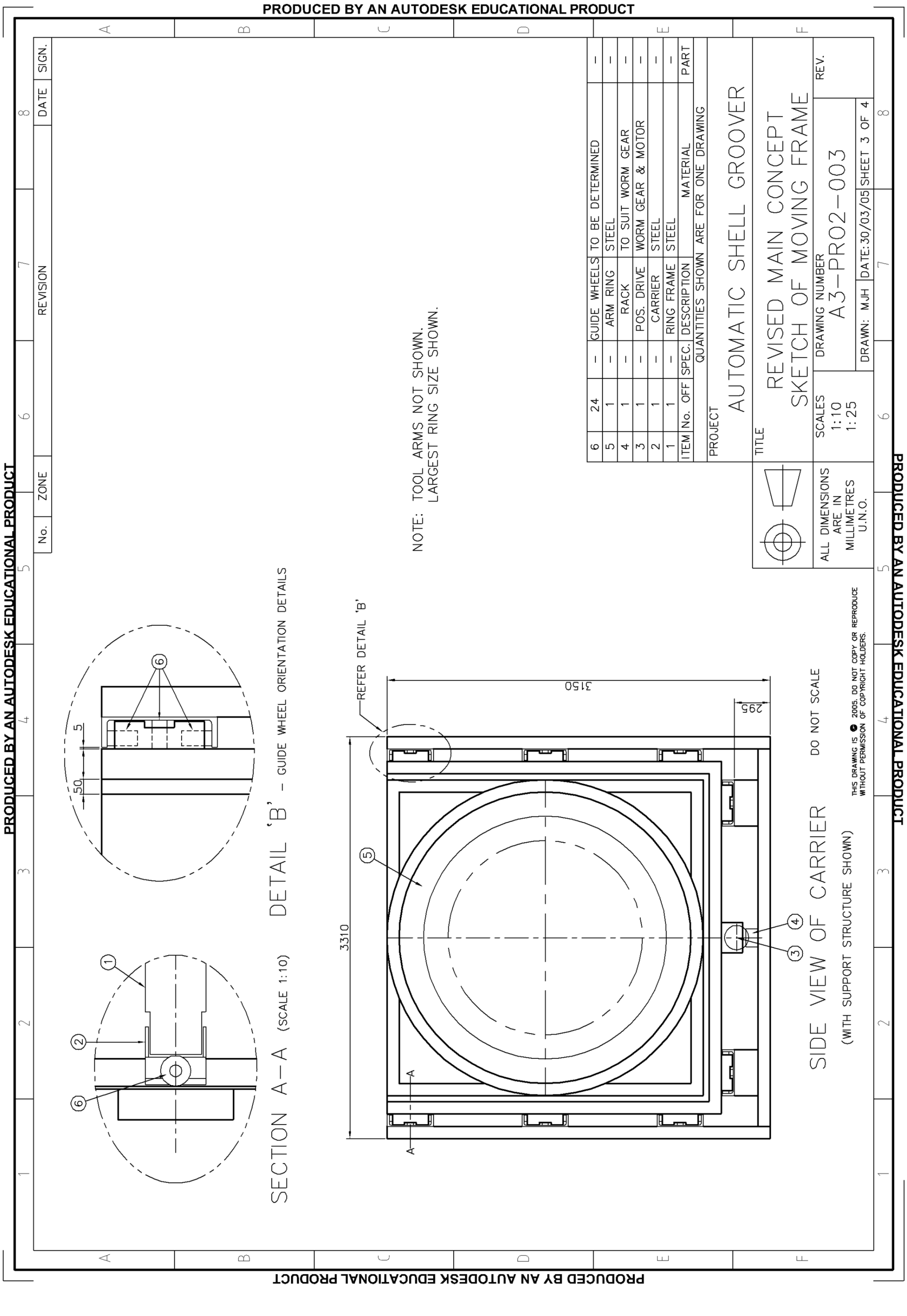


Figure D.4: Reduced copy of second design proposal, page 3/4

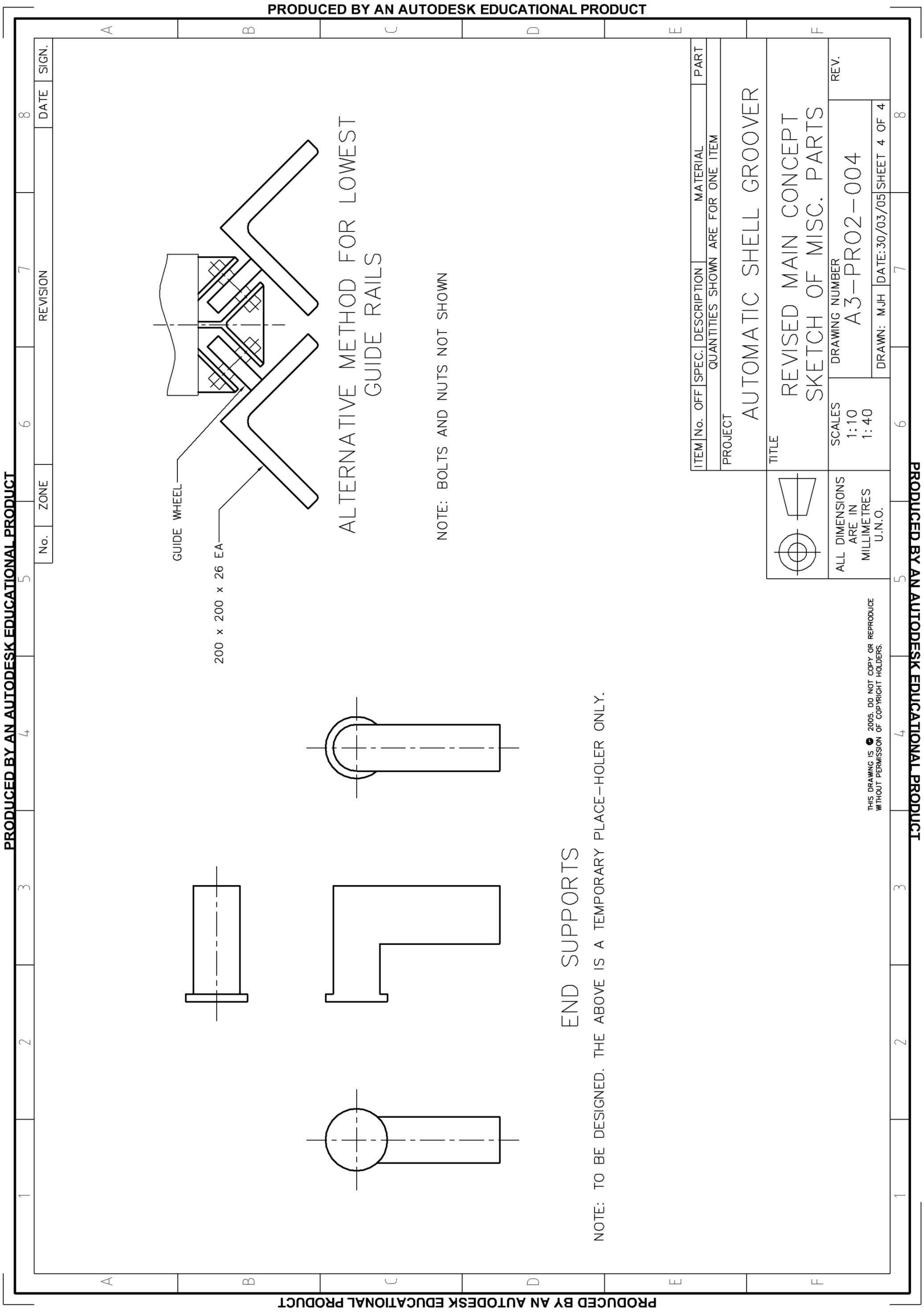


Figure D.5: Reduced copy of second design proposal, page 4/4

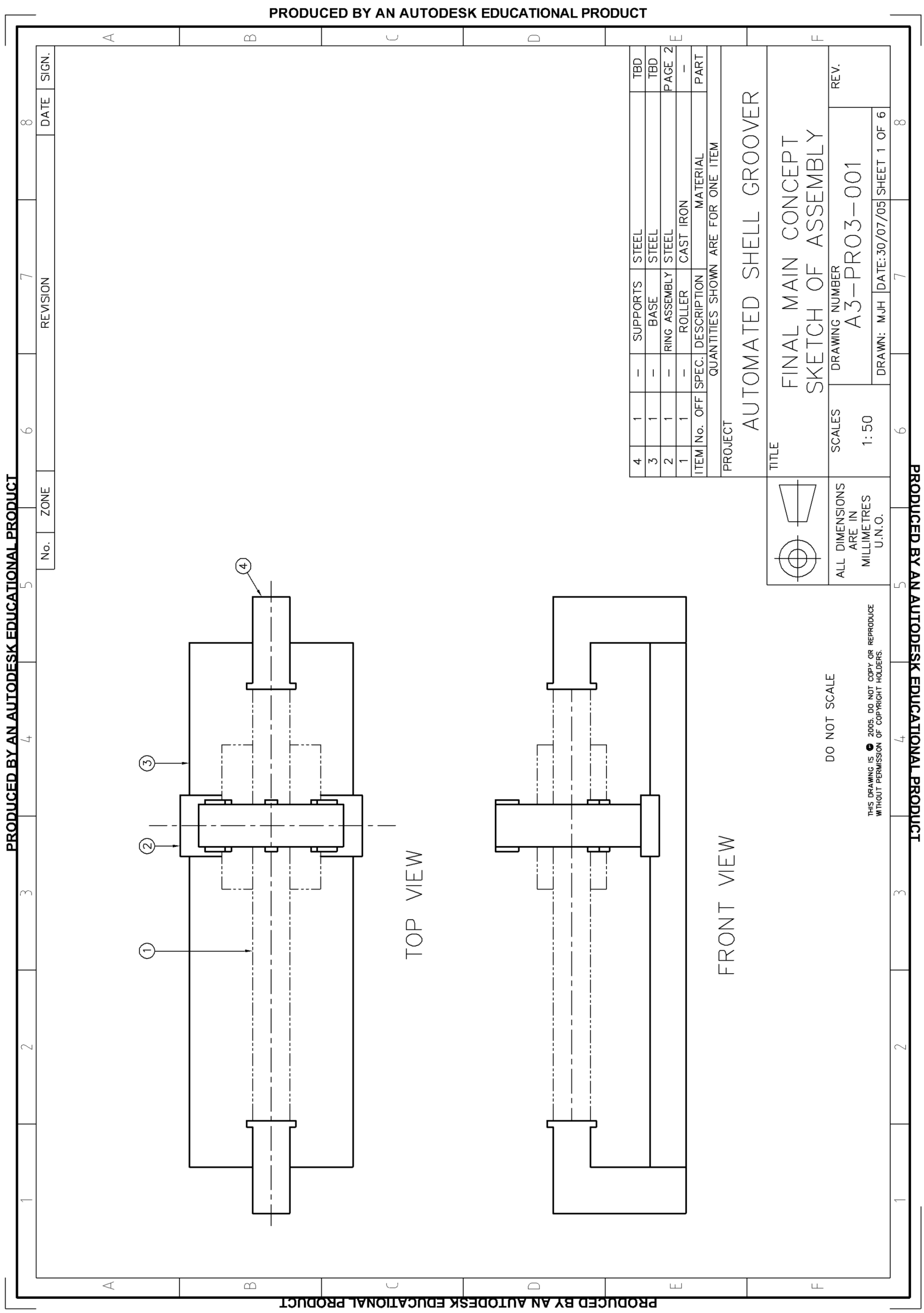


Figure D.6: Reduced copy of final design proposal, page 1/6

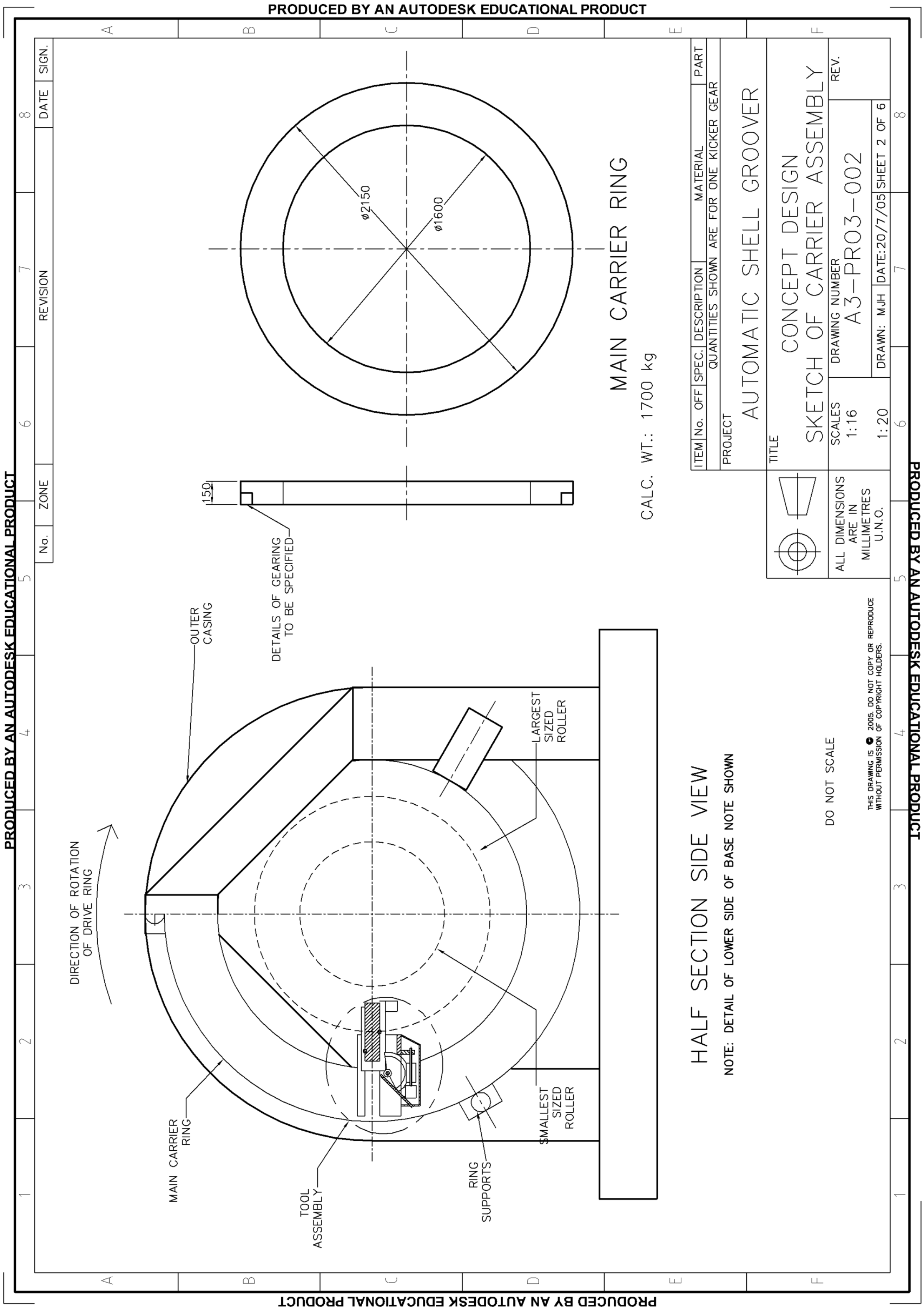


Figure D.7: Reduced copy of final design proposal, page 2/6

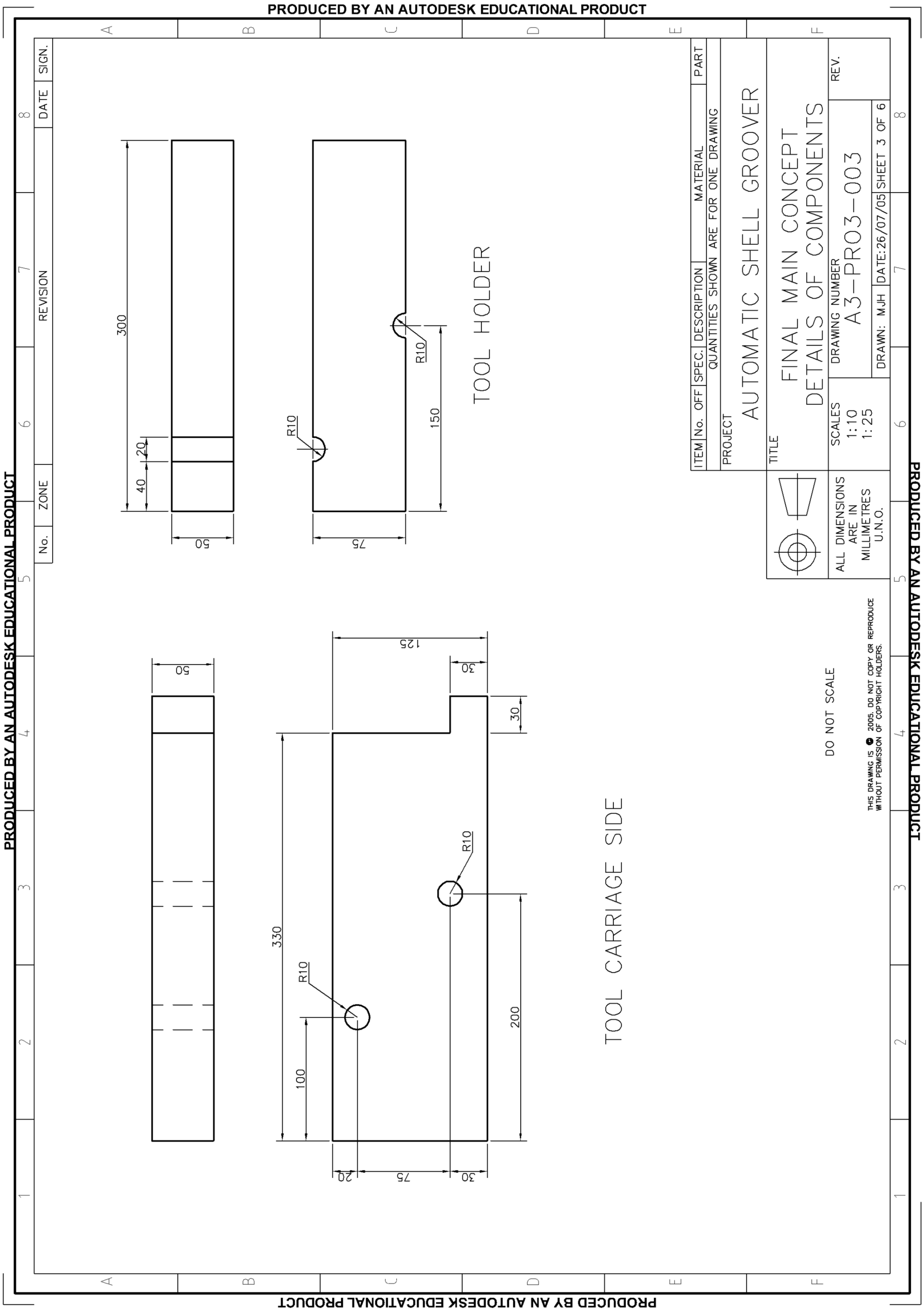


