The Development of an Automatic Discharge System for Small Filter Presses

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Declaration

The work described in this Thesis is the original work of the author and was carried out without the assistance of others, except where explicit credit is given in the text. It has not been submitted, in whole or in part, for any other degree at any University.

Andrew Jaffrey

For my mother and father, Rena and Dan, for giving me life;
and to my wife Alison for making that life wonderful.

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Abstract

Automatic sequencing of all stages of the filter press operating cycle is well known and has long been widely incorporated in industrial filtration operations. The objective in this work was to achieve full, automatic, discharge without the operator intervention currently required to guarantee complete detachment of filter cake from the filter cloths of a filter press. This is a particularly desirable objective when the filtered materials are hazardous or subject to contamination, and where labour costs are of critical importance.

Means have been devised for identifying residual filter cake deposits on the filter cloths of a small production-scale filter press after normal gravity discharge has occurred. A scanning laser-generated image of each cloth face is analysed to identify cake deposits and establish their size and location. This information is used by the control code of a four-axis gantry robot to direct and actuate a scraper blade in such a way as to dislodge each deposit from the filter cloth.

The imaging and robot systems are designed to serve a group of presses, thus reducing the capital cost per press installed.

The thesis describes the principles and development equipment used, the results obtained and the limitations of the system. Ways round these limitations are discussed and further work is proposed.

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Chapter 1

Introduction

Filtration is the removal of solid particles from a fluid by passing the fluid through a filtering medium. This process plays an important role in modern life. It is an everyday household occurrence in making tea and coffee but it extends from such elementary activities to industrial operations in which the handling of many tonnes per hour of solids, or many cubic metres of liquid, must be carried out, producing separation to precise limits and liquids and solids within close tolerances on quality.

When it is applied to industrial filtration in the processing of natural materials; the recovery of saleable bye-products; the recirculation of water; the manufacture of valuable products or the disposal of effluent; filtration becomes a complex science.

Industrial filtrations range from simple straining of large particles to the removal of cloudiness in beer. The fluid may be a liquid or a gas; the solid particles may be of very diverse sizes, shapes and types; feed suspensions (slurries) vary from very high to very low solids content and may be at high or low temperature, under vacuum or pressure. The absolute and relative monetary values of the separated phases, whether full or partial separation is required, and product toxicity or sensitivity to contamination, are further questions to be considered in choosing suitable equipment to meet a filtration requirement.

Most industrial filters are either pressure filters or vacuum filters. They are also either continuous or discontinuous. The flow of liquid through a discontinuous filter must be interrupted regularly to discharge the accumulated solids from it; the discharge of solids and liquids from a continuous filter is uninterrupted while the machine is operating.

Some of the more common types of filter typical of those developed to deal with industry's many and varied requirements are now discussed briefly. It is assumed that some labour requirement exists for all filter presses, e.g. maintenance. Not all known types of equipment are included in this discussion, merely examples to highlight representative features common to most.

- Rotary vacuum filters are particularly suited for applications where large amounts of liquids and/or solids have to be handled continuously. They operate continuously. The solids and liquids are discharged at steady rates, and automatically, without any labour being involved and without interruption of the filtration process.

  Vacuum filters feature a filter medium, often a synthetic fibre fabric, held onto a cloth support grid. The material to be filtered is introduced to one side of the filter medium under atmospheric pressure while the other side is subject to a vacuum. The filtered solids form a cake on the atmospheric side of the medium and the filtrate liquor flows through this into the vacuum system.

  The filter cake is accessible for washing and drying operations since it is formed in the atmosphere. The filter medium can pass continuously through the various zones of a filtration cycle in succession, so the the whole operation is continuous and automatic.

  The filter medium and its support grid can be arranged as panels on a rotating horizontal, cylindrical drum; or on both faces of vertical discs rotating on a horizontal shaft; or on the upper side of segments formed in the bottom of a horizontal rotating table.

Depending on the characteristics of the materials being handled, and on the type of vacuum filter used, extra facilities can often be fitted for cake washing and drying. Sealed enclosed hoods for operation under an inert gas blanket, or simple hoods to limit the escape of vapours, can often be supplied by the filter manufacturers.

- Drum filters of approximately 30 to 60 m^2 filtering surface have become very common. A 100 m^2 size is used in the bauxite industry for red-mud dewatering; the largest drum filters, 120 m^2, usually have a diameter of around 4 m and a length of 10 m. These dimensions offer quite a challenging mechanical engineering problem since sagging of the drum impairs its concentricity, which is particularly important where cake removal is by a fixed blade.

  The filter cake on a drum filter is formed by upward suction; the area of cake formation is influenced by varying the filling height of the slurry trough through which the drum rotates.

  The filter cake can be removed from a drum filter in at least three ways.

  1. Knife discharge. The filter cake is discharged by rotating the drum against a knife edge, the cake being dislodged from the cloth either by its own weight or, more usually, by applying compressed air to the underside of the cloth. Knife discharge is suitable for many applications extending from some which produce thin sticky cakes to some producing thick friable cakes.
  2. Belt discharge. In some applications it can be advantageous to wash the filter cloth either continuously or intermittently without diluting the contents of the filter trough. This can readily be done if the cloth is in the form of an endless belt passing over the drum and a (discharge) roller parallel to it. In this case the filter cloth is made to act also as

the filter cake discharge conveyor, the cake being supported between the main drum and the discharge roll. If this is of sufficiently small diameter, the cake will break away from the cloth as the latter passes over the roller. Cakes of low inherent strength can be handled in this way and discharged with higher filtration rates than can be achieved by other discharge systems.

3. String discharge. Endless strings pass around the drum onto a discharge roll, a return roll and back onto the drum, thus acting as an open conveyor through which filtration takes place and on which the filter cake is built up. Blow back is not needed to assist with cake discharge and consequently wire winding to secure the filter cloth is not required. Mechanical wear on the cloth is minimal and this means a wide range of cloths can be used.

The principal arguments in favour of a drum filter are the possibility of continuous cloth cleaning and the resulting easier cake removal, especially when handling slurries with high concentrations of superfine grains.

- Rotary disc vacuum filters operate in a similar way to drum filters, but a greater filtration surface can be provided for a given equipment volume, since the vacuum compartments are formed on both sides of each disc. An array of such discs, radius r, on a shaft of length l can give a greater filtration area than a drum of radius r and length l if the spacing between the discs is less than r. Machines of this type can thus give a relatively large filtration area in a comparatively small floor space. Disc filters can have filtering areas up to around 400 m^2, with diameters up to 6 m and up to 10 discs arranged on one shaft. The filter cake is formed laterally and the cake removed by means of scrapers or blown off with compressed air. Only one side of the cloth can be cleaned while the machine is at rest under normal circumstances.

- Horizontal filters have been applied since the nineteen-twenties to wash filtration and for the dewatering of coarse-grained suspensions. In such filters the filter cake is formed by downward suction. The horizontal filtering area is in the flat surface of a disc which rotates about a vertical axis. A disadvantage of this design is that the speed of the cake increases with distance from the axis of rotation. Discharge is by means of a screw, a helical conveyor-scraper which moves the solids radially to the discharge point. A layer of material should always remain on the filter cloth so as to reduce cloth wear by this action. Large horizontal filters have filtering areas of approximately 50 m^2 at disc diameters of around 8 m.

The general operating characteristics of rotary vacuum filters have been the subject of some criticism. Rotary filters react to poor slurry characteristics by lowering their cake rate and increasing residual moisture. These phenomena highlight the difficulties of upward sucking rotary vacuum filters. The effective pressure drop is determined in part by the type of vacuum pump used, but more by the slurry to be handled and the specific operating conditions of the filter; it therefore varies with the application.

Table 1.1 is a comparison of features common to the rotary vacuum filters discussed, and includes values for a large filter press.

1.1 The Filter Press

The filter press is a batch-filtration device apparently first introduced in the 18th Century, which nevertheless retains today an important place as the filtration method chosen for many widespread process situations. The basic mechanism of the filter press has remained essentially unchanged since its introduction. Until the so-called automatic filter press was put to use, batch filter presses were increasingly abandoned in favour of continuous filtration devices, which saved labour. Since the nineteen-fifties, however, the introduction of the so-called automatic filter press has made filter press operation less labour intensive. This improvement, together with the later introduction of the membrane or diaphragm plate discussed in Section 1.1.1, has led to a reappraisal of the filter press relative to other means of filtration. Certain significant advantages of the filter press have been recognised; namely, less floor space per unit of filtering area and filtering capacity, high filtration pressures, and low moisture content of filter cakes.

The filter press has at least two unmatched advantages over more sophisticated filtering arrangements operating continuously and automatically: It allows filtration and subsequent solids washing to proceed in a totally enclosed system of minimal free volume; and in the case of modern diaphragm or membrane or expression presses, it offers a uniquely rapid, effective and low cost means of dewatering the filtered solids by squeezing them in situ against the filter cloth by application of hydraulic pressure to the membrane bounding the other face of the filter cake. The filter press is thus particularly recommended for use with hazardous or easily contaminated materials, and in applications where the recovered solids must be dry before they can be further processed or disposed of.

Figure 1.1 illustrates the general arrangement of a small, non-automated, side bar filter press (meaning that the filter plates are supported at their sides) of the type used in this work.

The following is intended as a brief summary of the sequence of operating phases of a horizontal, individual filter cloth-type filter press and serves to introduce terms used throughout this thesis. Each phase, or operations relating to it, is described in greater detail at an appropriate point in the thesis.

A filter press is designed to pump slurry under pressure into an array of chambers lined with a filtration medium (filter cloth) so that the slurry liquid (filtrate) is forced through the cloth and out of the press via pipework. The filtrate is either collected as product or discarded as waste; the solid matter is retained within the chambers. The pumping of slurry is stopped when the chambers are so filled with solid matter (filter cake) that the applied pressure required to continue the liquid flow becomes inconveniently large, or alternatively, when the flow rate of filtrate out of the press drops to a predetermined level.

On completion of the pumping phase a cake wash may be carried out. Here the compacted solids are rinsed, often with high temperature water, while still in the filtration chambers. After washing, a cake squeeze may be applied. Membranes fitted to alternate filter plates allow the filter cakes to be squeezed by reducing the volume of the filtration chambers by forcing air (usually) between each membrane and its associated filter plate. Such squeezing allows high cake dryness values to be achieved and reduces filtration cycle times. Prior to cake discharge a core blow may be performed. A charge of compressed air blasts through the slurry feed port, in the reverse direction to slurry pumping, to blow the slug of wet slurry material, from the duct created through the filter press by the slurry feed hole in each filter plate, back to the feed tank. If this wet material was left in place prior to the discharge phase the dry solids would be mixed with a small amount of wet matter, compromising quality. Traditionally cake discharge has been effected by manual (small plates) or automatic (large, > 0.5 m square, plates) plate movement to expose each filtration chamber in turn. The removal of one complete supporting face from the exposed filter cake detaches it from the filter cloths with gravitational assistance. Once all chambers have been emptied, often with human assistance, the press is closed, usually by compression of the plate stack by a hydraulic ram. The press is then ready for the next pumping phase. A cloth wash cycle is performed at intervals determined by experience of each slurry and filter cloth combination. Often automatic, this procedure cleans cloths by jets of high pressure water to remove blinds, particles built-up in the weave of the cloths reducing the efficiency of the filtration operation.

1.1.1 Filter Plates

The filtration chambers are essentially the spaces between cloth-covered plates. Different designs of filter press use different types of filter plate, e.g. the recessed plate, membrane plate and plate and frame arrangements. As the designation suggests, two kinds of component are used in the plate and frame arrangement to form a chamber for filtration, discussed later in this subsection. The recessed and membrane types of filter plate were used in this work and all subsequent discussion is based on this fact.

Figure 1.2 illustrates a recessed filter plate, the component of the filter press which, in conjunction with similar components, forms the filtration chambers, allows slurry into those chambers and provides the passages for filtrate to leave the chambers. The chambers in which the cakes of filtered solids collect are formed between pairs of adjacent filter plates. The recessed area of each plate forms a chamber with its neighbour and the remaining, non-recessed, outer area forms a seal when the plates are pressed together to isolate the chamber from the environment. These outer areas of the filter plates are hereafter referred to as the gasketing faces.

The filtrate is either drained along a channel system formed by appropriate cored holes in the plates or through individual taps at each of the plates [1].

Developed in the nineteen sixties, the expression or membrane filter plate has significantly improved the achievable dryness of filter cakes. As illustrated in Figure 1.3 a membrane is fitted over each face of alternate filter plates. Hydraulic or pneumatic pressure is applied to the back of these membranes to move them away from their natural positions. When such an inflation is applied to a filter cake-filled chamber formed by a membrane plate and a standard recessed plate, the volume of the chamber is reduced. This causes the cake to be compressed, or squeezed, Figure 1.4. This compression is applied after pumping has stopped, which on a press so equipped happens before it would on a non-membrane plate press since cake dryness is not dependent on pumping for as long as it is possible to do so. This reduced pumping time, early squeezing approach cuts out the most inefficient part of the normal filtration cycle, thus considerably reducing the overall pressing time. The squeezing action increases filtrate removal rates, thus reducing the length of the normal filtration cycle. This technique is widely used and is very effective. Not all products are suitable for membrane squeezing, but those that are benefit with substantially increased filter cake dryness. It is somewhat difficult to quote dryness figures, since this is highly dependent on the cake material, however, figures of between 30% and 50% dry solids in squeezed filter cakes have been quoted [2].

Cycle time reductions of a third are typical of the difference between presses equipped with membrane filter plates and those not so equipped [3]. Shorter cycle times generally mean an increase in filter press output. This can often avoid the need for additional presses and their associated equipment. With cake moisture reduced to a minimum significant savings can be made when the filter cake is normally passed through drying ovens or incinerators. With the use of membrane filter plates a filter press becomes a filter of variable volume thus catering easily and efficiently for changes in batch sizes and products.

The application of hydraulic pressure to the finished cake, and indeed the pressure developed within the chambers between the plates during entry of the slurry, may not be the same at every instant for all pairs of plates. Where the plates are small and robust, any such inequality of hydrostatic pressure between adjacent chambers is unlikely to deform the plates significantly. Plates over 1 m square, however, require, or include as a precautionary aid against plate deformation under load, stay bosses to provide support between opposing recessed faces. A minimum of four stay bosses is usual, often arranged in a square pattern around the (central) slurry feed hole, each roughly halfway between the filter plate's centre and an outside corner of the plate. Each boss projects from the recessed surface as a cone truncated in the plane of the gasketing faces. On a

2 m filter plate each boss is typically around 200 mm diameter at its truncated face.

When the press is closed the faces of the stay bosses align with each other and effectively butt together. This means that the walls of the filtration chambers are supported against inward deformation or collapse consequent on any local failure of slurry or fluid supply to a particular chamber. The small filter plates used in this work did not have stay bosses.

By assembling a stack of filter plates on a common axis, as illustrated in Figure 1.5, a large filtration volume is generated within a relatively small floor space. The plates of a filter press are compressed into a stack, normally a horizontal array, which may contain over a hundred plates, by a hydraulic ram which is kept under pressure during the filtration cycle to maintain a liquid-tight seal at each gasketing face.