Figure D.8: Reduced copy of final design proposal, page 3/6

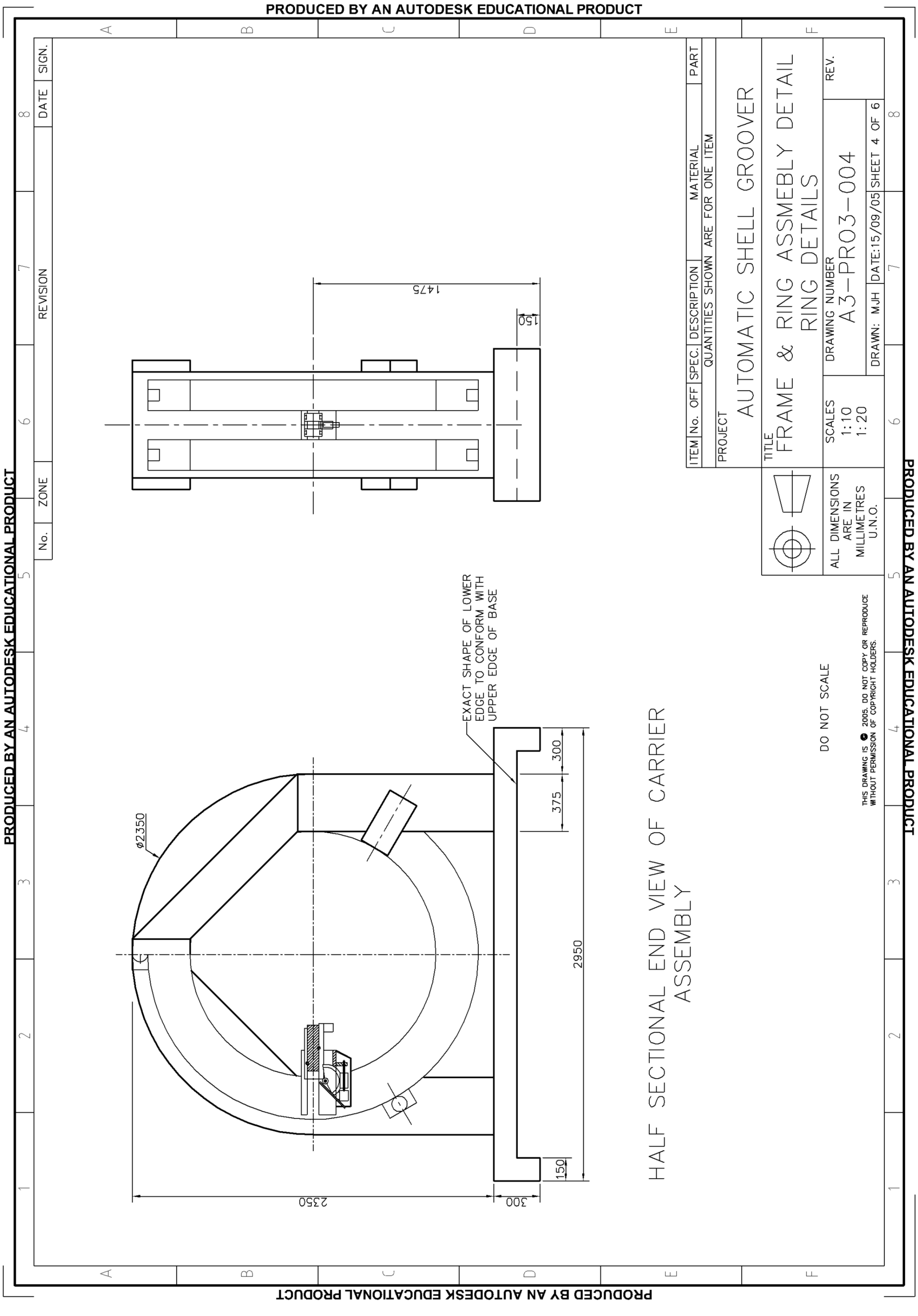


Figure D.9: Reduced copy of final design proposal, page 4/6

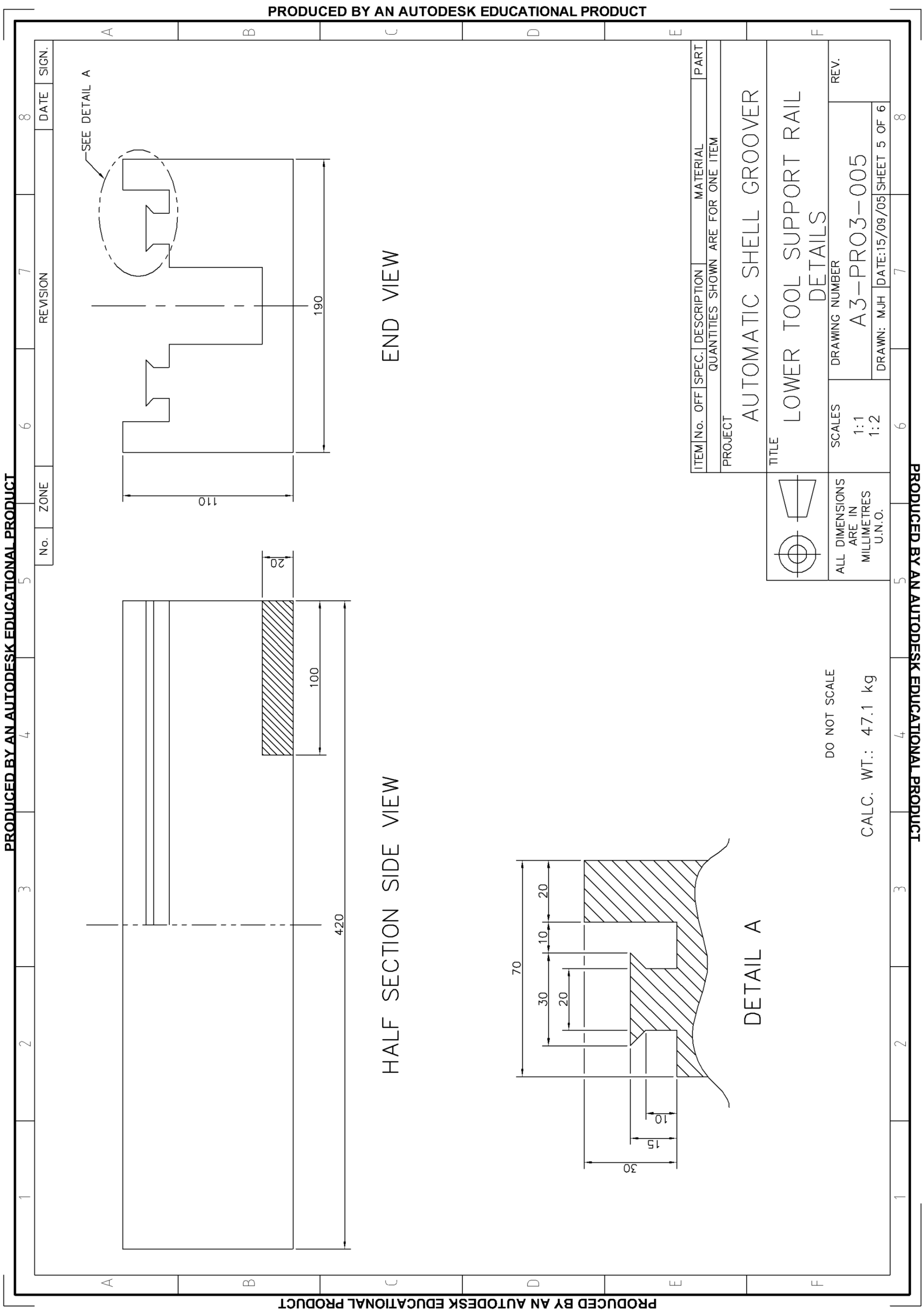


Figure D.10: Reduced copy of final design proposal, page 5/6

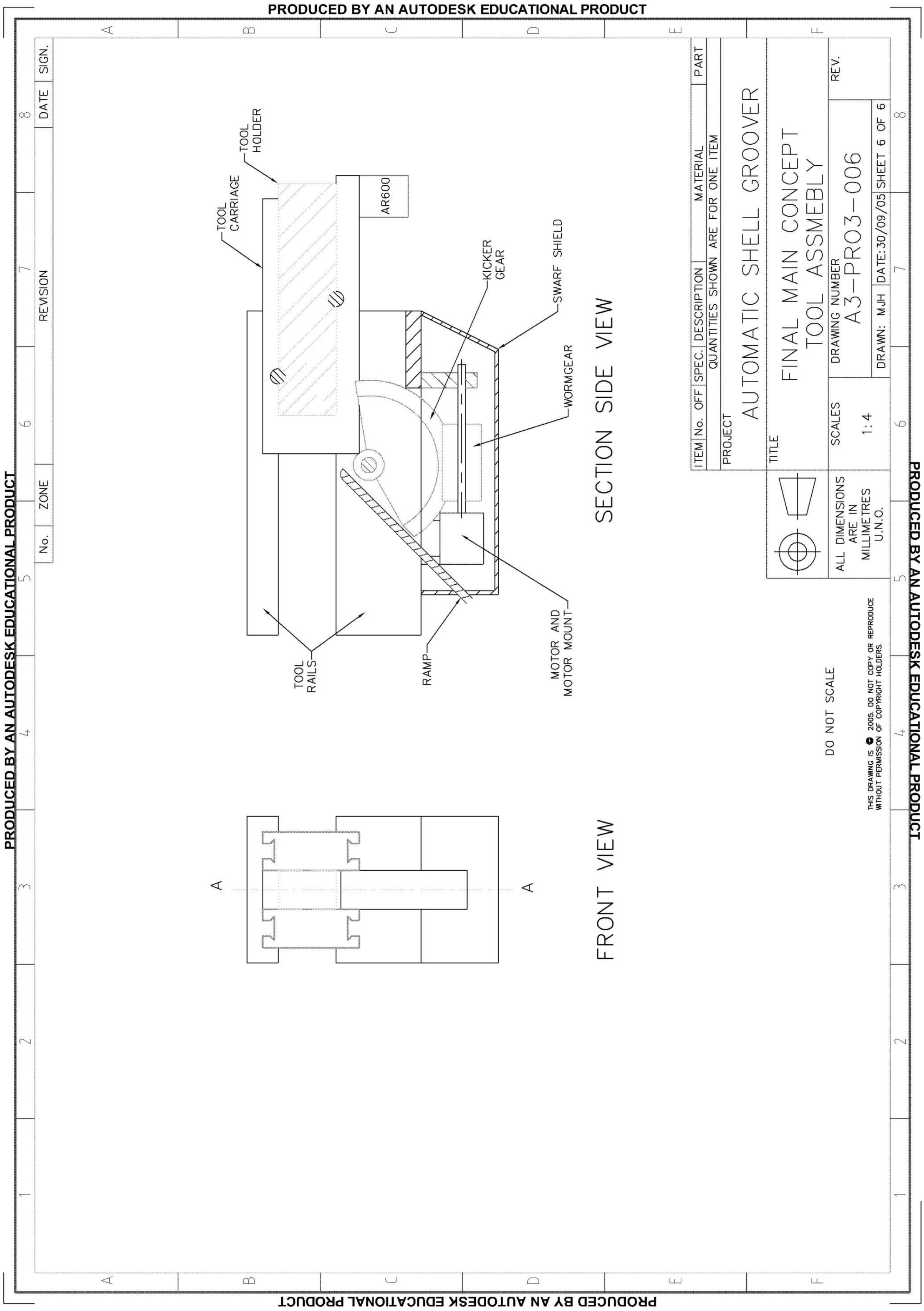


Figure D.11: Reduced copy of final design proposal, page 6/6

Appendix E

AR600 Datasheet

AccuRange600™ laser displacement sensors with measurement capabilities from inches to feet

The AR600 family of triangulating laser displacement sensors includes twelve models to satisfy your range requirements with excellent accuracy and sensitivity. These sensors employ CMOS line cameras for high sensitivity on wood, glowing steel, liquid surfaces and other targets. AR600 measuring sensors are self-contained and require no external controller or specialized PC card.