1.1.2 Filter Cloths

A filter cloth is fitted to each filter plate so that the recessed and non-recessed areas are covered, as shown in Figure 1.6. Each filter cloth is topologically equivalent to a very short tube with very large, square, flanges (the 'flanges' are the large, planar pieces of fabric which cover the faces of a filter plate). The tube passes through the slurry feed hole (SFH) in the filter plate. To mount a cloth on a plate one of the large 'flanges' must be passed through the slurry feed hole prior to the tubular section which remains in the slurry feed hole. The second 'flange' remains on the side of the plate through which the cloth was passed. Such a design of filter cloth ensures that all internal surfaces of the filter press, that is to say all filter plate surfaces which are isolated from the environment outwith the press, are covered with filter cloth.

Filter cloths are manufactured in a wide range of materials and weaving patterns. Examples of cloth materials and some of their properties are listed in Table

B.1 [4], and some weave patterns are illustrated in Figure 1.7 [5]. The nature of a slurry will determine the type of filter cloth most suitable for use in its filtration. The cloth material is chosen to withstand chemical attack by the slurry; the weave pattern and closeness of weave determines or influences the minimum particle size retained by the cloth, the fluid pressure drop across the cloth, the tendency of the cloth to 'blind' or clog with fines, its susceptibility to cleaning by back-washing, the adhesion of the compressed cake to the cloth and the cost of the cloth.

At the end of the filtration cycle it is common practice for a core-blow to be carried out prior to plate separation and filter cake discharge. The core-blow operation is necessary when slurry pumping is stopped at the end of actual filtration because the passage through the press which is formed by the slurry feed holes and their connections is left full of slurry. This slurry is not dry since it has not been filtered because it cannot get to a filter cloth due to of the build up of filtered solids in the plate chambers. If this core of wet material is left in the press until discharge it will be discharged along with the dried solids, contaminating them with unseparated liquor. The total amount of such wet core material may be small in relation to the quantity of dry solids discharged, but may, nonetheless, be enough to spoil the batch. To prevent this, such wet material is removed from the press before discharge. Typically this removal is effected by venting the press slurry supply line to its slurry tank and applying high pressure air to the opposite end of the press' slurry core. This action is intended to blow the core of wet material out of the press, back to the slurry tank for filtration in the next cycle. When applied successfully this technique is very effective, but problems, e.g. poor slurry consistency, can seriously impair the efficiency of the core blow, leading to feed ports being blocked with sludge during discharge.

A treatment often applied to filter cloths is to coat certain parts of the cloth with latex, namely, the gasketing face, the area covering the plate's stay bosses and the tubular portion lining the slurry feed hole. This is done to prevent filtration at these points and so aid core-blowing and cake discharge. If the cloth in the feed hole is not latex coated, a solid plug can develop which can be very difficult to remove on core blowing. If the patches over the stay bosses aren't treated, only a very thin cake can develop over the region of small clearance (if any) between butting bosses. The result of such localised, thin cake build up is a complication of cake washing as the wash water tends to by-pass fully caked areas that it should be addressing, the water following the path of least resistance through the thin cake over the stay bosses and through the cloth in surrounding areas. Coating the gasketing faces of the filter cloth prevents water from migrating to the edge of the filter cloth during filtration and causing a constant flow of water out of the press; such edge leakage is messy and is undesirable to plant operators. The latex coating is applied to both sides of filter cloths. Some users buy their filter cloths with the latex coating already applied; others prefer to treat the cloths in-house[1].

1.1.3 Recovering the Solids

At the end of every filtration cycle the accumulated solids in each filtration chamber must be removed. This is the discharge stage of the operating cycle and is, in theory, very straightforward. The hydraulic ram compressing the filter plates is retracted and each filter plate in turn is moved away from the stack of plates, either manually or mechanically. As each plate is moved the solid content of its bounded chamber is exposed and the containment thus removed from one side of the filter cake. Without restraint the cake falls from the cloth faces due to gravity into a hopper, or onto a conveyor, below the press. This simple sequence is illustrated in Figure 1.8.

The operation is complicated in practice by a tendency of the filter cake to adhere to the filter cloth. This almost invariably necessitates the use of specific

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[1] Source : Mr Terry Cole, Process Engineering Manager, B.A. Chemicals Ltd., Burntisland, Fife.

means of cake removal, additional to the action of gravity. The completion and monitoring of the removal of cake from the exposed cloths is at present performed manually. This research sought to address some of the problems involved in automating arrangements for cake discharge and monitoring.

1.2 Filter Press Development

Some of the advances with regard to automating the discharge of filter cakes are now considered.

The automatic plate shifting mechanisms fitted to modern filter presses, the way in which the filter cloths are attached to the plates, and the vibrating of filter cloths are all designed, at least to some extent, to aid the discharge of filter cake and reduce the need for manual labour at this stage of the operating cycle of the filter press.

A classificatory system can be applied to the various types of filter press as follows.

- Recessed plate and plate and frame
- Vertical and horizontal
- Fixed filter cloth and travelling filter cloth
- Membrane and non-membrane equipped (expression & non-expression)

Most so-called automatic filter presses are of the recessed plate type. This is because of the difficulties associated with automatically removing filter cake from the frame of the plate and frame type press.

In a horizontal filter press the filter plates are arranged horizontally, each plate being oriented vertically. The vertical filter press, on the other hand, has the plates horizontal and stacked vertically.

A number of styles of filter cloth and cloth attachment are available; individual cloths, fixed and travelling. The individual type of cloth is attached one per plate and when each plate is moved during discharge the cloth moves with it and (ignoring human intervention) discharge of the filter cake from the chamber is due solely to gravity.

The fixed type filter cloth is configured between the filter plates so that when two plates are separated a section of cloth common to both is inclined away from the top portion of each plate, the apex of the inverted V thus formed by the cloth being supported by a sprung horizontal rod; when the plates are separated the bulk of the cake is discharged due to gravity, the inclination of the cloth and the flexing of any slab-like deposits bridging the inclined and undisturbed sections of cloth. In a recent modification, vibration is applied to the supporting rod so that the cloth is also vibrated, with the intention of removing any remaining fragments of filter cake [6].

The travelling type of filter cloth can be subdivided into individual and endless types. The individual travelling type cloth is moved around the filter plate to which it is attached; the endless type passes through the whole filter press. Travelling round rollers, the whole cloth is moved through the press bringing cake into contact with carefully placed scraper bars which dislodge the filter cake.

The vertical type of filter press has certain advantages over the horizontal one, mainly the reduced floor space needed. However, the height of this type of press is a disadvantage as it hinders maintenance and adding chambers is difficult. A vertical type press is usually fitted with the travelling, endless type filter cloth to take advantage of the automatic presentation of cake deposits to scraping bars during cloth movement. On the automatic type vertical press only the upper surface of each filter plate is available for filtration, the lower surface is recessed to form the filtration chamber and is covered with a membrane, consequently the cost per unit of filtering area is high. Cakes are not always retained on the filter cloth, they may adhere to the squeezing membrane and remain in the press after the cloth movement (cake discharge) operation has been carried out.

On horizontal filter presses there are advantages associated with the travelling-type filter cloth; a number of chambers may be opened at once and thin layers of cake can be removed by dint of the cloth passing round rollers and being broken up. Manufacturing costs of such systems are increased by their complexity, however, and regular maintenance and replacement of filter cloths is more difficult on this type of filter press. Cloth wear seems to be a problem associated with this design, leading to blow-outs; mechanical problems are also common. Cloth replacement is a further disadvantage because of the size of the item. A single fault on the cloth requires that the whole cloth be replaced, a costly exercise. Fixed, individual type filter cloths have the advantage that the press can be extremely large, say 150 chambers, whereas the travelling design of press is restricted in the number of chambers they can accommodate due to the one-piece nature of the endless cloth used. Typically they will only have up to 40 chambers. The disadvantage of the large fixed cloth-type press is the longer discharge time over the travelling type. Other operations such as cloth washing also take significantly longer.

A vertical, recessed plate, endless filter cloth-type filter press is illustrated in Figure 1.9. This type of filter press is offered by Larox [7].

Further ways of classifying presses refer to the slurry delivery system and the filtrate discharge system. One filter press can incorporate many permutations of the characteristics listed above. The choice of press will depend on the application and the users' specific requirements.

1.3 The Automation Problem

Automatically sequenced filter presses, in which all the stages in the filtration cycle are successively initiated in predetermined fashion, are in widespread use; but operator intervention is invariably required for monitoring the cake discharge and, on occasion, completing it by removing adherent cake fragments from the cloth by manual raking or scraping. This labour is particularly expensive and uncongenial when the operator must wear protective clothing, either to isolate him from hazard or to shield the product from contamination.

If the slurry is of the correct consistency, the filter cloths are initially clean and free of contaminants, the pumping pressure is correct, the pumping period is correct and all other filtration variables are satisfactory, then the filter cake will probably discharge readily. This is the ideal situation. Even in such circumstances, however, the cake may be intrinsically sticky; and in any case, if one or more of the filtration variables is incorrect this may lead to the cakes sticking to the filter cloths and not discharging properly. In this situation some of the cake may fall away and leave small or large patches of cake adhering to the cloths.

These adhering deposits must be removed before another filtration cycle can be performed, particularly when they would interfere with the closing and sealing of the press, or if they are so disposed around the feed port of any plate as to hinder the flow of slurry into the corresponding chamber after the press is closed. Hence, in the present state of the art, an operator must be present to take notice of such deposits and remove them.

Even if a filter cake has dropped, apparently successfully, it may give rise to another problem if any part of it falls upon and adheres to a gasketing face (Figure 1.2). When this happens and goes unnoticed there is a risk of a blow-out of slurry from the press when pumping commences for the next cycle. This is caused by the imperfect seal between two plates which have foreign matter adhering to their sealing surfaces. This situation must be avoided. The responsibilities of the operator, therefore, include checking the gasketing surfaces of each plate for deposits and removing them.

Another major responsibility incumbent upon the operator is assessing the condition of the filter cloth. It must be checked visually for defects such as tears and folds, i.e. locations of high stress where tears may develop. Any such tear renders a filter cloth useless and requires its immediate replacement.

As a matter of increased safety, it is desirable to remove operators from what is often the unpleasant and potentially hazardous environment experienced in the immediate vicinity of a filter press. Similarly, where the presence of operators can lead to product contamination, e.g. of pharmaceuticals, it is desirable to remove them to a remote location such as a plant control room.

If an automatic discharge system could be implemented, the risk to personnel from filtration-related hazards would be immediately reduced, as would the possibility of product contamination: this assumes the consequent introduction of a system of work to ensure personnel are not on the plant when filtration (including discharge) is under way.

In addition to the safety and product quality benefits, certain purely economic advantages would accrue to the operating company from the introduction of an automatic discharge system. It is argued in Chapter 8 that the freedom of an automatic system from tea-breaks, changing shifts etc., would lead to cost savings and greater plant utilisation, even allowing an automated system to take slightly longer to discharge a filter press than a human operator.

Consistency in the discharge operation is more likely to be achieved by a machine than an operator; furthermore, new techniques and procedures, necessitated by changes in materials or process conditions, could possibly be more readily (and certainly more consistently) introduced to a robotic system, for example, by way of reprogramming.

It is acknowledged that resistance to change is well-known in manufacturing environments, both at shopfloor and boardroom level; nevertheless, introducing an automated system as a replacement for one or more workers is a common practice, though naturally unpopular with those who suffer redundancy as a result. A system such as the one discussed in this thesis, however, would require skilled supervision. It would also require operators to tend to the maintenance of a filter press so equipped, e.g. replacing filter cloths. It is likely that introducing such a system would lead to job losses, which would indeed provide a significant part of the cost benefit; but it may also lead to higher level, safer, roles requiring better training for those chosen to operate it.

Perhaps the most obvious solution to the problem of removing cake deposits automatically is to scrape all the parts of all the cloths in a filter press at discharge. The disadvantages of such a scheme significantly outweigh the advantages, however. The advantages include; simple scraping devices wielded by simple mechanisms, reduced set-up times and simplicity of programming relative to more complex solutions, such as described later. There are three main disadvantages; time, cloth damage and lack of feedback on cloth condition.

The time taken to scrape every part of every filter cloth in a filter press, when compared with the time required to scrape only those areas requiring attention, is considerable, assuming a reasonably successful 'natural' discharge of cake prior to scraping and that a small scraping head is used, i.e. not a plate-wide one. For an automatic system to be viable it must have a cycle time not significantly longer than an operator's; hence, given that an operator will only address caked areas of a cloth, so must an automatic system. This assumes deposit-specific scraping. A plate-wide scraper addressing the whole cloth, even for a small deposit, would reduce the automatic discharge time relative to a deposit-specific scraping approach, but increase cloth wear. Such a plate-wide scraper also faces formidable mechanical design problems since the filter plates underlying the cloths are not plane.

Damaged filter cloths contribute to filter press downtime and filtration failure, hence any measures which may reduce the likelihood of damage are worthy of investigation. One source of damage to filter cloths is wear caused by scraping. Each time a scraper is pushed across the face of a filter cloth some wear will result. This makes it important that an 'only-scrape-where-necessary' policy is followed. Again, this follows a human operator's procedure of only scraping caked areas. Whereas different operators will scrape with different forces applied to the filter cloth, an automatic system has the advantage of applying a consistent, measurable and programmable force. Indeed, one operator's scraping force will vary over one complete discharge cycle since this may take an hour or more depending on the size of the filter press and fatigue will naturally take its toll on the operator.

Simply scraping all the cloths in a filter press regardless of their condition does not guarantee that full discharge of adherent deposits will occur. It will be argued here that verification of filter cake discharge is the key to the question of automatic discharge. With such an ability to identify cake deposits on cloths, the notion of scraping all cloths can be abandoned and deposit specific scraping becomes possible.

To be of widespread use in the process industries, an automatic discharge system for filter presses must be operable in very diverse environments. The systems developed here and described below involve relatively sophisticated mechanical and optical devices. Some of the engineering difficulties to be overcome in operating these under a wide variety of process conditions may include; choosing construction materials and methods to withstand, or isolate delicate components from, chemical attack; and finding optical wavelengths for vision systems to 'see through' clouds of water droplets or other fine particles. These considerations were deemed to be outwith the scope of this initial research.

1.4 Previous Work

Very little of direct relevance was found in the literature to support this research. There appear to be a number of reasons and possible explanations for the lack of published work on filter press automation of the nature detailed in this thesis.

1. Discussion with reference to other designs is not possible since such a system does not currently exist in the market place.
2. Manufacturers are unlikely to publish details of investigations which fail to deliver new products, but reports of which may be of benefit to their competitors. Filter press manufacture is a very competitive business [2].
3. No-one may have thought of the approach taken in this work.
4. One of the ways in which the problems of solids separation from the cloths of filter presses has been overcome is the use or development of alternative filtration techniques, e.g. drum, vacuum, belt and centrifugal type filters. These devices offer continuous filtration advantages over the batchwise filter press, unless a particular process requires the specific advantages of the filter press, e.g. enclosed volume and easy dewatering; to that extent the need to develop a truly automatic filter press has been reduced.
5. Filter press developments in the area of discharge have concentrated on automatic devices to perform set operations, e.g. shaking the filter cloth [6] or moving a one-piece cloth through the whole press to dislodge cake by contact with static scrapers [7]. As stated elsewhere, the approach taken in this work is based on actively checking a filter cloth's condition and acting

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[2] This observation was made by a filter press manufacturer (David Hughes of Edwards & Jones Ltd.)

on the results; a totally different approach to the problem which, with one possible exception, no-one else appears to have discussed or tried to exploit. This supports comment 3 above.

In view of this, the lack of published material on the automation of filter press discharge operations is hardly surprising.

The only reference of direct relevance to this work was found in the 1987 Engineering Index [8]. The paper's author was contacted for more information. A reply was received from Alex Yelshin of the then USSR, indicating that he would be happy to collaborate in the work. His offer was not pursued due to pressures of time and distance. This may have been a mistake since Mr Yelshin appears to be an authority on filter presses. In addition to his article of interest, he was a regular contributor to the Filtration and Separation journal.

In his article Mr Yelshin appeared to indicate that he had done everything this project was aimed at, i.e. automating the manual labour aspects of filter press operation by the application of industrial robots. This proved to be misleading; it was clear from his answering letter that he had only thought about the possibilities of this subject, he had not actually done the work to introduce robots to filtration.

In searching such information sources as the Science Citation Index (SCI) it was apparent that most recorded work done on 'filters' is to do with the electronic component of the same name, not the solid/liquid separation kind.

Details of filter press manufacturers contacted for product information during this work are given in Appendix C.

The automatic discharge system arrived at in this work involved three distinct areas outwith filtration. These are discussed in Chapter 3, Section 3.7 and Chapter 4. The need for these systems and the progress of the author's ideas towards them is discussed in Chapter 2.

Filter type	Disc	Drum	Horizontal	Belt	Filter press
Filtering area (m^2)	60	60	60	60	1500
Floor space (m^2)	15	35	85	100	50
Mass (tonnes)	11	21	27	31	250
Cake formation	lateral, upward suction	vertical, upward suction	downward suction	downward suction	pressure
Cake removal	scraper, blown off	scraper, blown off, cloth discharge	screw	gravity	gravity
Cloth cleaning	one side discontinuous	one or twosides	one side, discontinuous	both sides, continuous	one side, discontinuous
Filter area / floor area	4 : 1	1.7 :1	0.7 : 1	0.6 : 1	30 : 1

Table 1.1: Comparison of filter parameters

NOTE: The value of 250 tonnes for the filter press mass is for a press which is fully loaded, and includes the mass of filter cake at end of a typical filtration cycle. (Source : David Bates of Edwards & Jones Ltd.)

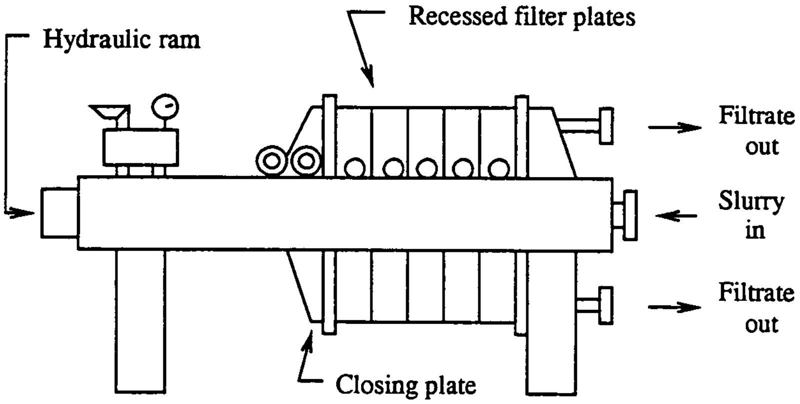

Figure 1.1: Typical small, side bar-type filter press

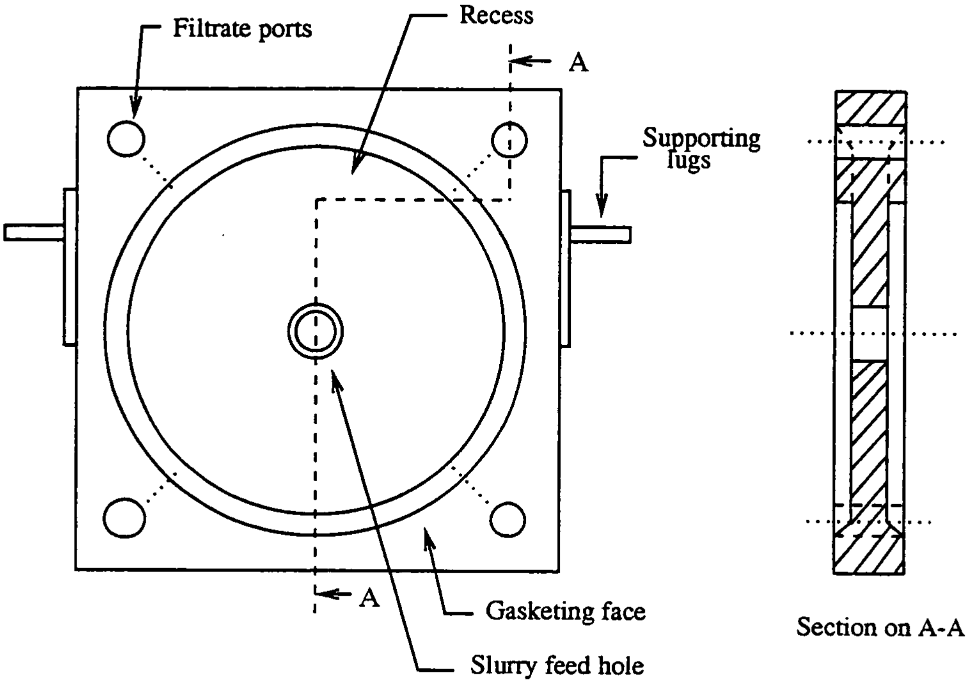

Figure 1.2: Filter plate

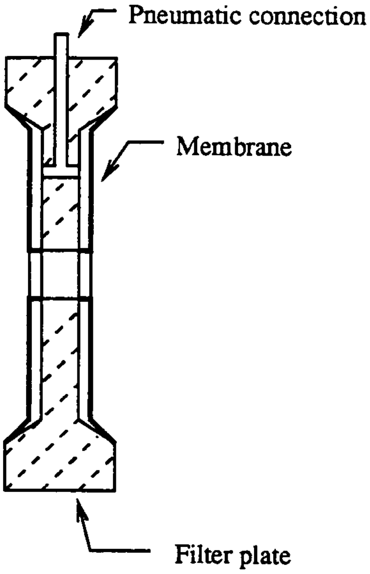

Figure 1.3: Membrane filter plate

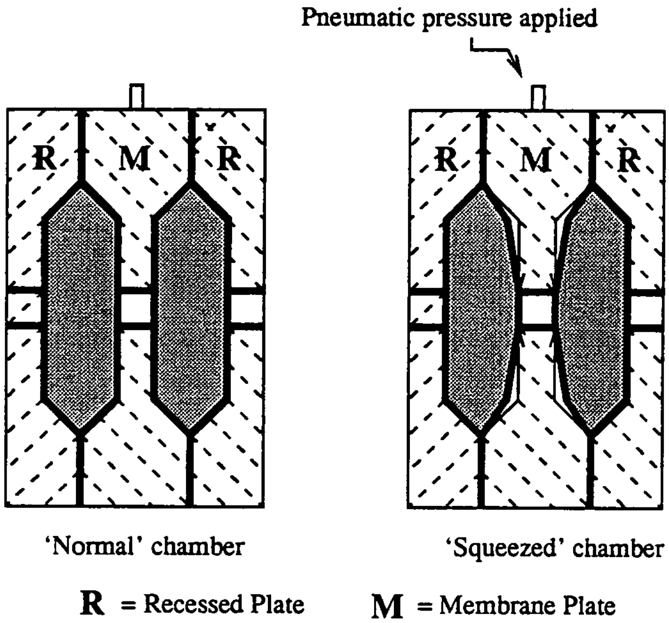

Figure 1.4: Squeezing a filter cake

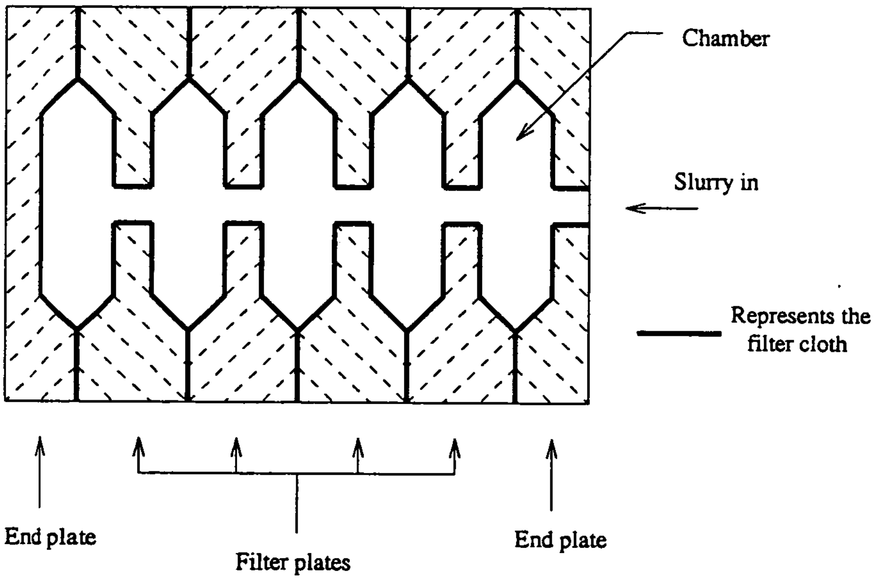

Figure 1.5: Simplified cross-section of compressed stack of filter plates

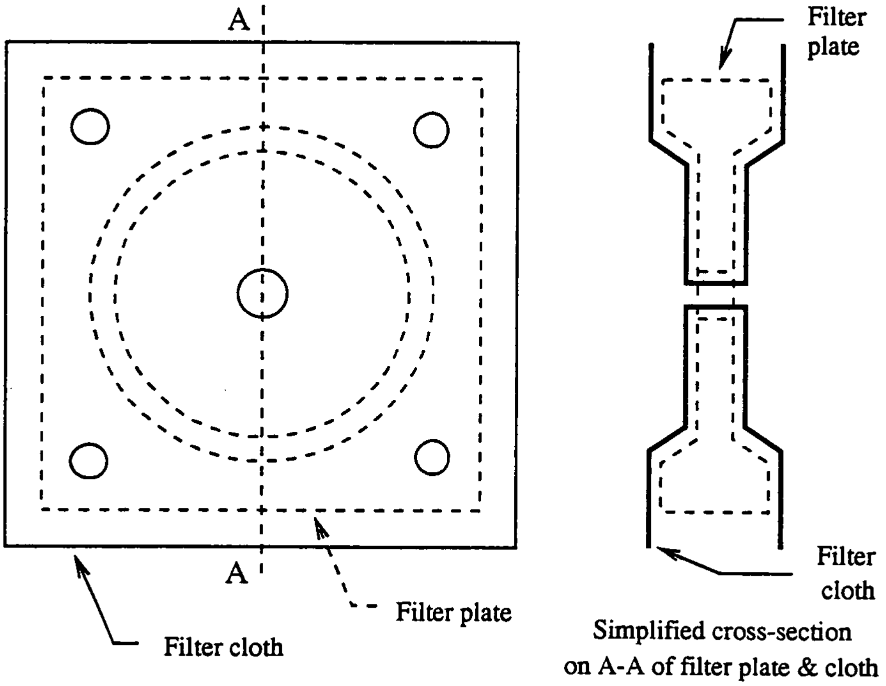

Figure 1.6: Filter plate with filter cloth fitted

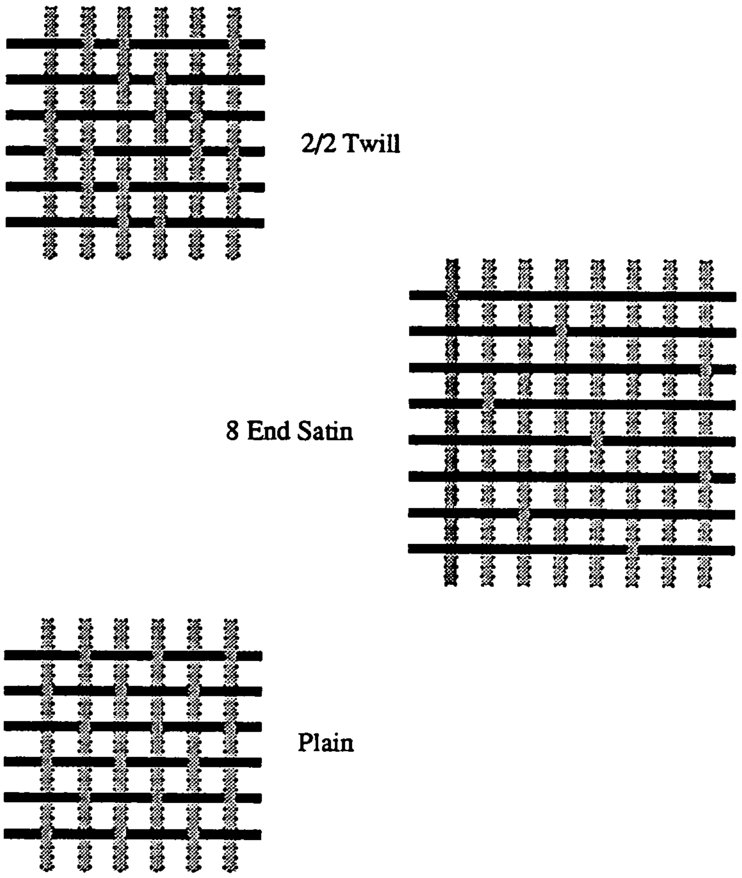

Figure 1.7: Some weave patterns used in filter cloths

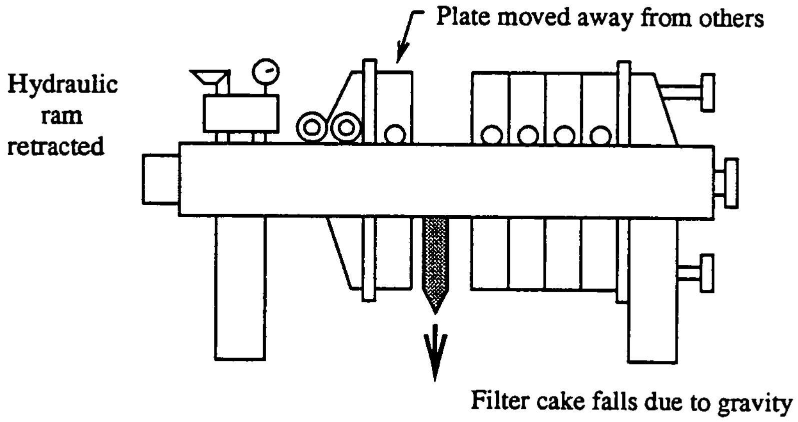

Figure 1.8: Filter press discharging

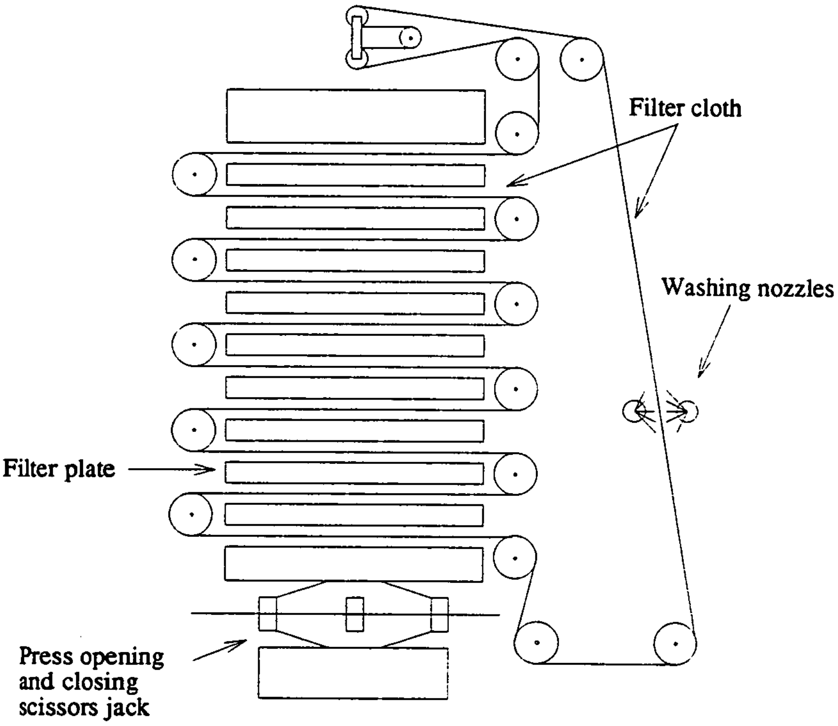

Figure 1.9: Vertical, recessed plate press

Chapter 2

Development of a strategy

This Chapter reviews the consideration of two alternative cake removal strategies. The original concept, removal of caked plates to a cleaning station, was discovered to be infeasible; an alternative approach, cake removal in situ, was accordingly developed which proved to be successful.