AR600 Common Specifications

Laser class	
AR600-0125 to -6	650 nm, Class II
AR600-8 to -50	670 nm, Class IIIa
Sensor	CCD digital line scan camera
Power	12 - 24 V D.C. (75 mA at 15V), 20 mA added with current loop option
Weight	See Model Specification Chart
Resolution	
with Hi-Res option	0.01% of Full Scale Span
standard resolution	0.03% of Full Scale Span
Operating Temperature	0 to 50°C, negligible accuracy drift
Enclosure	cast aluminum; meets NEMA-4 and IP-67 requirements
Sample Rates (configurable)	
maximum	
at Standard Resolution	1250 samples / sec
with Hi-Res option	200 samples / sec
minimum	0.2 samples / sec or sample on request
Cable Length	6 feet
Cable Configurations	Moulded serial with 9 pin connector and four-conductor power and analog cable
Regulatory	CE

AR600 Outputs

The AR600 sensors are standard with serial RS-232 output. Sensor data cables are terminated with a DB-9 connector for direct connection to a PC and other equpment. AR600 sensors can be ordered with current loop or RS-422 outputs.

Serial Output	
ASCII	up to 11 bytes/sample, terminal readable
Binary	3 bytes/sample: 0-50000 over full scale span Hex FF terminated
RS-232 (standard)	300 - 56 K baud
RS-422 (optional)	300 - 56 K baud, 4000 ft. max line length
Analog signals (optional)	4-20 mA current loop, installed internally

Principles of Operation

The AR600 sensors project a beam of visible laser light that creates a spot on a target surface. Reflected light from the surface is viewed from an angle by a line scan camera inside the AR600 sensor. The target's distance is computed from the image pixel data. The AR600 can not be overloaded and measures accurately even when a mirror reflects the entire light beam back to the detector.

Definitions

Target Standoff: Distance from the face of the sensor to the middle of the span. Accuracy is greatest at the standoff distance for the AR600.

Span: Working distance between measurement range endpoints over which the sensor will reliably measure displacement.

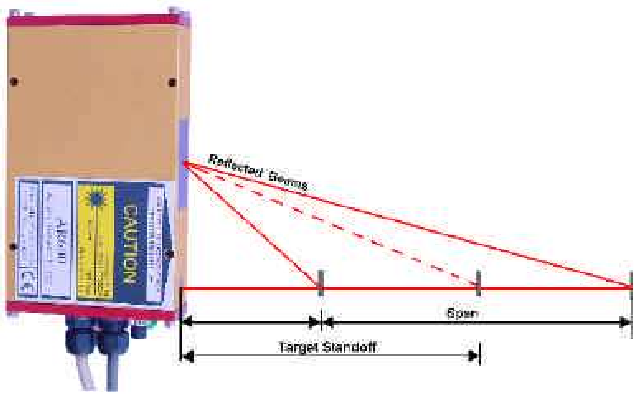
Resolution: Smallest change in distance that a sensor can detect. Stated as +/- % of the span.

Linearity: The largest deviation from a best-fit straight line over the measurement range, created by data from the sensor with reference taken from a true distance scale. Stated as +/- % of the span.

Sample Rate: Rate that data samples are obtained from the sensor. The maximum attainable sample rate is determined by the selected operating mode and target reflectance.

Background Light Elimination (BLE): A user-selected operating mode that improves measurement in bright surroundings by capturing an image with the laser off and subtracts it from the image taken with the laser on. Sample rates are lowered as a result.

Sensitivity: A measure of the relative ability to detect small amounts of reflected light. The better the sensitivity, the higher the attainable sample rate on surfaces such as clear glass, gloss black paint or shiny plastic. See Sensitivity section of this data sheet.

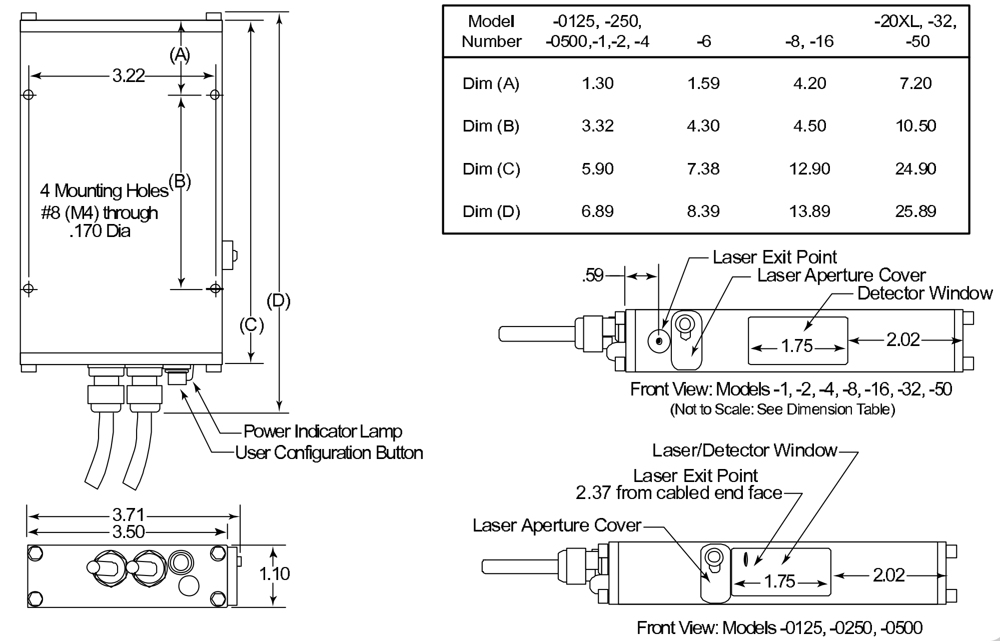


AR600 Model Specifications

Length measurements are reported in inches unless noted differently.

AR600 Model #	**-0125**	**-0250**	**-0500**	**-1**	**-2**	**-4**	**-6**	**-8**	**-16**	**-20XL**	**-32**	**-50**
Span	0.125	0.25	0.5	1.0	2.0	4.0	6.0	8.0	16.0	20.0	32.0	50.0
mm	3.175	6.35	12.75	25.4	50.8	102	152	203	406	508	813	1270
Target Standoff	0.5625	0.725	1.15	3.0	3.25	5.5	10.0	17.0	19.5	48.0	42.0	55.0
mm	14.288	18.415	29.21	76.2	82.55	139.7	254	432	495	1220	1067	1397
Linearity standard	+/- 0.1%											
Linearity w/ Hi Res	+/- 0.03%											
Resolution (10^{-3} in.)	.038	.075	.150	.30	0.60	1.20	1.80	2.40	4.80	6.0	9.60	15.0
microns	.953	1.905	3.825	7.620	15.24	30.60	45.60	60.90	421.8	152.4	243.9	381.0
Resolution w/HiRes (10^{-3} in.)	.013	.025	.050	.10	.20	.40	.60	.80	1.60	2.00	3.20	5.00
microns	.318	.635	1.275	2.540	5.080	10.20	15.20	20.30	40.60	50.80	81.30	127.0
Laser spot size												
@ span center (micron)	30	35	40	60	65	70	95	120	150	275	250	300
@ span endpoints	50	100	130	200	220	300	350	400	750	350	500	750
Weight less cable (oz.)	19	19	19	19	19	19	22.5	36	36	50	50	50
grams	539	539	539	539	539	539	638	1021	1021	1418	1418	1418
Laser Class	II	II	II	II	II	II	II	IIIa	IIIa	IIIa	IIIa	IIIa

Mechanical Dimensions (inches)



Model Number	-0125, -250, -0500,-1,-2, -4	-6	-8, -16	-20XL, -32, -50
Dim (A)	1.30	1.59	4.20	7.20
Dim (B)	3.32	4.30	4.50	10.50
Dim (C)	5.90	7.38	12.90	24.90
Dim (D)	6.89	8.39	13.89	25.89

AR600 Sensitivity for typical surfaces and relative amounts of diffuse light

Most surfaces reflect light in two ways. Some light is diffusely scattered over wide angles and some is reflected specularly, as from a mirror. Diffuse reflections are typically used for measurement, since they scatter widely and can be detected without precise alignment. The AR600 boasts great sensitivity to small amounts of the diffuse component from shiny surfaces. Versions of the AR600 sensor can measure many materials using either specular or diffuse reflections.

Examples of diffuse scattered light from various materials

Material	Diffuse Reflectance (normalized)	Max sample rate (Hz)
White Paper	0.85	1250
Unpolished Metals (iron, steel)	0.2 - 0.5	1250
Wood (various)	0.1 - 0.7	1250
Flat Black Paint	0.03	1250
Gloss Black Paint or plastic	0.003	600
Polished Metals (Al, st. steel)	0.8 - 0.0005	1250 - 100
Clear glass (polished fused silica)	0.0004	100
Laser Mirror	0.0004	100

AR600 Inputs

AR600 sensor command set through pushbutton or serial interface commands:

Set Sample Interval between 0.2 to 1250 Hz
Set Current Loop Span
Current Loop ON/OFF
Background Light Elimination ON/OFF
Sampling ON/OFF
Set Zero Point (to anywhere in measurment range)
Set Baud Rate between 300 and 57600 baud
Serial Flow Control ON/OFF
Write Configuration data to non-volatile memory
Read Configuration data from non-volatile memory
Serial Output Control between inches / mm
Initialize Configuration to factory defaults
Set Sample Priority between Quality/Rate
Set Serial Outuput between ASCII/Binary
Take Single Sample (serial only)

AR600 Signal and Power Interface

The table below shows the wiring of AR600 sensors ordered without power supplies.