The idea of removing filter plates from a filter press to a cleaning station is apparently not a new one. The German company VON ROLL AG patented a system in 1992 [9] whereby an automatic filter plate transport mechanism is fitted above a filter press, raises the filter plates one at a time from the press and transports them to a cleaning chamber. In this cleaning chamber the plates, with cloth attached, are either sprayed with water or other cleaning solvents or actually immersed in a bath of suitable cleaning fluid. Other processes to which the plates are subjected in this chamber include disinfection or impregnation of the cloth and drying. The chamber can accommodate two filter plates at any one time, thereby allowing the transport mechanism to be used more efficiently, i.e. always bearing a filter plate, not travelling empty at any time. The requirement behind the development of this system was a need for higher purity of the filtrate liquor in some processes. The transport mechanism used in this system to move plates between the press and the cleaning chambers is a very simple apparatus, akin to a pick and place robot in having linear axes and simple drive systems, albeit under Programmable Logic Controller (PLC) control.

While this idea is very similar to that originally proposed in this work some years earlier, the emphasis is different, in that the patented system is used to clean filter cloths and plates to a very high standard in the interest of product purity whereas the original approach adopted in this work required that the filter cloths would be discharged at the central cleaning station, rather than being subjected to actual cloth cleaning.

2.1 First Approach

The case for support submitted in 1986 to SERC for funding for this work was based on the concept that filter plates could be lifted out of a filter press by a cheap pick and place robot, delivered to a dedicated cleaning station for thorough discharge and possibly cleaning, then returned to the press by the robot. This idea was thought to be applicable to very small presses being used in low volume, high value processes such as pharmaceuticals manufacture. It was also thought that a group of filter presses could be economically automated this way, by using one cleaning station and one robot to serve several presses.

For this 'cleaning station' concept the immediate questions of interest were considered to be:

1. What kind of filter press to use for experimental work? Considerations to be borne in mind were;
    - use in industries likely to be interested in this work,
    - availability of such presses in small sizes,
    - cost.
2. How to gather representative information about designs of interest?

3. What sort of experimental set-up will give:
    (a) insight into fundamentals of problems of importance, and
    (b) a demonstration to outside bodies that these problems have been overcome?
4. What are representative difficulties in automatic handling of filter cakes?
5. What kind of pick and place robot to use for filter plate transfer to work centre? It turns out that the answer to question 1 shows very strongly that a very special pick and place robot would be required – prohibitively special in fact.
6. What are the advantages in local preliminary cleaning of cloths at each press? (Cost benefit design study involving time and capital cost trade-off).
7. Which local plate-handling devices to use on each press, e.g. plate shifting mechanisms?
8. What cleaning arrangements to make for cloths at central and local work-places? (Depends on answer to 4). Should cloth renewal be automated?
9. Which sensors or monitoring devices to install to control progress of cloth cleaning? (Depends on answer to 4).
10. What arrangements should be made for handling different product filter cakes from different filter presses?
11. How to detect when each press is ready to discharge, i.e. when filtration is complete?
12. Will scheduling problems occur, particularly if presses handle different products, or cloth changing is automated?

13. Do changes in concepts of filtration suggest themselves as fitting automation?

14. What influence does the working environment have on choices of mechanism(s)?

Systematic consideration of these points, aided by information gathered from industrial press users proved that a 'cleaning station' approach to the automatic discharge of filter presses was not practical. In relation to question one, for example, so far as can be established the smallest filter press used in production has filter plates 0.5 m square. Modern filter presses are built to DIN 7129 which has become the de facto standard for the industry; British or American standards for filter press design do not exist[1]. The smallest example of a DIN 7129 press has 0.5 m square plates, the largest has 2 m by 2 m plates.

This has a powerful bearing on point five above. A steel-cored, rubber coated, 0.5 m square filter plate has a mass of approximately 29 kg (64 lbs). To lift, transport and manipulate such a mass would require a powerful robot, certainly not a cheap pick and place device.

A further objection to the idea of removing plates from a press for cleaning is associated with the increasing use of membrane presses. A pneumatic or hydraulic connection is required to each membrane plate and, although detachable, it would normally be left in place during the press discharge operation. Disconnecting such a supply prior to lifting a plate robotically requires time, which is at a premium, and a degree of sophistication inconsistent with a basic pick and place device.

A final point leading to the abandonment of the cleaning station concept appeared from industrial information answering questions four and eight above. From this it appears that cake detachment from filter cloths is not in general a difficult operation; the required means are readily provided in situ.

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[1] Source:- Dr. Ian Young, Edwards & Jones Ltd.

2.2 Revised Approach

For these reasons, viz; filter plate mass, the expense of a robot capable of lifting the plate, filter plate connections to other systems, the relative ease of in situ cake release and the time required to pick and place between a filter press and a remote cleaning station, the concept of a cleaning station was abandoned and effort was directed at cleaning filter cloths in situ. This approach was felt to be more realistic and to offer a fair chance of achieving a solution to the objectives stated earlier, albeit in a very different way. It was decided to attempt to develop a filter cake detection system which could identify filter cake deposits and allow a robot borne scraper to be directed to the deposits to remove them. This is believed to be a novel approach to automatic filter cake removal as it is based on the actual condition of the filter cloth, not an assumed condition.

In consequence of this change of direction, weeks of work were written off. It is instructive to consider why a false and unprofitable trail was pursued initially. The model used for raising the questions earlier in this Chapter was a small filter press used in a Departmental laboratory for teaching duties. The device had many 180 mm x 180 mm recessed filter plates and cloths. This size and style of filter press proved to be very different from the 'small' presses used by industry. In consequence, the preliminary ideas for automatic cake discharge which had been developed, based upon the use of the tiny press, were not practical for even the smallest 'real' filter press.

2.3 Fundamental Observations

In the early stages of the work a number of visits were made to users of filter presses. Some observations of particular note made during these visits are:

1. An automatic discharge system such as that proposed would undoubtedly be of benefit to the process industries.

2. Filter cakes which did not discharge under gravity were readily removed by operators with only a small degree of force being applied. The operators did not usually have to scrape the whole filter cloth as most of the filter cake fell off once a small portion of it had been disturbed.

   This observation supported the idea that a real-time sensing system working interactively with a scraping device would be an excellent configuration for an automatic discharge system. This wasn't the approach ultimately adopted, but is an interesting possibility.

3. The main area of difficulty during cake discharge is the filter plate's recess rim, where this meets the plate's gasketing face. Here the cake is thinner, possibly slightly damp and has a tendency to stick. The operator decides from experience if the deposits are likely to cause problems and will remove them as appropriate. This implies the need for a degree of knowledge, or careful decision making, to be imparted to an automatic system.

4. Some users of filter presses, but not all, carry out a cake-wash as part of their filtration cycle. This occurs at the end of a filtration cycle and involves water being pumped into the press, while the cake is still in the chambers, to flush the cake through. The water is usually at a high temperature, which can subsequently cause steam to be released from the plate chambers during plate separation at discharge.

   Steam may be a problem for an overhead mounted optical sensing system. Scanning a filter cloth through a thick cloud of water vapour may pose problems in image acquisition and subsequent interpretation.

The sequence of operations involved in a filtration cycle can be summaried as follows.

1. Covering filter plates with filter cloths (infrequent).
2. Compressing a stack of these plates.
3. Supplying slurry to the filter press under pressure (filtration).
4. Cake treatment, e.g. washing, squeezing.
5. Draining or core blowing.
6. Relaxation of plate stack pressure.
7. Individual separation of filter plates.
8. Detachment of filter cake from plates (gravity).
9. Operator intervention to remove remaining cake deposits from filter cloths as necessary.
10. Washing filter cloths (infrequent).
11. Recompression of stack, recommence cycle.

Two company visits in particular (to Roche Products Ltd., Dalry and ICI Dyestuffs, Grangemouth), were of great importance in confirming these observations.

In light of these findings the sequence of press operations for automatic discharge, numbered in Section 2.3, became:

1. Automatic filter cloth changing would not be attempted in the short term, but arrangements to detect and signal the need for cloth replacement would need to be established.
2. Should in general, but not for all manufacturers, include a membrane inflation stage for final dewatering.

8. Take the form of paddle-scraping only, after gravity has been allowed to detach the filter cake. This operation of scraping must be monitored in the mechanical system and carried out in situ. Monitoring must take care of :-
    (a) patches of adherent cake on the main filter cloth area,
    (b) cake adhesions on sealing surfaces around the plate edges,
    (c) obstruction of slurry inlet ports,
    (d) cloth defects, e.g. tears and creases .
9. Now disappears, except in sense of (1)

The research and development programme was thus reduced to:-

1. Development of in situ monitoring devices for registering the condition of filter plates and cloths during stepwise separation.
2. Development of appropriate paddle-wielding actions adapted to available robot functions.

In principle, the in situ automation of discharge on these lines could be extended to any size of filter press.

2.4 Development Strategy

The immediate tasks were accordingly set as:-

1. Procurement of a suitable filter press.
2. Devising a video monitoring system, looking at lighting; camera resolution; identification of 'targets' (e.g. solids aggregates and cloth defects such as creases), with available cameras.

3. Establishment of a co-ordinate system for robot guidance with software.
4. Selection of a paddle-wielding robot and of sensing devices to control paddle forces.

In addition, as it soon became evident that any press procurable under 1. would have manually shifted filter plates, a further necessity for the development programme would be:-

5. Consideration of plate separation mechanism.

As discussed earlier, all known previous attempts at automating the discharge operation of filter presses have differed from the approach outlined here in one fundamental way. Where others have attempted, by design of the press, to guarantee complete discharge of the filter cake, the system discussed here assumes incomplete discharge and utilises automatic systems to sense and remove remaining deposits. The difference in the approaches can be summarised thus; while one system attempts to guarantee discharge will occur, the other guarantees discharge has occurred.

Following redirection of the project (Section 2.1) a number of assumptions and decisions were made regarding the scope of the work. It was felt that small presses should be addressed, that is those with filter plates of 0.5 m by 0.5 m; that the developed solution should be applicable to a group of presses, i.e. the capital cost of the system would be spread over a number of filter presses; and the products being filtered would probably be low volume and high value in nature, e.g. pharmaceuticals.

It was also assumed that, in the first instance, the automatic system would address filter cakes which would normally discharge well under gravity, and whose residual deposits could be readily removed by the application of controlled force.

Materials which are invariably sticky and do not discharge at all well with gravity and require considerable effort by an operator to effectively remove adherent deposits, were not considered suitable as a first case objective. Stated more concisely, the system was to deal initially with discrete areas of caked cloth, not fully formed 'stubborn' filter cakes.

Another narrowing of the work objectives was the decision, in the first instance, not to attempt to develop a discharge system with the ability to detect small flaws in filter cloths. While it may be possible to do this using imaging systems, it is also possible to use more basic sensors e.g. monitoring the filtrate flowrate, elevated conductivity, etc. Although it would be desirable to utilise an automatic flaw detection system which would find defects in filter cloths at the discharge stage, thereby preventing flawed cloth from being used in subsequent filtrations, the technology already exists to detect faulty cloths when the press is operational. The automatic detection of cloth faults was thus here of secondary importance to proving that the discharge stage of the operating cycle of filter presses could be made fully automatic.

It was not part of the research remit to develop a fully ruggedised industrial automatic filtration system. The aim was to demonstrate that all the major mechanical, electronic and computational difficulties associated with this task had been, or could in principle be, overcome and that a successful prototype system had been, or could in principle be, built.

In considering how to successfully replace a human operator with an automatic system, many routes were considered. It was finally concluded that the requirement for discharge verification entails that three vital areas have to be addressed, associated with a basic sequence of actions akin to that employed by a human operator.

In the most basic type of automatically verified cake discharge system very little information about each deposit needs to be obtained. Using only the area of each filter cake deposit a decision can be taken to implement action against the full area of a filter cloth, e.g. either shaking it or scraping it with a plate-wide scraper. This ensures that all deposits are removed, regardless of their position on the cloth. This remedial action would be taken when the total area of retained deposits exceeded a predefined level.

In the developed automatic discharge system, however, the size and location of cake deposits must be established before any directed action can be taken against them. The first step in doing this requires some form of sensor to act as the system's 'eye'. Alternative ways of acquiring data representing the surface condition of a filter cloth, i.e. which did not involve vision, were considered (Chapter 3); however, the system finally chosen for the task is basically a machine vision device (Section 3.3).

Acquiring a representation of the surface of a filter cloth was thought to be the key to the question of verified automatic filter cake discharge. Without comprehensive, reliable data about the condition of the cloth, other system components, e.g. the scraper manipulator, are ineffective. As the most important factor in the research, this aspect received a great deal of attention. Chapter 3 covers this vital aspect of the work in detail.

After looking at a filter cloth, an operator decides what action to take. So it is with the automatic system; i.e. the next step is to analyse the surface condition data, or assess the image. Image processing and analysis techniques are applied to the surface condition data (image) to clarify and appraise the size and location of any filter cake deposits.

While a pictorial representation is useful for human reference, for automatic action the image data is required in numeric form. The computer screen co-ordinates used to display the deposits are converted to 'real-world' co-ordinates; that is, they are converted to relate to an external physical datum, rather than the top left corner of the computer screen. A detailed account of processing the sensing system's output to locate cake deposits is presented in subsection 3.7.1.

Having identified filter cake deposits which must be removed and determined the action which will be taken to achieve this, an operator takes action to dislodge each deposit. This was the third major element in the discharge sequence to be considered in the research.