Red	Power, +15V (12-24 VDC)
Black	Ground
Orange	Optional Current Loop Range (out)
Brown	Current Loop Return (ground)
Shield	Ground at supply end

AR600 Sensor Options

High Resolution Option: Available on all AR600 models. Improves linearity to .03% of Full Scale Span. Improves resolution to .01% of Full Scale Span. Maximum sample rate is reduced to 200/second. BLE is alway on with the High Resolution Option.

Road Profiling Bundle: Road Profiling package for AR600-1, -2, -4, -6, or -8. Includes optics, 20 mW laser, and signal processing firmware optimzed for use in high-speed or low-speed road surface profiling.

5 mW Laser Upgrade: Upgrade laser power from 1 mW visible to 5 mW Visible. For high sample rates on dark or shiny targets.

20 mW Laser Upgrade: Upgrade laser power from 5 mW visible to 20 mW infrared. For high sample rates on dark or shiny targets at long distance or use on radiating surfaces. Includes 780 nm, Class IIIb infrared laser with safety interlocks.

RS 422 Output: Differential serial output for communication up to 4000 feet. 300 - 57600 baud. Replaces standard RS232 output.

Current Loop Output: 4-20 mA analog signal, installed internally. Not for High Resolution option

Optical Filter: Optical Filter for brightly-lit or glowing targets, installed internally. to be used with 5 and 20 mW lasers only.

Power Supply: Universal AC power supply. 100 240 V, 50 - 60 Hz

Software Library: Software Library for AR600 using serial interface. Includes tested functions for C, C++, VBA and Microsoft® Excel.

Display: Encased display with bright green characters, 9 mm high for output from AR600 in mm or in. Dimensions: 246.4 x 71.1 x 116.8 mm (L x H x D)

AccuRange™ 4000 sensor series with 0 - 54 foot range and 0.1 inch accuracy

AccuRange™ Line Scanner with spinning mirror and encoder assembly for measuring surface profiles

AccuRange™ 200 short range sensors with spans of 6, 12, 25 and 50 mm

AccuRange™ Line Scanner Environmental Enclosure for industrial environments

AccuRange™ High Speed Interface for rapid sampling with AR4000 and Line Scanner

See chart for laser classification of each model. This product complies with 21CFR 1040.10 and 1040.11. Specifications subject to change without notice.

Acuity product of SMS
Schmitt Measurement Systems, Inc.
2765 NW Nicolai St.
Portland, OR 97210
Tel: 503-227-5178 Fax: 503-227-5040
www.acuityresearch.com

Appendix F

OneSteel Datasheet Extract

Parallel Flange Channels

Table 21 Parallel Flange Channels — Dimensions and Properties

Designation	Mass per metre	Depth of Section d	Flange Width b_f	Flange Thickness t_f	Web Thickness t_w	Root Radius r_1	Depth Between Flanges d_1	$\frac{d_1}{t_w}$	$\frac{(b_f-t_w)}{t_f}$	Gross Area of Cross-Section A_g	Coordinate of Centroid x_L	Coordinate of Shear Centre x_0	About x-axis I_x	Z_x	S_x	r_x	About y-axis I_y	Z_{yR}	Z_{yL}	S_y	r_y	Torsion Constant J	Warping Constant I_w	Designation
	kg/m	mm	mm	mm	mm	mm	mm			mm^2	mm	mm	10^6mm^4	10^3mm^3	10^3mm^3	mm	10^6mm^4	10^3mm^3	10^3mm^3	10^3mm^3	mm	10^3mm^4	10^9mm^6	
380 PFC	55.2	380	100	17.5	10.0	14.0	345	34.5	5.14	7030	27.5	56.7	152	798	946	147	6.48	89.4	236	161	30.4	472	151	380 PFC
300 PFC	40.1	300	90	16.0	8.0	14.0	268	33.5	5.13	5110	27.2	56.1	72.4	483	564	119	4.04	64.4	148	117	28.1	290	58.2	300 PFC
250 PFC	35.5	250	90	15.0	8.0	12.0	220	27.5	5.47	4520	28.6	58.5	45.1	361	421	99.9	3.64	59.3	127	107	28.4	238	35.9	250 PFC
230 PFC	25.1	230	75	12.0	6.5	12.0	206	31.7	5.71	3200	22.6	46.7	26.8	233	271	91.4	1.76	33.6	77.8	61.0	23.5	108	15.0	230 PFC
200 PFC	22.9	200	75	12.0	6.0	12.0	176	29.3	5.75	2920	24.4	50.5	19.1	191	221	80.9	1.65	32.7	67.8	58.9	23.8	101	10.6	200 PFC
180 PFC	20.9	180	75	11.0	6.0	12.0	158	26.3	6.27	2660	24.5	50.3	14.1	157	182	72.9	1.51	29.9	61.5	53.8	23.8	81.4	7.82	180 PFC
150 PFC	17.7	150	75	9.5	6.0	10.0	131	21.8	7.26	2250	24.9	51.0	8.34	111	129	60.8	1.29	25.7	51.6	46.0	23.9	54.9	4.59	150 PFC
125 PFC	11.9	125	65	7.5	4.7	8.0	110	23.4	8.04	1520	21.8	45.0	3.97	63.5	73.0	51.1	0.658	15.2	30.2	27.2	20.8	23.1	1.64	125 PFC
100 PFC	8.33	100	50	6.7	4.2	8.0	86.6	20.6	6.84	1060	16.7	33.9	1.74	34.7	40.3	40.4	0.267	8.01	16.0	14.4	15.9	13.2	0.424	100 PFC
75 PFC	5.92	75	40	6.1	3.8	8.0	62.8	16.5	5.94	754	13.7	27.2	0.683	18.2	21.4	30.1	0.120	4.56	8.71	8.20	12.6	8.13	0.106	75 PFC

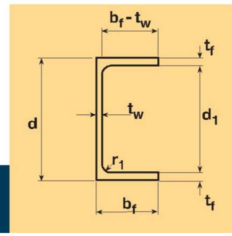
Table 22 Parallel Flange Channels — Properties for Assessing Section Capacity

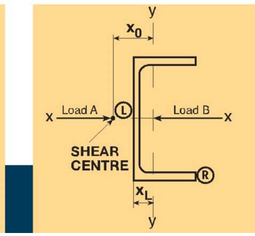
Designation	Yield Stress Flange f_y	Yield Stress Web f_y	Form Factor k_f	About x-axis Z_{ex}	About y-axis Load A Z_{ey}	About y-axis Load B Z_{ey}	Yield Stress Flange f_y	Yield Stress Web f_y	Form Factor k_f	About x-axis Z_{ex}	About y-axis Load A Z_{ey}	About y-axis Load B Z_{ey}	Designation
	MPa	MPa		10^3mm^3	10^3mm^3	10^3mm^3	MPa	MPa		10^3mm^3	10^3mm^3	10^3mm^3	
			300PLUS*							***AS/NZS 3679.1-350***			
380 PFC	280	320	1.00	946	115	134	340	360	1.00	946	104	134	380 PFC
300 PFC	300	320	1.00	564	82.3	96.6	340	360	1.00	564	77.2	96.6	300 PFC
250 PFC	300	320	1.00	421	88.7	89.0	340	360	1.00	421	84.9	89.0	250 PFC
230 PFC	300	320	1.00	271	45.1	50.4	340	360	1.00	271	42.6	50.4	230 PFC
200 PFC	300	320	1.00	221	46.7	49.1	340	360	1.00	221	44.5	49.1	200 PFC
180 PFC	300	320	1.00	182	44.9	44.8	340	360	1.00	182	44.1	44.8	180 PFC
150 PFC	320	320	1.00	129	38.5	38.5	360	360	1.00	129	38.5	38.5	150 PFC
125 PFC	320	320	1.00	72.8	22.8	22.8	360	360	1.00	72.0	22.5	22.8	125 PFC
100 PFC	320	320	1.00	40.3	12.0	12.0	360	360	1.00	40.3	12.0	12.0	100 PFC
75 PFC	320	320	1.00	21.4	6.84	6.84	360	360	1.00	21.4	6.84	6.84	75 PFC

* 300PLUS replaced Grade 250 as the base grade for these sections in 1994.
300PLUS hot rolled sections are produced to exceed the minimum requirements of AS/NZS 3679.1-300.

Notes

1. For 300PLUS sections the tensile strength (f_u) is 440 MPa.
2. For Grade 350 sections the tensile strength (f_u) is 480 MPa.