A human operator usually dislodges adherent deposits from filter cloths in a very simple way. A scraping device akin to a rowing oar is pushed between the cake and the cloth and passed behind the cake, thus prising it off the cloth. The scraper, usually wooden, is long enough to reach all parts of a cloth when wielded by an operator standing on one side of the press. Operational access is often limited to one side of a filter press, so most scraping is done horizontally from one side only. The end of the scraper, which is flat and broad, has a rubber tip to reduce the amount of cloth wear caused by the scraper being pushed across the filter cloth.

A similarly simple approach was taken for automatic deposit removal. A scraping head, mounted on the lower end of the vertical arm of a gantry robot, is delivered to a position on a filter cloth calculated to be a suitable starting point for a scrape of a specific deposit, and then moved through the caked area to dislodge the deposit(s). The co-ordinates for the move are calculated from the data generated by the image analysis procedure.

Chapter 4 describes in detail the factors which influenced the choice of robot, the scraping and controller considerations and the development of a scraping philosophy. Chapter 6 discusses the software written to control the various elements of the discharge system individually and collectively.

Chapter 3

Deposit Identification

3.1 General Considerations

It was the author's opinion throughout the work that deposit identification was the key element in the research; i.e. success depended on developing a suitable deposit sensing system and integrating it with the deposit removal device. Many means of deposit sensing were considered, including mechanical devices, but criteria were specified which much reduced the list of possible solutions, viz.

- the system should allow determination of the location and size of filter cake deposits adhering to filter cloths,
- ideally, the solution should be based on an available proprietary system,
- deposit identification should be rapid.

Consideration was given to mechanical devices which would determine the surface profile of the cloth's filtration area. Such a direct contact approach was not pursued, however, due to concerns over the time needed to profile each filter cloth and the possible fouling of the device by soft filter cake.

Weighing the filter cloths (in situ) was also considered, since determining whether a 'critical mass' of cake is adhering to a cloth may be relatively straightforward although accuracy may be low. While this approach yields the amount of adherent cake it doesn't give any indication as to its location and was, therefore, of little value in this project where deposit-specific details were needed.

It was therefore decided that some kind of optical imaging arrangement should be used for deposit identification and location. The original concept for the sensing system was based on a TV camera capturing an image of the filter cloth and using image recognition, processing and analysis functions to interpret the image data.

Since the Machine Vision Association of the American Society of Manufacturing Engineers defines computer or machine vision to be 'the use of devices for optical, non-contact sensing to automatically receive and interpret an image of a real scene, in order to obtain information and/or control machines or processes' [10], it is clear that the solution required can be classified as a machine vision system.

A vision system typically comprises five main parts; a camera or imaging system of some kind; image processing hardware, a picture store, a computer and system software. Each of these will be considered briefly in the preliminary discussion below.

It was assumed initially that the imaging system would be a camera mounted above the experimental filter press because the press' side-bar configuration prevents viewing of the cloth faces from any other direction (except below, which was not thought to be feasible). Operating a sensing system from this overhead 'vantage point' has disadvantages, however, as illustrated in Figure 3.1. The viewing angle of the cloths from this position is very restricted. On small filter presses (0.5 m) the inter-plate gap is typically 150 mm at most. The cloth is, therefore, viewed at a very acute angle from above. This unfavourable geometry precluded many of the vision systems offered by potential suppliers; systems requiring short stand-off distances and orthogonal viewing, such as used to inspect PCBs, were unsuited to this application, at least without major modifications. The difficulties associated with the sensing task were confirmed when an acknowledged specialist in the field of machine vision, on being consulted, stated "You certainly have a difficult application! The problems created by a narrow viewing angle and, in particular, low contrast, make the prospect rather daunting..." [11]. It was thus clear that development of a specialised optical imaging system for this application would be an important task, not addressable by the straight-forward use of a proprietary TV camera. This development is described at length in Section 3.3.

Image analysis systems and software have been available commercially for some time, but industry has only relatively recently started to implement vision systems for recognition and inspection, robot intelligence and process control. This is due in part to the limitations of the template matching technique used by early vision systems. Images were digitised and stored in an image buffer then compared with template images stored in the system's memory. The principal advantage of this technique was that it was relatively fast. Among the disadvantages of the method were the large (for the time) amounts of memory required and the fact that variations in component lighting and positioning could cause the rejection of good components. The limitation of the technique was that the method only produced a PASS/FAIL decision.

The choice of imaging equipment used to be based primarily on the hardware which was to be used, the choice of software being very restricted [12]. While ever more powerful and featured hardware devices are constantly being developed, software availability, performance and diversity has also improved enormously. Image processing software is now available which will work with many different computer architectures and operating systems. Such a choice now means that great care must be taken in choosing the correct package for each application. Among the items to be considered are the hardware platform; is it a mainframe, workstation or PC?; is the end use of the information for image storage and management, image enhancement for human visual interpretation, or image analysis and the automatic extraction of data?

It was decided that this project required a PC-based system for automatic data extraction: because it is generally accepted that real-time control of processes is easier with PCs than multi-tasking workstations; PCs are cheaper; and it was felt that since PCs are becoming more common in industrial environments they are a representative choice.

Traditionally, the mainstay of image processing equipment was the framegrabber [13]. These board-level products have been commercially available for many years and offer image capture, storage and display of images in real time. The early boards do not have any on-board processing, all processing being done on the host computer; hence the only limiting factor for these older boards is the power of the software used. Boards are now available with on-board processing, offering the advantage of the greater speed of hardware processing over software processing. Such an advantage was not thought to be important in this developmental work.

Other advances in hardware design have made a considerable impact on the speed of imaging systems. A problem addressed by NEL [14] was to recognise an object in the system's field of view and guide a robot to pick the component up. The system worked well on conventional computer systems apart from the time taken to recognise the component, which was about two minutes. This was deemed unacceptable and a transputer was used in the computer in an attempt to reduce the time. This system proved to be eight times faster than the original. A network version using six transputers was developed; this system is about 200 times faster than the original system. Such examples of performance increases are important where a successful imaging and processing system is found which is unsatisfactory only because of slow operation due to computing limitations.

3.2 Requirements for a Cake-Fragment Imaging Device

It is evident from the above outline survey that in applying existing techniques of machine vision to the detection and location of cake fragments of filter plates in situ, the chief difficulty lies in the formation of an image of the plate surface on which deposits can be identified by available methods of image analysis.

Image analysis systems are available not only as monochromatic devices but as full colour systems [15], [16].

In most filter press applications and most obviously in dyestuffs filtration, filter cloths take the colour of the liquid being passed through them and the cloths are often almost the same colour as the cake deposits. This precluded consideration of systems working on the principle of background-foreground colour contrast for this work.

Other kinds of image analysis are available if different radiation detectors are used. Thermal imaging, IR imaging and thermography, useful in medical and plant monitoring situations and monitoring hydrogen fires are some of the techniques and applications possible with more specialised detection equipment [17], [18]. Such approaches were considered, but rejected for two principal reasons. Firstly, expense. Infra-red cameras are much more expensive than conventional CCD cameras. Secondly, feasibility. Filter slurries are not usually heated, so adherent cake deposits at discharge are unlikely to be significantly warmer than the surrounding filter cloth. Any rise in slurry temperature during pumping is likely to be lost by discharge time, particularly if there is a membrane cake squeeze, for example, since this may last half an hour or more. There is a case where the cake temperature is raised significantly, however. Cake washing with very hot (80°C) water will alter the cake's temperature markedly. This operation is not always carried out, but it is possible that infra-red detection apparatus would successfully allow expedient location of still hot cake deposits at discharge. Further investigation of this approach may be worthwhile.

Nevertheless, in general, and for the purposes of the present programme, it appeared that cake fragments should be identified as protrusions above the cloth surface. Such protrusions, however, are difficult to detect with the oblique viewing system of Figure 3.1.

An alternative to a sensing device mounted overhead was one which entered the between-plates gap. This would allow the use of very simple technology to detect cake fragments as protrusions from the normally-viewed cloth surface.

Working initially from an idea using ultrasonics, then light as the operating medium, the author proposed a device which would enter the inter-plate gap in a discharging filter press and assess the cloths as it passed down between them, scanning both opposing cloth faces at once. The principle of operation was that used by General Motors in their 'Consight' system [19]. In this system two lines of light are projected onto a conveyor such that they are co-incident at its surface, Figure 3.2. A camera is mounted between, and in the same horizontal plane as, the light sources and detects one line of light on the conveyor when this is uncovered by objects. As parts pass along the conveyor they pass through the beams of light, thus changing the distances from light source to detection surface and detection surface to camera. The change in distance from the light sources to the detection surface means that, as detected by the camera, the beams no longer converge to one, two distinct beams are registered. The greater the distance the detected beams are apart the higher the part must be passing under the camera. This is a very simple but effective way of sorting or identifying parts.

In the author's adaptation, the light sources and detector, not necessarily a camera, would travel down between the plates. Variations in the distance from the sensor to the cloth (lumps and bumps) would thus be found without the need for image processing, frame-grabbing, background, foreground distinction, acute viewing angles etc. 'High' spots on the cloth would readily be found and, assuming that a means of relating the vertical position of the sensor to the 'depth' of the resulting image was incorporated and there was sufficient lateral resolution in the sensor to place high spots laterally, the size and location of objects assumed to be deposits of filter cake on the cloth could be established. This information is needed if deposits are to be removed individually. A simpler system would only need to detect object size if whole-cloth action was to be taken to remove deposits. See Chapter 4 for an expansion of this theme.

A refinement of this twin light stripe idea was suggested by Dr. Macleod, using one stripe of light focused to a set width across the face of the cloth. A light-sensitive sensor would measure the width of the stripe at many intervals along its length, a broadening of the beam indicating a shortening of the distance and a narrowing indicating an increase. It was originally thought that fibre optics would be used to direct the light from its source down the gap to the projecting arrangement and onto the cloth face. This idea was scrapped due to the likely cost and potential difficulties of developing such a system from scratch.

Such devices, introduced into the gap between plates and mechanically scanning the cloth surfaces, were ultimately deemed unacceptable for the purposes of this project because:

- the time required for a device to travel and scan the full plate depth and be recovered would be excessive, and
- the risk of fouling the sensing head with sludge or other filtration substances is very great.

The proposed devices do, however, embody in primitive form a ranging principle for measuring cake fragment protrusion which has been applied elsewhere in ways which ultimately suggested a more satisfactory approach.

Examples of scanning laser range measurement imaging augmented by a reflected light image can be found. One such system has been developed to demonstration standard for the inspection of printed circuit boards in the electronics industry [20]. Here, however, the requirements of the application are very different from filter cloth inspection. The accuracy of the ranging system is 0.0127 mm (0.0005 in) and the inspection rate at 0.0225 m^2/s implying a scanning time of more than 20 seconds for the 0.5 m filter plates in this work. The complexity of the system is great because the targets themselves and the spacing between targets which must be addressed are very small. This system measures the surface reflectivity, or luminance, at each point at which the range is measured. Two images of the components on the inspected PCB are thus generated, one from range values, the other from reflectance. Two differently composed images of the same area are thought to offer greatly enhanced flexibility for machine vision systems. Such flexibility is particularly important in instances where items must be detected which are in the same plane and, therefore, not detectable by range methods. If they are of different materials, or reflectivities, then they may be distinguished by measurements of reflected light.

This application, i.e. inspection of PCBs and other electronic components and assemblies, is a common one for machine vision and automatic inspection systems. The requirements of such systems are very different from those required in monitoring the automatic discharge of filter presses; e.g. the total area to be inspected, the type of feature sought, the end use of the image data, and the inspection environment differ very greatly between the two cases. The size of even a small filter plate compared with a PCB is huge, hence a one-view inspection as utilised in PCB inspection, is not possible. This, and the much larger stand-off which would be required to address a filter plate rather than a PCB, mean that the optical system of a PCB inspector would need to be radically redesigned to image a larger area. This, coupled to all the other changes which would be required, would make such a conversion infeasible. These differences make PCB inspection systems unsuited for filter press inspection. Excluding this category of equipment, however, greatly reduces the number of available systems which may be thought to have potential for inspecting filter cloths.

A machine vision system capable of detecting surface protrusions on a different principle is described by NEL [21] working by Moiré Fringes. Anticipated advantages of this system over other non-contact methods are its ability to distinguish between concave and convex surfaces (thus making cake and cloth undulation distinction easier) and a wide variety of object shapes and surface finishes. This system may offer powerful possibilities in detecting adherent filter cake deposits, but was not investigated further because of cost and the greater availability of the STRIPE system, also from NEL.

Sourcing this system proved decisive in achieving a demonstrable automatic discharge system for filter presses.

3.3 The STRIPE System of NEL

The STRIPE (Scanning Triangulation Range Imaging Package for Engineering) system is a laser scanning camera for three dimensional sensing. The STRIPE camera generates 'range images' in which each picture element (pixel) is characterised by a range or depth value.

The system employs a combination of optical triangulation, scanning and digital image analysis. As illustrated in Figure 3.3, an unexpanded round beam of high intensity (laser) light is projected onto a rapidly oscillating mirror which sweeps the beam across the surface of interest via a plane mirror to generate a stripe of illumination which has constant intensity along most of its length. The stripe is traversed regularly across the working area by a scanning motion of a plane mirror. A camera views the working area via the plane scanning mirror at a small angle to the axis of illumination and forms an image of the working area in the plane of an area array of photodiodes. When an object is present in the working area it is illuminated by the moving stripe of laser light. From the viewpoint of the camera, if the illuminated surface of the viewed object is not plane, the stripe at any instant appears deformed from a straight line by the topography of the scene. Analysis of the instantaneous shape of the stripe allows a range profile of the illuminated surface to be acquired along the corresponding line of illumination. Figure 3.4 illustrates the difference in the camera's view of a stripe falling on flat and undulating surfaces.

By analysing images at successive stripe positions as the stripe is scanned across the scene, range data can be obtained over the full scene.

Since both the imaging and illumination paths are reflected from the scanning mirror, the angle between the axes of illumination and imaging remains constant throughout the scanning of the light stripe. As a result, the relationship between the topography of the scene and the extent of stripe deviation remains constant throughout the scan, i.e. stripes viewed on a TV monitor connected to the system's camera remain stationary, but change shape according to the relief of the object. The position of the stripe (and one co-ordinate of any relief feature detected on it) can be inferred from the position of the scanning mirror. The second co-ordinate is obtained from the perturbation along the stripe. Simple electronic hardware applies the same analysis procedure to each light stripe image, and range data are thus generated as the stripe scans across the scene.

Determining surface profiles by the use of the observed distortion of projected stripes of light is not a new technique. The relevant principles and relationships were described previously by a member of staff of this University [22], [23].

The usual operating mode of the STRIPE system is to project laser light normal to the surface under investigation, i.e. the sweep plane of the oscillating laser beam is nearly perpendicular to the surface. In this orientation there is very little variation in the intensity of the back-scattered light detected by the camera unless the surface is very irregular or changes state or composition over the scanned area. In an application having a normal path orientation and reflective surfaces the stripe is a readily detected bright line over the full scanned surface, resulting in detailed range-based images being generated. When the STRIPE light source and camera are placed nearly overhead of vertical filter plates, however, very little back-scattered light is detected from the cloths. Due to the acute angle of incidence of the laser light to the scanned surface (see Figure 3.5), most of the light is diffusely reflected by the filter cloth away from the detector, though some small amount of back-scattered light is detectable.