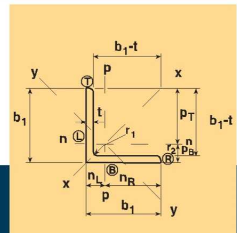


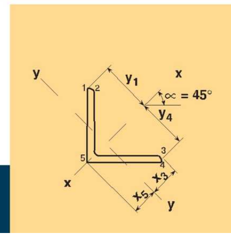


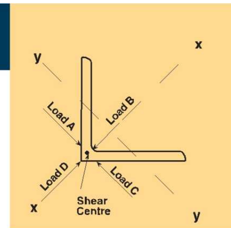
Equal Angles

Table 25 Equal Angles — x-axis and y-axis — Dimensions and Properties

Designation: Leg-size $b_1 \times b_1$, Nominal Thickness	Mass per metre	Actual Thickness t	Radii: Root r_1	Radii: Toe r_2	$\frac{(b_1-t)}{t}$	Gross Area of Cross-Section A_g	Coordinate of Centroid: $n_L = p_B$	Coordinate of Centroid: $n_R = p_T$	About x-axis: I_x	About x-axis: $y_1 = y_4$	About x-axis: $Z_{x1} = Z_{x4}$	About x-axis: S_x	About x-axis: r_x	About y-axis: I_y	About y-axis: x_3	About y-axis: Z_{y3}	About y-axis: x_5	About y-axis: Z_{y5}	About y-axis: S_y	About y-axis: r_y	Torsion Constant J	Designation
mm mm mm	kg/m	mm	mm	mm		mm^2	mm	mm	10^6mm^4	mm	10^3mm^3	10^3mm^3	mm	10^6mm^4	mm	10^3mm^3	mm	10^3mm^3	10^3mm^3	mm	10^3mm^4	
200 x 200 x 26 EA	76.8	26.0	18.0	5.0	6.69	9780	59.3	141	56.8	141	402	643	76.2	14.9	73.9	202	83.8	178	329	39.0	2250	200 x 200 x 26 EA
20 EA	60.1	20.0	18.0	5.0	9.00	7660	57.0	143	45.7	141	323	511	77.2	11.8	72.9	162	80.6	147	260	39.3	1060	20 EA
18 EA	54.4	18.0	18.0	5.0	10.1	6930	56.2	144	41.7	141	295	464	77.6	10.8	72.6	149	79.5	136	236	39.4	778	18 EA
16 EA	48.7	16.0	18.0	5.0	11.5	6200	55.4	145	37.6	141	266	417	77.9	9.72	72.3	135	78.4	124	212	39.6	554	16 EA
13 EA	40.0	13.0	18.0	5.0	14.4	5090	54.2	146	31.2	141	221	344	78.3	8.08	71.9	112	76.6	105	176	39.8	304	13 EA
150 x 150 x 19 EA	42.1	19.0	13.0	5.0	6.89	5360	44.2	106	17.6	106	166	265	57.2	4.60	54.9	83.8	62.6	73.5	135	29.3	657	150 x 150 x 19 EA
16 EA	35.4	15.8	13.0	5.0	8.49	4520	43.0	107	15.1	106	142	225	57.8	3.91	54.3	71.9	60.8	64.2	115	29.4	386	16 EA
12 EA	27.3	12.0	13.0	5.0	11.5	3480	41.5	108	11.9	106	112	175	58.4	3.06	53.7	56.9	58.7	52.1	89.3	29.6	174	12 EA
10 EA	21.9	9.5	13.0	5.0	14.8	2790	40.5	109	9.61	106	90.6	141	58.7	2.48	53.4	46.4	57.3	43.3	72.0	29.8	88.9	10 EA
125 x 125 x 16 EA	29.1	15.8	10.0	5.0	6.91	3710	36.8	88.2	8.43	88.4	95.4	153	47.7	2.20	45.4	48.5	52.1	42.3	77.8	24.4	313	125 x 125 x 16 EA
12 EA	22.5	12.0	10.0	5.0	9.42	2870	35.4	89.6	6.69	88.4	75.7	120	48.3	1.73	44.7	38.6	50.1	34.5	60.8	24.5	141	12 EA
10 EA	18.0	9.5	10.0	5.0	12.2	2300	34.4	90.6	5.44	88.4	61.6	96.5	48.7	1.40	44.4	31.5	48.7	28.8	49.0	24.7	71.9	10 EA
8 EA	14.9	7.8	10.0	5.0	15.0	1900	33.7	91.3	4.55	88.4	51.5	80.2	48.9	1.17	44.2	26.5	47.7	24.5	40.8	24.8	40.6	8 EA
100 x 100 x 12 EA	17.7	12.0	8.0	5.0	7.33	2260	29.2	70.8	3.29	70.7	46.6	74.5	38.2	0.857	35.8	23.9	41.3	20.8	37.9	19.5	110	100 x 100 x 12 EA
10 EA	14.2	9.5	8.0	5.0	9.53	1810	28.2	71.8	2.70	70.7	38.2	60.4	38.6	0.695	35.4	19.6	39.9	17.4	30.7	19.6	56.2	10 EA
8 EA	11.8	7.8	8.0	5.0	11.8	1500	27.5	72.5	2.27	70.7	32.0	50.3	38.8	0.582	35.2	16.5	38.9	14.9	25.6	19.7	31.7	8 EA
6 EA	9.16	6.0	8.0	5.0	15.7	1170	26.8	73.2	1.78	70.7	25.2	39.3	39.1	0.458	35.0	13.1	37.9	12.1	20.0	19.8	14.8	6 EA
90 x 90 x 10 EA	12.7	9.5	8.0	5.0	8.47	1620	25.7	64.3	1.93	63.6	30.4	48.3	34.5	0.500	31.9	15.7	36.4	13.8	24.6	17.6	50.5	90 x 90 x 10 EA
8 EA	10.6	7.8	8.0	5.0	10.5	1350	25.0	65.0	1.63	63.6	25.6	40.4	34.8	0.419	31.7	13.2	35.4	11.8	20.5	17.6	28.6	8 EA
6 EA	8.22	6.0	8.0	5.0	14.0	1050	24.3	65.7	1.28	63.6	20.1	31.6	35.0	0.330	31.5	10.5	34.3	9.62	16.1	17.8	13.4	6 EA
75 x 75 x 10 EA	10.5	9.5	8.0	5.0	6.89	1340	22.0	53.0	1.08	53.0	20.4	32.8	28.4	0.282	26.6	10.6	31.1	9.09	16.8	14.5	41.9	75 x 75 x 10 EA
8 EA	8.73	7.8	8.0	5.0	8.62	1110	21.3	53.7	0.913	53.0	17.2	27.5	28.7	0.237	26.4	8.99	30.1	7.87	14.0	14.6	23.8	8 EA
6 EA	6.81	6.0	8.0	5.0	11.5	867	20.5	54.5	0.722	53.0	13.6	21.6	28.9	0.187	26.2	7.15	29.0	6.44	11.0	14.7	11.2	6 EA
5 EA	5.27	4.6	8.0	5.0	15.3	672	19.9	55.1	0.563	53.0	10.6	16.7	29.0	0.147	26.1	5.62	28.1	5.22	8.61	14.8	5.28	5 EA
65 x 65 x 10 EA	9.02	9.5	6.0	3.0	5.84	1150	19.6	45.4	0.691	46.0	15.0	24.3	24.5	0.183	23.7	7.71	27.7	6.60	12.5	12.6	35.1	65 x 65 x 10 EA
8 EA	7.51	7.8	6.0	3.0	7.33	957	19.0	46.0	0.589	46.0	12.8	20.5	24.8	0.154	23.4	6.56	26.8	5.73	10.5	12.7	20.0	8 EA
6 EA	5.87	6.0	6.0	3.0	9.83	748	18.3	46.7	0.471	46.0	10.2	16.2	25.1	0.122	23.1	5.26	25.8	4.71	8.25	12.8	9.37	6 EA
5 EA	4.56	4.6	6.0	3.0	13.1	581	17.7	47.3	0.371	46.0	8.08	12.7	25.3	0.0959	23.0	4.18	25.0	3.83	6.46	12.9	4.36	5 EA
55 x 55 x 6 EA	4.93	6.0	6.0	3.0	8.17	628	15.8	39.2	0.278	38.9	7.14	11.4	21.0	0.0723	19.6	3.69	22.3	3.24	5.82	10.7	7.93	55 x 55 x 6 EA
5 EA	3.84	4.6	6.0	3.0	11.0	489	15.2	39.8	0.220	38.9	5.66	8.93	21.2	0.0571	19.4	2.94	21.5	2.66	4.57	10.8	3.71	5 EA
50 x 50 x 8 EA	5.68	7.8	6.0	3.0	5.41	723	15.2	34.8	0.253	35.4	7.16	11.7	18.7	0.0675	18.1	3.73	21.5	3.14	6.00	9.66	15.2	50 x 50 x 8 EA
6 EA	4.46	6.0	6.0	3.0	7.33	568	14.5	35.5	0.205	35.4	5.79	9.30	19.0	0.0536	17.8	3.01	20.5	2.61	4.76	9.71	7.21	6 EA
5 EA	3.48	4.6	6.0	3.0	9.87	443	13.9	36.1	0.163	35.4	4.61	7.32	19.2	0.0424	17.6	2.40	19.7	2.15	3.75	9.78	3.38	5 EA
3 EA	2.31	3.0	6.0	3.0	15.7	295	13.2	36.8	0.110	35.4	3.11	4.90	19.3	0.0289	17.6	1.65	18.7	1.55	2.53	9.90	1.01	3 EA
45 x 45 x 6 EA	3.97	6.0	5.0	3.0	6.50	506	13.3	31.7	0.146	31.8	4.59	7.41	17.0	0.0383	16.0	2.39	18.8	2.04	3.79	8.71	6.32	45 x 45 x 6 EA
5 EA	3.10	4.6	5.0	3.0	8.78	394	12.7	32.3	0.117	31.8	3.66	5.84	17.2	0.0303	15.8	1.91	18.0	1.68	2.99	8.76	2.96	5 EA
3 EA	2.06	3.0	5.0	3.0	14.0	263	12.0	33.0	0.0790	31.8	2.48	3.92	17.3	0.0206	15.7	1.31	17.0	1.21	2.02	8.85	0.875	3 EA
40 x 40 x 6 EA	3.50	6.0	5.0	3.0	5.67	446	12.0	28.0	0.0997	28.3	3.53	5.75	15.0	0.0265	14.3	1.86	17.0	1.55	2.95	7.71	5.60	40 x 40 x 6 EA
5 EA	2.73	4.6	5.0	3.0	7.70	348	11.5	28.5	0.0801	28.3	2.83	4.55	15.2	0.0209	14.0	1.49	16.2	1.29	2.33	7.75	2.63	5 EA
3 EA	1.83	3.0	5.0	3.0	12.3	233	10.8	29.2	0.0545	28.3	1.93	3.06	15.3	0.0142	13.9	1.02	15.3	0.930	1.58	7.82	0.785	3 EA
30 x 30 x 6 EA	2.56	6.0	5.0	3.0	4.00	326	9.53	20.5	0.0387	21.2	1.83	3.06	10.9	0.0107	10.7	0.993	13.5	0.790	1.59	5.72	4.16	30 x 30 x 6 EA
5 EA	2.01	4.6	5.0	3.0	5.52	256	8.99	21.0	0.0316	21.2	1.49	2.45	11.1	0.00839	10.5	0.799	12.7	0.660	1.26	5.72	1.98	5 EA
3 EA	1.35	3.0	5.0	3.0	9.00	173	8.30	21.7	0.0218	21.2	1.03	1.67	11.2	0.00573	10.3	0.554	11.7	0.488	0.862	5.76	0.605	3 EA
25 x 25 x 6 EA	2.08	6.0	5.0	3.0	3.17	266	8.28	16.7	0.0210	17.7	1.19	2.03	8.89	0.00600	8.97	0.669	11.7	0.513	1.07	4.75	3.44	25 x 25 x 6 EA
5 EA	1.65	4.6	5.0	3.0	4.43	210	7.75	17.3	0.0173	17.7	0.980	1.65	9.07	0.00469	8.73	0.537	11.0	0.428	0.849	4.72	1.66	5 EA
3 EA	1.12	3.0	5.0	3.0	7.33	143	7.07	17.9	0.0121	17.7	0.685	1.13	9.22	0.00319	8.56	0.373	9.99	0.319	0.583	4.73	0.515	3 EA