3.4 The Modified STRIPE System

A modification of the original STRIPE system was therefore introduced. In addition to this range-finding mode of operation, the STRIPE system used in this project incorporates a new, intensity-measuring, mode. Variations in the back-scattered light intensity along the detected stripe are processed to produce an image supplementary to that generated in the normal STRIPE mode from range information. This new technique was the subject of a joint patent application by the University and NEL [24].

The success of the back scattering system in application to filter cake detection is due to the nature of the fracture surfaces of the cake fragments being sought. When a filter cake discharges incompletely the remaining fragments adhering to the cloth are generally at some distance below the uppermost edge of the filtration recess of the filter plate. Cake detachment by gravity is usually by peeling away of the sheet of solids from the cloth under its own weight, this process beginning usually at the top of the cloth. Furthermore, if this progressive peeling away of the cake is interrupted by abnormal adhesion of the cake to the cloth at some point, the detaching cake will fracture in a plane nearly perpendicular to the cloth, usually forming an upward-facing ledge, i.e. approximately horizontal in both lateral and longitudinal planes. Each such fracture ledge is a reflective surface perpendicular to the cloth surface, hence nearly normal to the light projected by the STRIPE system and, therefore, ideally oriented to back-scatter the incident light such that it is readily detected. When laser light is projected by the STRIPE system onto such a ledge there is a noticeable increase in the intensity of that part of the detected stripe, the length of which is proportional to the lateral extent of the fragment. The rest of the stripe is less intense, corresponding to those portions of the projected stripe which lie either side of the cake fragment ledge, on the filter cloth.

This intensity variation image for each scanned stripe position over the whole filter cloth is then electronically processed to yield information on possible filter cake fragments (subsection 3.7.2). Two sources of information for detecting the presence of deposits are thus offered by the modified STRIPE system; one from range-finding data, the other from intensity variation data. This modified system was built and supplied by NEL to the author's specification on a contractual basis.

3.5 Installation of the Modified STRIPE

The initial cost of a STRIPE system quoted by NEL was thought by the University to be high. After negotiation a more acceptable arrangement was arrived at, whereby the University paid for the intensity detection modifications to a STRIPE system and had the use of said system for a period of three years, with an option to purchase it after one year. This option was taken up.

Figure 3.6 shows the mounting position of the STRIPE system on the gantry robot which was used for deposit removal (Chapter 4).

The system was mounted such that the axis of the scanning mirror was 1.5 m above the top edge of the filter plates. This large stand-off distance was required to achieve the desired system resolution in the original STRIPE mode, which was specified as detecting a 20 mm high (normal to the cloth) deposit at both the top and bottom edges of a 500 mm square filter plate.

In order that both opposing filter cloth faces of an open filtration chamber are scanned, the imaging system must be positioned in two longitudinal locations with respect to the longitudinal axis of the filter press. In one location the STRIPE system scans the exposed face of the filter plate most recently moved away from the compressed stack of plates. This scanning setup is referred to as a forward scan; since the imaging system is longitudinally behind the face being scanned – the direction of plate travel away from the compressed stack being taken as forward. Conversely, the imaging system must be positioned ahead of the exposed face of the plate against the compressed stack. This setup is called a backward scan.

One of the most unsatisfactory aspects of the STRIPE system is its poor performance in high ambient light conditions. A black-out had to be built over the entire research rig to lower the ambient light level to a degree allowing the sensing system to operate consistently. Several ways of improving the ambient light performance of the system have been proposed (Chapter 7).

The STRIPE system is not particularly robust; it contains a CCD camera with conventional lenses, two mirrors, two motors and electronic hardware. It is unclear how well the system would withstand shock loads or exposure to a harsh environment. The enclosure fitted over the system is for light and access restriction purposes, not to isolate the equipment from its environment. These factors were not thought not to be disadvantages to this work since a) the operating environment in the University laboratory was benign, b) although the system would have to be moved many times during a press discharge cycle the motion would be imparted by a programmable device which would not induce rapid acceleration or deceleration and c) the system would not be required to function while being moved, only when stationary.

The investigative nature of the work allowed the use of non-ruggedised equipment in this way. Making a system capable of fulfilling its duties in an industrial environment is a different project, not what was intended in this work.

Safety issues concerning the use of a laser system were addressed by research staff and NEL staff. A document prepared by NEL [25] covers these important aspects of this application of the STRIPE system.

3.6 Testing the Modified STRIPE

Numerous tests were conducted to determine the capabilities of the modified STRIPE system in this application. The tests included scanning fresh, i.e. damp filter cakes, dry filter cakes, partially and fully caked filter cloths, pieces of teaching chalk and small pieces of paper secured to the cloth and using narrow stripes of light and horizontal filter plates, i.e. normal to the incident light.

Several important observations were made during these tests (detailed results of which can be found in Chapter 7), allowing the following conclusions on scanning system performance to be drawn.

- It was found that reflective targets less than one centimetre square were readily detected by the intensity imaging or back-scattering function of the modified STRIPE system (exceeding the specification). This performance was achieved with the plane of each target horizontal, i.e. perpendicular to the plane of the filter plates. This orientation was chosen as being representative of the upward facing, and therefore detectable, fracture edge of cake deposits.
- In general, dry and partially dry filter cake deposits are more easily detected than damp ones, as they produce clearer images. Similarly, dry filter cloths produce much more detailed images than damp ones.

- When a filter plate is oriented so that its plane is perpendicular to the incident scanning stripe, useful information is obtained from the ranging function, in addition to that from the registration of intensity variations. This confirms that given such a favourable inspection configuration, i.e. the scanned surface being normal to incident light, a standard STRIPE system would meet the imaging requirements and the intensity registration modification would not be required.

  Even in this advantageous orientation, however, when dry filter cakes are wetted there is a marked degradation in the images. Therefore, the previously noted relationship between filter cake wetness and poor images is not simply a function of the scanning orientation used in this work, i.e. plates vertical.

- Reducing the length of the scanning laser stripe, thereby increasing the intensity of the light along its length, produces much clearer, more detailed intensity and range images (only partial images of the cloth since a full plate width stripe is not used). Although a half plate-wide stripe, and, therefore, half-width image, is not of practical use, this finding demonstrated very clearly the relationship between the intensity of the scanning stripe and the quality of the resulting image; the more intense the stripe, the better the image. Also, by increasing the stripe intensity, the range information image shows a very big improvement. The wet cake imaging performance is also much better than that attained using full width stripes.

3.6.1 Example STRIPE Images

A typical intensity-based greyscale image obtained from the scanning system is shown in Figure 3.7. This image is of a filter cloth with chalk targets attached in the upper left and lower right quadrants of the filtration recess as viewed. Some residual filter cake can also be seen very clearly below the lower right quadrant of the central slurry feed hole. The circular nature of the recess is very clear and all four filtrate ports can also be seen, one at each corner of the plate. The effect of viewing a square, vertical surface from a very acute overhead angle is also clearly illustrated by the elongation of the image vertically and also the narrowing taper. This distortion of the image complicated the conversion of image co-ordinates to real world co-ordinates for deposit removal. This is covered in subsection 3.7.3. The black vertical lines visible above and through the two white horizontal pieces of chalk are the pieces of adhesive tape used to hold the chalk in place on the cloth. The two black vertical lines at the bottom of the image (the left one being more than twice the length of the one on the right) are the cable ties used to hold the neighbouring plates' filter cloths in place. Either side (horizontally) of the slurry feed hole but within the limit of the circular recess, two features can be observed. They are undulations in the clean filter cloth, and give some idea of the difficulty of distinguishing cloth bumps from cake lumps if only ranging data are used for object detection. It can also be very difficult to detect whether such features are concave or convex (they are convex in this case).

Figure 3.8 shows another greyscale intensity image with many of the features described in the previous figure. Only a couple of pieces of filter cake are apparent on the area bounded by the filtration recess and the slurry feed hole, while a third is evident on the rim of the slurry feed hole. The undulations in the cloth are quite striking, while the circularity of the recess is slightly less well defined than in the previous image. An interesting point to note is the brightness of the two lower filtrate ports. These localised areas of greater reflectance would have been caused by water lying in the ports at the time of scanning. Again the distortion of the image is quite clear.

3.7 Image Processing and Analysis

Image processing and image analysis are generally considered to be separate techniques.

Image processing is concerned with the appearance, or quality, of an image. By employing different techniques, e.g. noise reduction, smoothing, sharpening and contrast enhancement, an image can be processed to highlight different aspects of the data. Processing, therefore, is applied to data to enhance the image in a particular way, possibly as a precursor to analysing it.

Image analysis is applied to an image to extract information from it about, for example, number, size, shape, location and grey scale intensity of features, for subsequent classification and comparison.

Images are usually stored in digital form and can be accepted by analysis devices from a great variety of imaging sources, including TV cameras, optical and electron microscopes, microdensitometers, photometers, other computer systems, and any other device which can produce image data.

The identification of image features can be based on a variety of concepts, e.g. in monochrome images, features of interest may be identified with areas containing similar grey intensity values, areas of similar grey level texture, or areas enclosed by contrast edges or boundaries.

In general the ease of discrimination of image components depends on the quality of the original image preparation, e.g. where appropriate, the mounting, cutting, polishing, staining or etching of the sample material and its presentation, i.e. illumination, viewing technique, magnification and hence the resolution of detail. These are directly under the control of the user.

Detected image features can be modified either automatically or manually prior to being quantified by geometric or densitometric measurements.

The applications of image analysis are many and varied. Frame rate image analysis, real time, can be used for motion analysis, tracking of objects, e.g. target monitoring [26]. Optical character recognition (OCR) applications include reading type numbers on IC chips, sell-by dates on pharmaceutical packaging, pallet numbers in automated warehouses and serial numbers in product tracking [27]. Table 3.1 lists some other areas and examples of image analysis usage.

Image analysis systems are available which can be programmed interactively. These systems usually have pull-down menus which aid users in developing each solution to their image analysis problems. The sequence of manually applied operations established by the user to analyse each image as necessary can be recorded as an inspection program which can subsequently be run as an automatic inspection routine with or without intervention by the user. These systems are ideal for developing or modifying automatic inspection tasks where the code is checking for conformance of parts, or errors are predefined. They are relatively cheap, readily available [28], [29], packages, not necessarily needing a framegrabber. Other packages are available which offer a library of image analysis functions.

Speed of operation at the image assessment stage of automatic filter press discharge was felt to be important in this work, but not vital. This, coupled with the need for programmability, ease of use and low cost, led to the rejection of expensive dedicated imaging hardware devices such as specialised framegrabbers in favour of software packages. Further, as the image data from the STRIPE scanner is written to computer memory, it was felt to be more appropriate to process it with software than hardware, i.e. an image framestore was not thought to be required at this stage of the work.

As discussed in Chapter 6 the computer software language used throughout the project was Borland's 'Turbo C'; so an analysis package written and programmable in 'C' was sought to simplify the task of integrating it with the code already written for the work, e.g. those programs controlling the robot and laser systems.

Discussions with image analysis specialists at NEL indicated that extracting information of interest from the STRIPE generated image would be a simple procedure, requiring a few, standard, analysis functions.

This opinion helped define a software specification as it implied that only a relatively basic package would be needed. Another very important requirement was programmability, i.e. the ability of the image analysis to be run 'hands-free'. Many image analysis software products require human interaction and have interfaces designed accordingly. For a discharge system to be automatic all stages of its operation, including analysing cloth images, must be capable of intervention-free operation. Such a feature implies programmability, which in turn suggests the use of a software function library. A package offering a library of image analysis functions is ideal, since only those functions which are required for image investigation or manipulation need to be included in the source. The resulting executable file is, therefore, smaller than one incorporating a range of unnecessary functions, thus minimising computer memory requirements. The entire image analysis process can be tailored to fit the requirement, and conform to a consistent, perhaps corporate, program appearance.

The requirements for an appropriate image analysis package were thus defined; a software package written in and programmable in 'C' and having a function library containing those functions thought to be appropriate to the filter cake identification task.

Table A.6 lists some of the companies contacted in the search for a suitable image analysis package. The C_Images function library written by Foster Findlay Associates Ltd., [30] met all the requirements and was purchased after a STRIPE generated test image sent to the company was readily manipulated and feature data extracted from it.

The C_Images function library (the hardware independent version of the company's code requiring only a VGA computer monitor to operate, i.e. not requiring a framegrabber), and the interactive package were procured. The interactive version was acquired to expedite development of a suitable analysis program to perform the required tasks; once a sequence of operations was found to be successful through interactive methods, the same sequence was programmed to happen automatically. The interactive version of the C_Images function library, PC_Image, uses the C_Images functions, hence this was felt to be an acceptable approach.

3.7.1 Analysis Procedure

The image analysis operation begins when the STRIPE generated image is read from a disc file where it was stored after acquisition. At this stage it is a greyscale image where each of its 512 by 512 pixels has one of 256 values. A region of interest is defined to limit the area of object detection; this area corresponds to the recessed region in a filter plate, i.e. the filtration area.

Given the exploratory nature of the project it was felt appropriate at this stage to limit the analysis, and hence scraping functions, to one area of a plate. Dealing with filter cake deposits elsewhere, e.g. on the gasketing faces, is a simple extension of the work required to achieve a solution for the filtration area.

The greyscale image is thresholded over the region of interest. This function converts the greyscale data into a binary representation, so that instead of a value between 0 and 255, each pixel can only have the value 0 or 1. The thresholding is necessary since the C_Images object detection functions, e.g. size and location, work only on binary images.

A threshold value must be defined for this operation; i.e. the greyscale value must be chosen below which pixels are set to 0, and above which pixels are set to 1. If the threshold value is too low, too many pixels will meet the specification for being above it and hence be set to 1. This would result in a mass of objects being highlighted, inflating the task of the scraping algorithms. Set too high, the majority of pixels would fail to reach the specified greyscale value and the converse problem of too few objects being highlighted would arise. A thresholding balance must be achieved so that items of genuine interest are highlighted while unimportant features are ignored. The thresholding value is thus an important factor in correctly analysing the scanning laser-generated image of the fouled filter cloth.

The optimum value for each thresholding operation depends on the contrast of the greyscale image, which in turn depends on a number of variables. As discussed in Section 7.7 the ambient light level, the aperture setting of the camera and the width of the projected stripe of light all influence the quality of the acquired image.

To facilitate the optimal choice of a fixed threshold value, an interactive section was added to the analysis code. This allows the user to change the threshold value and view the result of the operation, until the image is deemed to be optimised for the next stage of the sequence, deposit identification and data extraction. This optimisation is based on the experience of the user, i.e. knowing when the thresholded image gives the best guide to scraping requirements; ultimately, a more automatic thresholding procedure is desirable[1].

Simply thresholding a greyscale image into a binary image is not sufficient to detect items of interest. The binary image will contain many non-zero single pixels and small groups of pixels corresponding to non-significant or artefactual items, even after an 'optimised' thresholding operation. This 'noise' is removed from the image as the next stage of the analysis procedure and can be regarded

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[1] Subsequent work with the C_Images library by the author after completing this project yielded much more efficient techniques of automatically selecting ideal threshold values for greyscale images. If applied to the work described in this thesis, the performance of the imaging system would be greatly improved and a genuinely automatic discharge system offered. Several possible ways of achieving this are outlined in Section 3.7.4.

as a tidying-up operation.

The functions used in this tidying-up search the binary image for isolated or unconnected pixels and discard them, since they cannot represent significant deposits. This operation can be repeated a number of times to erode items from the image. Again a balance must be achieved or too much information will be removed. The erosion is followed by a dilation; the objects left in the image after erosion are added to, i.e. pixels are added to the perimeter of each item to define it more clearly. This can be done as many times as the user wishes, but again, in practice only in moderation; with excessive repetition the image field would be filled with one item, since images of any small objects would eventually coalesce as they enlarged.

The settings used in the development system are one erosion pass and two dilation passes applied to each image; these values have proved very satisfactory in tidying-up images and clarifying features.

The net result of these tidying-up operations is an image containing clearly defined items of interest. These should be discrete areas of filter cake, or the uppermost fracture edges of larger lumps of cake.

The effect of the foregoing operations can be seen in the following figures. Figure 3.7 from subsection 3.6.1 is the greyscale image used. Figure 3.9 shows the same image after thresholding to a binary image. The white areas represent binary 1. Many individual pixels which are clearly not features of interest can be seen. This unwanted noise is removed by the erosion operation. The result of the erosion of the binary image is seen in Figure 3.10. The image is much more clearly defined with loose pixels discarded. The dilation operation adds body to the remaining image features in Figure 3.11, this sometimes makes one feature out of two or more which reduces the number of targets the robot must scrape and can expedite discharge.

It should be noted that in these examples the whole image has been operated on. The system currently only applies these operations to the circular region of interest, hence many of the features seen in these examples would not be apparent in the operational case. Of particular note are the features in the top right corner of the images. These are a result of slightly too wide a scanning stripe illuminating the inward looking face of the side bar of the filter press. As it is painted white this has reflected the laser light back onto the filter cloth and has become a feature, albeit an unwanted one, in the image.

The bottom right of the images exhibit a mass of features which are actually only the filter cloth. On the original greyscale image (Figure 3.7) this area of the cloth can be seen to be quite light. If the thresholding operation had used a higher greyscale value to define the breakpoint for the binary image, much of this cloth information would not have been identified as probable filter cake.

The actual targets on the example filter cloth image, two pieces of chalk each in the upper left and lower right quadrants of the filtration recess, can be seen to progress through the various image processing operations to the final image (Figure 3.11) where they would be identified as targets and scraped accordingly.

3.7.2 Feature Detection

A binary image containing clearly defined objects, i.e. clusters of pixels each having the value 1, is easily searched to find such clusters. This is the object detection stage of the analysis, the success of which depends on the previous stages.

A great deal of information can be generated for each object, but it is possible to limit this only to that which is needed for a particular application. The following values of x and y co-ordinates are extracted for each item detected in a filter cloth image; centre x, centre y, minimum x, minimum y, maximum x and maximum y. These values represent the mid-depth value, mid-lateral value, top edge, rightmost, bottom edge and leftmost edge of the feature respectively. These values are screen co-ordinates taken with respect to the top left corner of the computer screen. In the system used here, the image is oriented on the screen such that the top edge of the filter plate is seen lying vertically at the left edge of the screen, while the bottom of the plate is at the right edge of the screen.

3.7.3 Conversion from Screen to Plate Co-ordinates

Computer screen co-ordinates are not directly useful in guiding the robot scraper; they must be converted to 'real world' co-ordinates. This conversion changes screen co-ordinates into distances relative to a datum, taken as the midpoint of the top edge of filter plates (Figure 3.12). This position was chosen because of the advantages it offered in developing the scraping algorithms (Section 4.4). Straightforward trigonometry is used for the conversion, but more refined methods, or optimised scaling values, are recommended for future systems as the present one is not regarded as very accurate.

Some important features of this process are illustrated in Figure 3.13. In that Figure it can be seen that the distance from the top edge of the screen to what is the filter plate's vertical centreline (in screen units of pixels) is defined as F_ROI_CENTRE_Y. Also, the distance from the left edge of the screen to what is in reality the horizontal centreline of the filter plate is called F_ROI_CENTRE_Z. The basic conversion process was derived as follows, using the notation of Figure 3.14.

In the Figure, which represents one half of the screen image of a scanned filter plate, 'A' is a point with y screen co-ordinate c. Point 'B' is a derived point with the true (actual or plate lateral) Y co-ordinate value of A, b.

Now,

$$\frac{AN}{PN} = \frac{b}{a} \tag{3.1}$$

and,

$$PM = f * \tan\alpha \tag{3.2}$$

but

$$\tan\alpha = \frac{a-e}{g} \tag{3.3}$$

so substitute Eqn 3.3 in 3.2, giving

$$PM = f * \frac{a-e}{g} \tag{3.4}$$

but since

$$PN = a - PM \tag{3.5}$$

then substitute Eqn 3.5 in 3.1, c for AN and rearrange, giving

$$b = \frac{a * c}{a - f * (\frac{a-e}{g})} \tag{3.6}$$

where a, e and g are constants.

The value f is derived from the point's Z value. It is defined as

$$f = Z\ value - TOP\_OFFSET \tag{3.7}$$

where TOP_OFFSET is a constant representing the distance from the left edge of the computer screen to the top edge of the filter plate in the screen image. This value was taken to be zero in the final, working solution.

The value c is derived from the point's Y value. It is defined as follows. If the Y value is greater than the value to the vertical centreline of the filter plate, c is taken as the Y value minus the value to the vertical centreline of the filter plate, i.e.

if (Y value > F_ROI_CENTRE_Y) then

$$c = Y\ value - F\_ROI\_CENTRE\_Y \tag{3.8}$$

This makes c a positive distance from the vertical centreline of the plate. Otherwise (if Y value is less than the distance to the vertical centreline of the plate) c is taken as that distance minus the Y value, i.e.

$$c = F\_ROI\_CENTRE\_Y - Y\ value \tag{3.9}$$

Equations 3.8 and 3.9 apply to the forward scan case only. For backward scans, where the plate image is displayed flipped over its horizontal (as viewed) axis, only one equation is needed as this, with the 'wrong' image, takes due account of signs. For backwards scans c is calculated thus.

$$c = B\_ROI\_CENTRE\_Y - Y\ value \tag{3.10}$$

The constants a, e and g in Eqn 3.6 are defined as F_HALF_WIDTH_TOP, F_HALF_WIDTH_BOT and F_DEPTH respectively. These values, in pixels, were found by observing and measuring many scanned images of filter plates on screen. The values are, therefore, only really valid for typical scan results. Inaccuracies or inconsistencies in robot position, scanning mirror position or speed will affect the accuracy of these 'constants' which are intended to define fixed parameters of all images. The exception to this is the backwards scan. All the F_ values in the code are replaced by corresponding B_ values. The 'fixed' backward scan parameters are subject to the same potential inaccuracies as the forward parameters.

Having found b, the 'true' Y co-ordinate of the point, in pixels, this value must be converted to millimetres relative to the 'real world' datum defined in Figure 3.12. This conversion is linear with depth for horizontal Y values but, because of the overhead mounting of the viewing system, is not linear with depth for vertical, Z values. Ideally a different scale factor would be used for each Z value dependent on how low down the filter plate the point is, i.e. how far above or below the horizontal centreline of the plate it is. The implemented solution used three different scaling values each for both forward and backward scans. One factor was for Y values and two were for Z values.

The value b is thus multiplied by F_SCALE_FACTOR_H to arrive at a dimension in millimetres specifying a lateral position. This position may be a target point (see Section 4.4) or an extremity of the detected deposit.

The actual value of Z co-ordinates is dependent on the depth of the point. If the Z co-ordinate is greater than F_ROI_CENTRE_Z, indicating that the point is in the lower half of the filter plate, the pixel value is multiplied by the scale factor F_SCALE_FACTOR_W_R. Otherwise (the point is in the top half) the value is multiplied by F_SCALE_FACTOR_W_L. The calculated depth position is thus in millimetres relative to the top edge of the filter plate.

Initially only one scale factor was used to convert pixels to millimetres and this was derived as follows. It was assumed that the whole of the left, vertical, edge of the displayed image was equal to the width of each filter plate. Careful setting of the zoom facility of the scanning system's camera lens enabled this. The height of the screen image was known to be 200 pixels and the width of the filter plate to be 500 mm. By division, 1 screen pixel was said to represent 2.5 mm in 'real' dimensions. Using this value as a starting point the various scaling factors required in the conversion process were manipulated until satisfactory results were achieved in tests using targets of known position, in millimetres. The values in use at the end of the research period ranged between 2.0 and 2.47, indicating that the initial assumption was a fair approximation, albeit not ideal.

The inaccuracies in the conversion method are due to inconsistent image datum locations, explained below and coarse scaling factor increments. It should be noted, however, that the size of the cake scraper is such that small errors induced in co-ordinate conversions do not cause a loss of scraping performance, i.e. the scraper is large enough to dislodge cake fragments provided the location errors are not of centimetre magnitude. Given that these errors have been observed to be typically less than 1 cm, further refining of this aspect of the system, while desirable, is not thought to be urgent.

The output of the analysis code after conversion of co-ordinates are the 'real-world' co-ordinates for the centre Z, centre Y, minimum Z, minimum Y, maximum Z and maximum Y of each detected item. This information is all that is required by the scraping algorithms to dislodge each deposit. Figure 3.15 shows the deposits identified after processing Figure 3.7.

Successfully and consistently converting co-ordinates highlights an assumption which was made in the image analysis area to achieve a basic, demonstrable discharge system.

The position of the region of interest superimposed on the greyscale image and the screen datum used in converting co-ordinates are defined with respect to the screen origin and are fixed, i.e. they are not interactively or automatically defined and adjusted to match the position of the greyscale image. While the position of the greyscale image on the computer screen is defined, the locations of specific items within it are not.

If the robot does not deliver the scanning laser to the correct distance from the face it is to scan then, since the viewing direction is oblique to that face, the datum for the scan is altered. Features such as the slurry feed hole or the recess rim will, therefore, not be in their anticipated positions in the image and the objects detected will be assigned incorrect 'real world' co-ordinates. Depending on whether the laser is too close or far away from a cloth at the beginning of a scan the object's vertical co-ordinates calculated from the resulting image will be either too low or too high.

A further implication results from the definition relative to the screen of the region of interest for object detection. The 'real world' region of interest is the filtration area of a cloth. With a datum shift of the image, some genuine objects lying in the filtration area will be ignored because that area of the image is not lying under the region of interest overlay. Analysing the whole cloth image for objects wouldn't have this problem, although in principle it would; some of the cloth could be out of the scanned area. As stated in subsection 3.7.1 the whole of the face of the filter cloth would be analysed in a fully developed, working, system.

In practice, it is indeed found that there is some variability in the laser-cloth distance as successive plates are presented for scanning. Position errors in locating deposits on the cloths will therefore arise. In the experiments reported here, the observed differences in the desired and actual positions of the laser with respect to the cloth of interest are small, a few millimetres; but they could prove to be more when full discharge cycles are attempted with different cloth and slurry types. This is because the irreproducibilities are due, not to defects in the robot's repeatability and accuracy of positioning, both of which are excellent, but to the variable effects of plate shifting.

When a filter plate is moved away from the compressed stack of plates after filtration, the cake in the chamber thus opened can have sufficient adhesion to both cloths lining the chamber to cause the filter plate behind the one being acted on to move. This movement doesn't last long as the adhesion is quickly broken, but it can be sufficient to move this secondary plate away from the position it is assumed to be in when programming the robot movements.

Similarly, if the plate being moved is not moved as far as anticipated, then it will be slightly out of position when it is scanned. The latter situation is likely to occur in the later stages of press opening. The first plate to be shifted is transferred from a stack that has been highly compressed during filtration against the pressure plate; subsequent plate transfers are from the diminishing compressed stack to the growing stack of moved and discharged plates at the other end of the press. This growing stack is much more lightly compressed, so successive plates are shifted through progressively shorter distances.

This discussion is based on observations of large, automatic plate shifting device equipped, filter presses. The plate shifting mechanism developed in this work and retrofitted to the research equipment would not suffer the double plate shifting problems outlined here (see Section 4.6).

Allowance could be made for these inconsistent plate positions by incorporating a sensing device, or using the scanning laser itself, to determine the correct position of the robot with respect to each cloth face. The present system uses dead reckoning to position the robot and hence the laser; this is acceptable for the time being in a development situation where available effort has to be concentrated on less tractable problems, but not in a manufacturing environment where a feedback system would be required to ensure consistent positioning of the scanner relative to the cloth face.

The sensitivity of the scanning and analysis systems to incorrect positioning of the scanner relative to the cloth face of interest has not been investigated quantitatively, but it is thought that a robot position of a few millimetres either side of the ideal does not give rise to significant inaccuracies in the calculation of 'real world' co-ordinates for detected features; the size of the scraping head allows for an on-cloth positioning margin of several millimetres. None of the runs of the research equipment gave rise to problems in this respect.

3.7.4 Overcoming Thresholding Limitations

To achieve automatic thresholding of the greyscale cloth image to a binary image a number of changes could be made to the existing system configuration.

The essential obstacle to using the current apparatus fully automatically is the variation in the ambient light level experienced around the filter press. This variation, which occurs despite the fabric enclosure built round the rig, is large enough to require the camera's aperture to be adjusted to compensate for it. Such an adjustment has a direct effect on the greyscale image generated and, therefore, on the value used to threshold the greyscale image into a binary image containing the optimal amount of pertinent information.

The STRIPE system is very sensitive to the amount of light admitted by the stripe detecting camera's aperture. If too much light passes through the aperture the resulting image is useless (an uninterpretable mess); the back-scattered laser light from the cloth surface is swamped by the ambient light also being admitted. If too little light is passed through the aperture, the amount of energy detected is so small that no distinguishable cloth image is formed.

One solution to this problem would be to use a light meter and a motor-controlled camera aperture. A light meter mounted on the robot would send its output to the controlling computer, which, using a previously derived look-up table, would set the aperture of the camera to the correct setting for that level of ambient illumination.

This technique would still require the ambient light level around the scanning area to be as low as possible, so that the laser energy would be clearly distinguished from all other light sources.

This distinction between laser and background light could also be facilitated by using a more powerful laser to project the light stripes and fitting a colour filter to the camera's lens. In this way the influence of ambient light on the generated image is reduced, while the relative strength of the stripe-forming illumination is increased.

Consider first a filter on the camera's lens. A narrow bandpass filter is designed to let light of a specified wavelength through and stop all other wavelengths. As shown in Figure 3.16 [31] a small amount of light of the wavelengths either side of that specified will also pass through the filter.

Applied to the STRIPE system the following benefits would be expected to be derived from fitting a filter, assuming the pass-band of the filter corresponded to the wavelength (and tolerance) of the laser. The only component of ambient light which will reach the camera's array will be that which has the same wavelength as the laser. This ambient component may be reduced further by tinting the skylights or windows in the vicinity of the apparatus so that the amount of naturally occurring light of the critical wavelength which is admitted to the area is reduced. Implemented with care this action should not materially reduce the perceived ambient light level and cause vision difficulties for operators or maintenance personnel in the area.

The amount of light of the desired wavelength passed by a narrow bandpass optical filter is well under 100%, so that its use effectively reduces the power of the laser. Experience gained during this work has shown that the high ambient light levels experienced in normal summer daylight in a laboratory with multiple large skylights, together with a narrow bandpass filter-equipped camera lens and a class 2 laser do not work well together. To significantly improve the imaging performance of the system, under industrial conditions, a more powerful laser would most likely be required.