Equal Angles

Table 26 Equal Angles — x-axis and y-axis — Properties for Assessing Section Capacity

Designation	Yield Stress	Form Factor	About x-axis	About y-axis		Yield Stress	Form Factor	About x-axis	About y-axis		Designation
			Load A or C	Load B	Load D			Load A or C	Load B	Load D	
	f_y	k_f	Z_{ex}	Z_{ey}	Z_{ey}	f_y	k_f	Z_{ex}	Z_{ey}	Z_{ey}	
mm mm mm	MPa		10^3mm^3	10^3mm^3	10^3mm^3	MPa		10^3mm^3	10^3mm^3	10^3mm^3	
			300PLUS*						**AS/NZS 3679.1-350**		
200 x 200 x 26 EA	280	1.00	602	267	267	340	1.00	602	267	267	200 x 200 x 26 EA
20 EA	280	1.00	479	218	220	340	1.00	469	214	220	20 EA
18 EA	280	1.00	427	196	204	340	1.00	417	192	204	18 EA
16 EA	300	1.00	369	172	186	340	1.00	362	169	186	16 EA
13 EA	300	1.00	285	136	158	340	0.956	278	132	158	13 EA
150 x 150 x 19 EA	280	1.00	248	110	110	340	1.00	248	110	110	150 x 150 x 19 EA
16 EA	300	1.00	212	95.7	96.3	340	1.00	209	94.5	96.3	16 EA
12 EA	300	1.00	155	72.3	78.1	340	1.00	152	70.9	78.1	12 EA
10 EA	320	0.958	114	54.5	64.9	360	0.906	111	53.1	64.9	10 EA
125 x 125 x 16 EA	300	1.00	143	63.4	63.4	340	1.00	143	63.4	63.4	125 x 125 x 16 EA
12 EA	300	1.00	110	50.3	51.7	340	1.00	109	49.6	51.7	12 EA
10 EA	320	1.00	83.2	38.9	43.1	360	1.00	81.6	38.1	43.1	10 EA
8 EA	320	0.943	64.3	30.7	36.8	360	0.892	62.7	29.9	36.8	8 EA
100 x 100 x 12 EA	300	1.00	69.9	31.1	31.1	340	1.00	69.9	31.1	31.1	100 x 100 x 12 EA
10 EA	320	1.00	55.1	25.2	26.1	360	1.00	54.4	24.8	26.1	10 EA
8 EA	320	1.00	43.7	20.4	22.4	360	1.00	42.9	20.0	22.4	8 EA
6 EA	320	0.906	30.9	14.8	18.1	360	0.856	30.0	14.4	18.1	6 EA
90 x 90 x 10 EA	320	1.00	45.0	20.4	20.6	360	1.00	44.5	20.1	20.6	90 x 90 x 10 EA
8 EA	320	1.00	36.0	16.7	17.8	360	1.00	35.4	16.4	17.8	8 EA
6 EA	320	1.00	25.9	12.4	14.4	360	0.954	25.3	12.1	14.4	6 EA
75 x 75 x 10 EA	320	1.00	30.5	13.6	13.6	360	1.00	30.5	13.6	13.6	75 x 75 x 10 EA
8 EA	320	1.00	25.4	11.6	11.8	360	1.00	25.1	11.5	11.8	8 EA
6 EA	320	1.00	18.7	8.85	9.66	360	1.00	18.4	8.70	9.66	6 EA
5 EA	320	0.927	13.2	6.47	7.82	360	0.876	12.8	6.30	7.82	5 EA
65 x 65 x 10 EA	320	1.00	22.5	9.90	9.90	360	1.00	22.5	9.90	9.90	65 x 65 x 10 EA
8 EA	320	1.00	19.2	8.59	8.59	360	1.00	19.2	8.59	8.59	8 EA
6 EA	320	1.00	14.7	6.76	7.07	360	1.00	14.5	6.66	7.07	6 EA
5 EA	320	1.00	10.6	5.05	5.75	360	1.00	10.4	4.94	5.75	5 EA
55 x 55 x 6 EA	320	1.00	10.7	4.84	4.86	360	1.00	10.5	4.78	4.86	55 x 55 x 6 EA
5 EA	320	1.00	7.88	3.70	3.98	360	1.00	7.75	3.64	3.98	5 EA
50 x 50 x 8 EA	320	1.00	10.7	4.71	4.71	360	1.00	10.7	4.71	4.71	50 x 50 x 8 EA
6 EA	320	1.00	8.69	3.92	3.92	360	1.00	8.69	3.92	3.92	6 EA
5 EA	320	1.00	6.60	3.08	3.22	360	1.00	6.50	3.03	3.22	5 EA
3 EA	320	0.907	3.82	1.90	2.32	360	0.858	3.71	1.85	2.32	3 EA
45 x 45 x 6 EA	320	1.00	6.88	3.06	3.06	360	1.00	6.88	3.06	3.06	45 x 45 x 6 EA
5 EA	320	1.00	5.39	2.47	2.52	360	1.00	5.32	2.44	2.52	5 EA
3 EA	320	1.00	3.19	1.55	1.81	360	0.954	3.12	1.52	1.81	3 EA
40 x 40 x 6 EA	320	1.00	5.29	2.33	2.33	360	1.00	5.29	2.33	2.33	40 x 40 x 6 EA
5 EA	320	1.00	4.25	1.93	1.93	360	1.00	4.22	1.92	1.93	5 EA
3 EA	320	1.00	2.59	1.25	1.40	360	1.00	2.54	1.23	1.40	3 EA
30 x 30 x 6 EA	320	1.00	2.74	1.19	1.19	360	1.00	2.74	1.19	1.19	30 x 30 x 6 EA
5 EA	320	1.00	2.23	0.990	0.990	360	1.00	2.23	0.990	0.990	5 EA
3 EA	320	1.00	1.50	0.714	0.732	360	1.00	1.48	0.705	0.732	3 EA
25 x 25 x 6 EA	320	1.00	1.78	0.769	0.769	360	1.00	1.78	0.769	0.769	25 x 25 x 6 EA
5 EA	320	1.00	1.47	0.642	0.642	360	1.00	1.47	0.642	0.642	5 EA
3 EA	320	1.00	1.03	0.479	0.479	360	1.00	1.03	0.479	0.479	3 EA

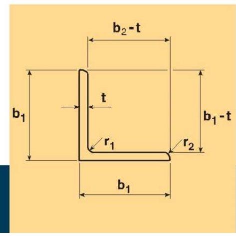
* 300PLUS replaced Grade 250 as the base grade for 125x125x8 equal angles and larger in 1994.
300PLUS replaced Grade 250 as the base grade for 100x100x12 equal angles and smaller in 1997.
300PLUS hot rolled sections are produced to exceed the minimum requirements of AS/NZS 3679.1-300.

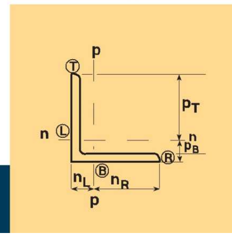
Notes 1. For 300PLUS sections the tensile strength (f_u) is 440 MPa.
2. For Grade 350 sections the tensile strength (f_u) is 480 MPa.

Equal Angles

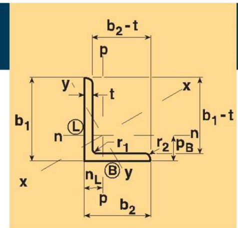
Table 27 Equal Angles — n-axis and p-axis — Properties

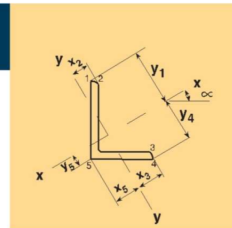
Designation	About n-axis and p-axis							Product of 2nd Moment of Area	Designation
	I_n=I_p	n_L=p_B	Z_{nB}=Z_{pL}	n_R=p_T	Z_{nT}=Z_{pR}	S_n=S_p	r_n=r_p	I_{np}	
mm mm mm	$10^6 mm^4$	mm	$10^3 mm^3$	mm	$10^3 mm^3$	$10^3 mm^3$	mm	$10^6 mm^4$	
200 x 200 x 26 EA	35.8	59.3	605	141	255	460	60.5	-20.9	200 x 200 x 26 EA
20 EA	28.8	57.0	505	143	201	363	61.3	-16.9	20 EA
18 EA	26.3	56.2	467	144	183	330	61.5	-15.5	18 EA
16 EA	23.7	55.4	427	145	164	296	61.8	-14.0	16 EA
13 EA	19.7	54.2	363	146	135	243	62.2	-11.6	13 EA
150 x 150 x 19 EA	11.1	44.2	250	106	105	189	45.4	-6.48	150 x 150 x 19 EA
16 EA	9.48	43.0	220	107	88.7	160	45.8	-5.58	16 EA
12 EA	7.46	41.5	180	108	68.8	124	46.3	-4.40	12 EA
10 EA	6.04	40.5	149	109	55.2	99.9	46.6	-3.56	10 EA
125 x 125 x 16 EA	5.32	36.8	144	88.2	60.3	109	37.9	-3.11	125 x 125 x 16 EA
12 EA	4.21	35.4	119	89.6	47.0	85.0	38.3	-2.48	12 EA
10 EA	3.42	34.4	99.4	90.6	37.8	68.4	38.6	-2.02	10 EA
8 EA	2.86	33.7	84.9	91.3	31.3	56.8	38.8	-1.69	8 EA
100 x 100 x 12 EA	2.08	29.2	71.1	70.8	29.3	53.2	30.3	-1.22	100 x 100 x 12 EA
10 EA	1.70	28.2	60.1	71.8	23.6	42.9	30.6	-1.00	10 EA
8 EA	1.42	27.5	51.7	72.5	19.6	35.7	30.8	-0.842	8 EA
6 EA	1.12	26.8	41.8	73.2	15.3	27.8	31.0	-0.661	6 EA
90 x 90 x 10 EA	1.22	25.7	47.3	64.3	18.9	34.4	27.4	-0.716	90 x 90 x 10 EA
8 EA	1.02	25.0	40.9	65.0	15.7	28.7	27.6	-0.604	8 EA
6 EA	0.805	24.3	33.2	65.7	12.3	22.4	27.7	-0.475	6 EA
75 x 75 x 10 EA	0.681	22.0	31.0	53.0	12.8	23.4	22.6	-0.399	75 x 75 x 10 EA
8 EA	0.575	21.3	27.0	53.7	10.7	19.6	22.7	-0.338	8 EA
6 EA	0.455	20.5	22.1	54.5	8.35	15.3	22.9	-0.268	6 EA
5 EA	0.355	19.9	17.9	55.1	6.44	11.8	23.0	-0.208	5 EA
65 x 65 x 10 EA	0.437	19.6	22.3	45.4	9.62	17.4	19.5	-0.254	65 x 65 x 10 EA
8 EA	0.371	19.0	19.6	46.0	8.07	14.6	19.7	-0.218	8 EA
6 EA	0.296	18.3	16.2	46.7	6.34	11.5	19.9	-0.175	6 EA
5 EA	0.234	17.7	13.2	47.3	4.94	8.97	20.1	-0.138	5 EA
55 x 55 x 6 EA	0.175	15.8	11.1	39.2	4.46	8.11	16.7	-0.103	55 x 55 x 6 EA
5 EA	0.139	15.2	9.12	39.8	3.48	6.34	16.8	-0.0814	5 EA
50 x 50 x 8 EA	0.160	15.2	10.5	34.8	4.61	8.38	14.9	-0.0928	50 x 50 x 8 EA
6 EA	0.129	14.5	8.90	35.5	3.64	6.63	15.1	-0.0756	6 EA
5 EA	0.103	13.9	7.36	36.1	2.85	5.19	15.2	-0.0602	5 EA
3 EA	0.0694	13.2	5.25	36.8	1.89	3.46	15.3	-0.0405	3 EA
45 x 45 x 6 EA	0.0922	13.3	6.93	31.7	2.91	5.30	13.5	-0.0538	45 x 45 x 6 EA
5 EA	0.0734	12.7	5.76	32.3	2.28	4.16	13.6	-0.0432	5 EA
3 EA	0.0498	12.0	4.14	33.0	1.51	2.77	13.8	-0.0292	3 EA
40 x 40 x 6 EA	0.0631	12.0	5.24	28.0	2.26	4.12	11.9	-0.0366	40 x 40 x 6 EA
5 EA	0.0505	11.5	4.39	28.5	1.77	3.24	12.0	-0.0296	5 EA
3 EA	0.0344	10.8	3.19	29.2	1.18	2.17	12.2	-0.0201	3 EA
30 x 30 x 6 EA	0.0247	9.53	2.59	20.5	1.21	2.22	8.71	-0.0140	30 x 30 x 6 EA
5 EA	0.0200	8.99	2.22	21.0	0.951	1.76	8.83	-0.0116	5 EA
3 EA	0.0138	8.30	1.66	21.7	0.635	1.18	8.93	-0.00804	3 EA
25 x 25 x 6 EA	0.0135	8.28	1.63	16.7	0.807	1.49	7.13	-0.00750	25 x 25 x 6 EA
5 EA	0.0110	7.75	1.42	17.3	0.638	1.19	7.23	-0.00632	5 EA
3 EA	0.00765	7.07	1.08	17.9	0.426	0.802	7.33	-0.00446	3 EA





onesteel market mills





Unequal Angles

Table 28 Unequal Angles — x-axis and y-axis — Dimensions and Properties

Designation Leg-size $b_1 \times b_2$	Normal Thickness	Mass per m	Actual Thickness t	Radii Root r_1	Radii Toe r_2	$\frac{(b_1-t)}{t}$	$\frac{(b_2-t)}{t}$	Gross Area of Cross Section A_g	Coordinate of Centroid p_B	Coordinate of Centroid n_L	About x-axis I_x	y_1	Z_{x1}	y_4	Z_{x4}	y_5	Z_{x5}	S_x	r_x	About y-axis I_y	x_2	Z_{y2}	x_3	Z_{y3}	x_5	Z_{y5}	S_y	r_y	Torsion Constant J	Tan Alpha	Designation
mm mm	mm	kg/m	mm	mm	mm			mm^2	mm	mm	10^6mm^4	mm	10^3mm^3	mm	10^3mm^3	mm	10^3mm^3	10^3mm^3	mm	10^6mm^4	mm	10^3mm^3	mm	10^3mm^3	mm	10^3mm^3	10^3mm^3	mm	10^3mm^4		
150 x 100 x	12 UA	22.5	12.0	10.0	5.0	11.5	7.33	2870	49.1	24.3	7.51	102	73.5	75.3	99.7	35.2	213	127	51.2	1.35	27.6	48.8	52.9	25.5	42.0	32.1	51.7	21.7	141	0.438	150 x 100 x 12 UA
	10 UA	18.0	9.5	10.0	5.0	14.8	9.53	2300	48.1	23.3	6.11	103	59.5	74.9	81.5	34.6	177	102	51.6	1.09	26.9	40.7	53.0	20.6	40.7	26.9	41.8	21.8	71.9	0.441	10 UA
150 x 90 x	16 UA	27.9	15.8	10.0	5.0	8.49	4.70	3550	52.5	22.7	8.80	99.5	88.4	71.9	122	41.9	210	154	49.8	1.32	24.6	53.8	49.9	26.5	38.9	34.0	55.9	19.3	300	0.353	150 x 90 x 16 UA
	12 UA	21.6	12.0	10.0	5.0	11.5	6.50	2750	51.0	21.2	6.97	100	69.4	71.3	97.8	40.8	171	120	50.4	1.04	23.4	44.5	50.1	20.8	37.2	28.0	43.8	19.5	136	0.360	12 UA
	10 UA	17.3	9.5	10.0	5.0	14.8	8.47	2200	50.0	20.2	5.66	101	56.1	70.7	80.1	40.1	141	96.6	50.7	0.847	22.6	37.4	50.4	16.8	36.1	23.5	35.4	19.6	69.0	0.363	10 UA
	8 UA	14.3	7.8	10.0	5.0	18.2	10.5	1820	49.2	19.6	4.73	101	46.7	70.3	67.3	39.5	120	80.1	51.0	0.710	22.1	32.2	50.6	14.0	35.2	20.2	29.5	19.7	39.0	0.364	8 UA
125 x 75 x	12 UA	17.7	12.0	8.0	5.0	9.42	5.25	2260	43.3	18.4	3.91	83.2	47.0	59.7	65.5	34.6	113	81.4	41.6	0.585	19.9	29.3	41.4	14.1	31.9	18.4	29.7	16.1	110	0.356	125 x 75 x 12 UA
	10 UA	14.2	9.5	8.0	5.0	12.2	6.89	1810	42.3	17.5	3.20	83.8	38.2	59.3	53.9	33.9	94.4	65.8	42.0	0.476	19.2	24.9	41.6	11.4	30.7	15.5	24.1	16.2	56.2	0.360	10 UA
	8 UA	11.8	7.8	8.0	5.0	15.0	8.62	1500	41.5	16.8	2.68	84.2	31.8	58.9	45.5	33.3	80.4	54.6	42.2	0.399	18.6	21.5	41.8	9.55	29.9	13.3	20.1	16.3	31.7	0.363	8 UA
	6 UA	9.16	6.0	8.0	5.0	19.8	11.5	1170	40.7	16.0	2.10	84.7	24.8	58.5	36.0	32.8	64.1	42.4	42.5	0.315	18.0	17.5	42.1	7.47	29.0	10.8	15.7	16.4	14.8	0.364	6 UA
100 x 75 x	10 UA	12.4	9.5	8.0	5.0	9.53	6.89	1580	31.8	19.4	1.89	69.2	27.3	54.5	34.6	18.6	101	46.5	34.6	0.401	22.3	18.0	36.4	11.0	32.2	12.5	21.2	16.0	49.1	0.546	100 x 75 x 10 UA
	8 UA	10.3	7.8	8.0	5.0	11.8	8.62	1310	31.1	18.7	1.59	69.4	22.9	54.3	29.2	18.2	87.0	38.7	34.8	0.337	21.8	15.4	36.4	9.26	31.3	10.7	17.8	16.0	27.8	0.549	8 UA
	6 UA	7.98	6.0	8.0	5.0	15.7	11.5	1020	30.3	17.9	1.25	69.7	17.9	54.0	23.1	17.9	70.0	30.1	35.1	0.265	21.4	12.4	36.5	7.27	30.3	8.75	13.9	16.2	13.0	0.551	6 UA
75 x 50 x	8 UA	7.23	7.8	7.0	3.0	8.62	5.41	921	25.2	12.8	0.586	50.8	11.5	37.8	15.5	18.0	32.5	20.0	25.2	0.106	14.2	7.46	26.4	4.01	21.7	4.88	8.19	10.7	19.5	0.430	75 x 50 x 8 UA
	6 UA	5.66	6.0	7.0	3.0	11.5	7.33	721	24.4	12.1	0.468	51.2	9.15	37.5	12.5	17.6	26.7	15.8	25.5	0.0842	13.6	6.17	26.5	3.18	20.8	4.04	6.48	10.8	9.21	0.435	6 UA
	5 UA	4.40	4.6	7.0	3.0	15.3	9.87	560	23.8	11.5	0.370	51.5	7.17	37.2	9.93	17.2	21.5	12.3	25.7	0.0666	13.2	5.03	26.6	2.50	20.1	3.32	5.09	10.9	4.32	0.437	5 UA
65 x 50 x	8 UA	6.59	7.8	6.0	3.0	7.33	5.41	840	21.1	13.6	0.421	44.9	9.37	36.3	11.6	11.6	36.4	16.1	22.4	0.0936	15.6	6.00	23.9	3.91	22.3	4.20	7.49	10.6	17.6	0.570	65 x 50 x 8 UA
	6 UA	5.16	6.0	6.0	3.0	9.83	7.33	658	20.4	12.9	0.338	45.2	7.48	36.1	9.35	11.2	30.2	12.7	22.7	0.0743	15.1	4.91	23.9	3.11	21.4	3.48	5.93	10.6	8.29	0.575	6 UA
	5 UA	4.02	4.6	6.0	3.0	13.1	9.87	512	19.8	12.4	0.267	45.4	5.89	35.9	7.43	10.9	24.5	9.92	22.8	0.0587	14.8	3.97	23.9	2.46	20.6	2.85	4.66	10.7	3.87	0.577	5 UA