Using a more powerful laser, and moving into class 3 use as a consequence, causes new problems. As can be seen in Table 3.2[2] the restrictions under which a class 3 laser may be operated safely are more stringent than those for a class 2 laser. These restrictions include provision of interlocks on the access to the laser environment for example.

Assuming such restrictions can be met, the benefits of using a more powerful laser will include more detailed and reliable cloth images obtainable under 'natural' press lighting conditions.

The more intense the laser energy projected onto the face of a filter cloth the better the images are likely to be, but there will be situations in which it isn't possible, or practical, to incorporate the safety measures required for class 3 laser operation.

It should be possible to achieve the same energy density along the length of a stripe of laser light using class 2 lasers as that produced by a class 3 laser. By

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[2] From the Committee of University Vice-Chancellors and Principals Notes of Guidance

utilising more than one class 2 laser, a higher intensity filter plate-wide stripe of light can be projected. The shorter the line of light created by the oscillating mirror, the more intense each point along its length will be. Thus, a number of class 2 lasers could be used to scan a filter cloth, each laser projecting a stripe of light onto a small section of the cloth. A small overlap of adjacent stripes would be required at the top of a filter plate, but this shouldn't be difficult to arrange, or cause problems during image analysis. One great advantage of this approach is that the whole system retains class 2 laser status, which reduces the safety requirements, and thus the cost of installing it, and reduces the potential inconvenience of the system.

The improved image thresholding technique alluded to in subsection 3.7.1 is actually standard practise to experienced image analysis workers, but was 'developed' independently by the author as a solution to a later imaging problem. The first step in the procedure to obtain the best binary image possible from a greyscale image is to generate a histogram of the greyscale image. The histogram lists the number of pixels in the image corresponding to each of the 256 greyscale levels previously described. The total of these occurrences must equal the number of pixels in the area of interest, and as such is already known. What is not known, from one image to the next, is the distribution of the pixels across the greyscale range, and it is this which limited the automation of the thresholding operation. If, as in this case, the objective of a thresholding operation is to highlight the bright objects in a greyscale image and to ignore all the darker ones, then the following technique is successful in achieving this.

The bright objects in the greyscale image have the highest greyscale values in the image, so by selecting a high greyscale value as the threshold value all the bright pixels are set to 1 in the binary image. The success of this depends on choosing the correct threshold value. If experience shows that typically the brightest 10% of the pixels generate the best binary image, this can be made automatic, regardless of the distribution of pixel greyscale values, by using the histogram. Counting backwards from the high greyscale end of the histogram (255) the number of pixels corresponding to each greyscale value are added together until this total equals or exceeds 10% of the total number of pixels in the area of interest. At this point, the counting loop in the controlling code stops and notes the greyscale value at which this condition was met. This greyscale value is then used as the upper limit in the thresholding operation, i.e. all pixels below this value are set to black, 0, and all those above to white, 1. This technique is very fast and very effective. Incorporating it in the image analysis code should be a priority for any future work on this project.

Material Sciences	Environment & Resources	Life Sciences	Industrial Inspection
particle sizing	asbestos monitoring	chromosome analysis	correct assembly
steel inclusions	coal petrography	autoradiography	component
grain sizing	marine biology	neurone analysis	flaw inspection
porosity	oceanography	cell structure	surface finish
cellular structures	forestry	electrophoresis	robot guidance
fibres	agriculture	micronuclei	robot assembly
crystal structure	mineralogy	3D reconstruction	texture
paper	seismology	DNA content	crack inspection
abrasives	cartography	bone structure	
metallurgy		tissue structure	
crystallography		muscle fibres	
food technology		dental decay	
tobacco		radiography	
lubrication		dermatology	
wood		cosmetics	
nuclear industry		silver grain counting	
plastics		intracellular free ions	
printing		pharmaceuticals	

Table 3.1: Representative list of areas in which image analysis is used

Class	Description	Reason for classification
Class 1	SAFE	Either (i) the output is so low that the laser is 'INHERENTLY SAFE', or (ii) because the laser is part of a 'Totally enclosed system' and is 'SAFE BY ENGINEERING DESIGN'. In either case the relevant M.P.E. cannot be exceeded.
Class 2	LOW POWER Visible c.w. & pulsed lasers	In the case of C.W. lasers eye protection is normally afforded by the natural aversion responses including the blink reflex. Hazard can be controlled by relatively simple procedures.
Class 3A	LOW-MEDIUM POWER LASERS	An extension of Class 2, where protection is still afforded by the natural aversion response, but direct intrabeam viewing with optical aids may be hazardous. This must be controlled.
Class 3B★		As for Class 3A but there is a slight hazard from viewing the direct beam. Power limited to 5mW. NB visible only.
Class 3B★★	MEDIUM POWER LASERS	Hazard from direct beam viewing and from specular reflections. More detailed control measures are necessary.
Class 4	HIGH POWER LASERS	Not only a hazard from direct viewing and from specular reflections but possible from diffuse reflections also. Their use requires extreme caution.

Table 3.2: Classification of lasers

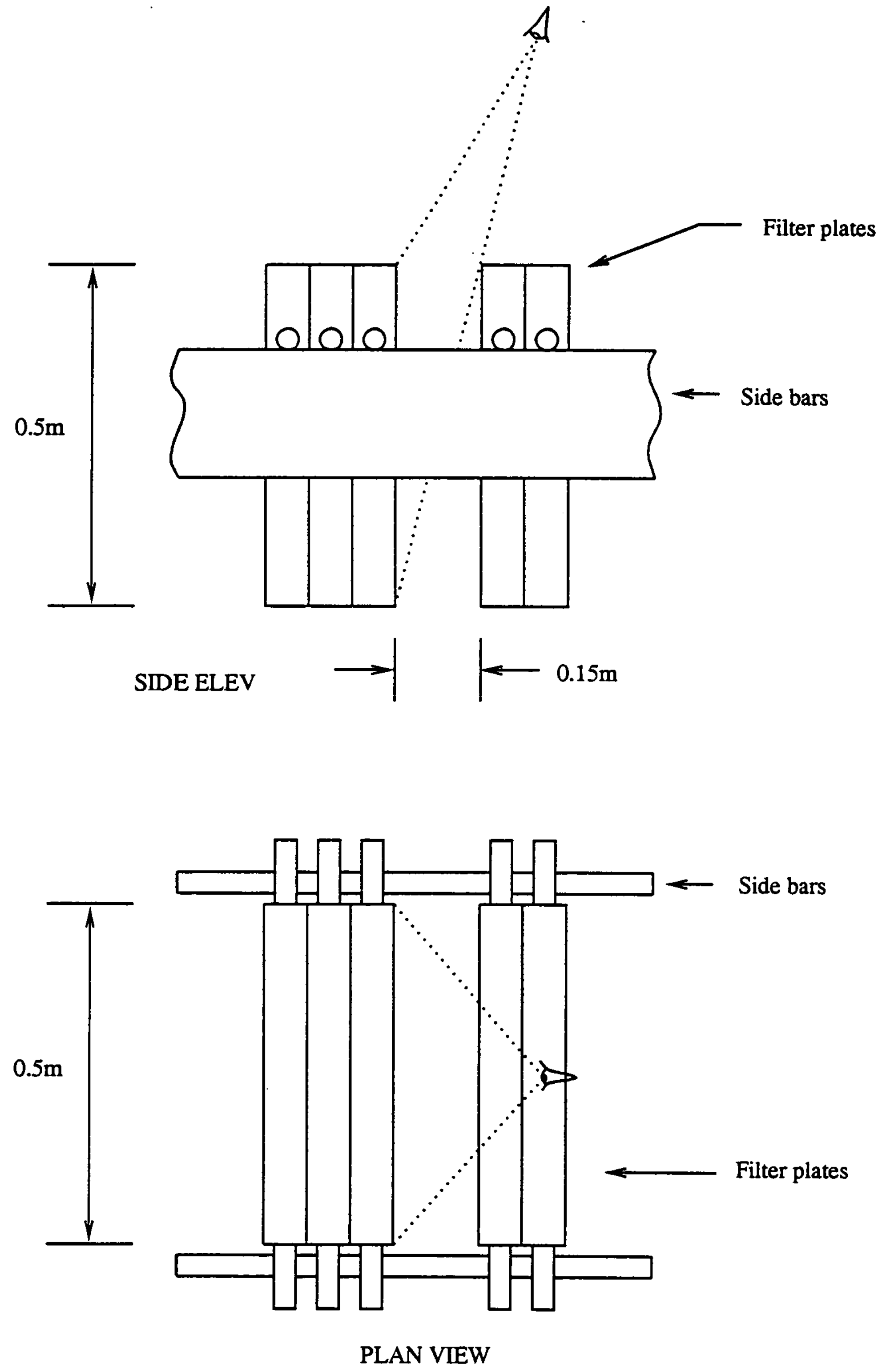

Figure 3.1: Overhead viewing problem

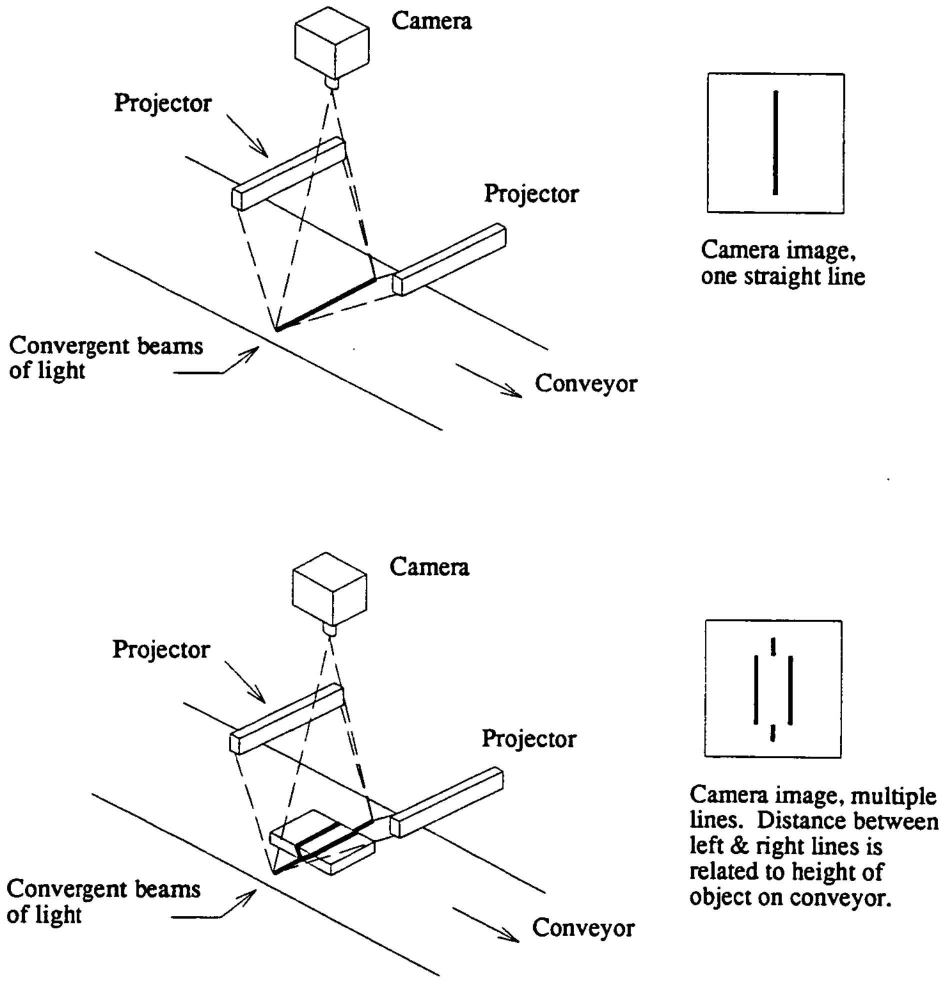

Figure 3.2: Consight system used by General Motors

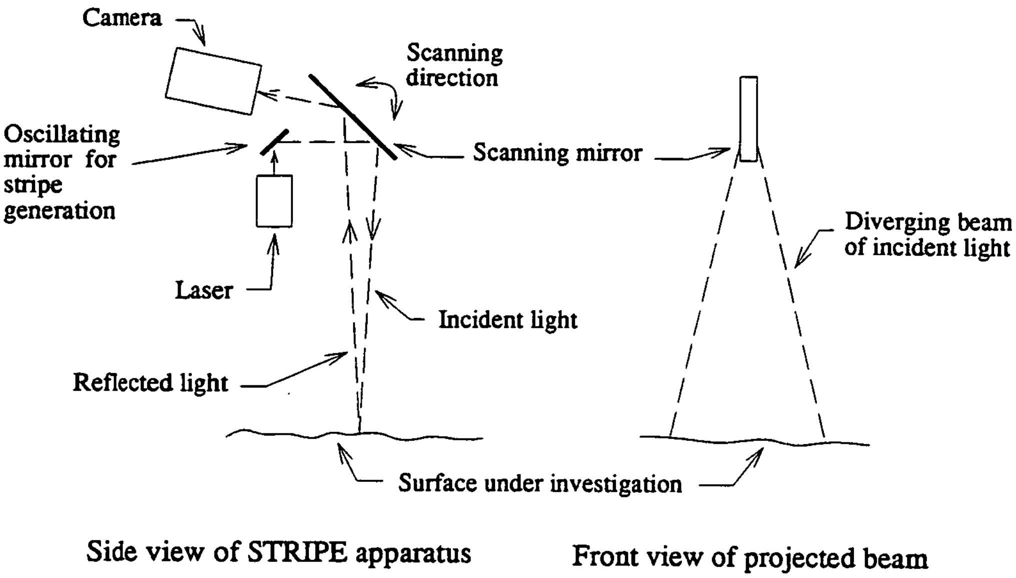

Figure 3.3: The elements of the STRIPE system

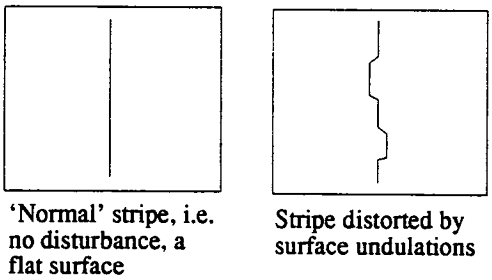

Figure 3.4: Observed deviation of stripe

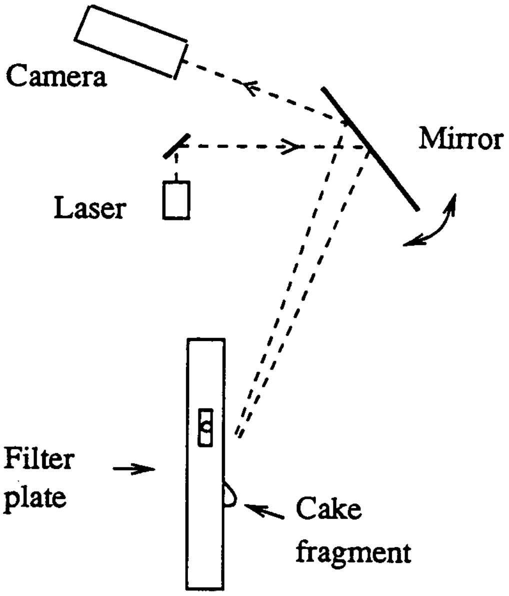

Figure 3.5: Orientation of STRIPE system to filter plates

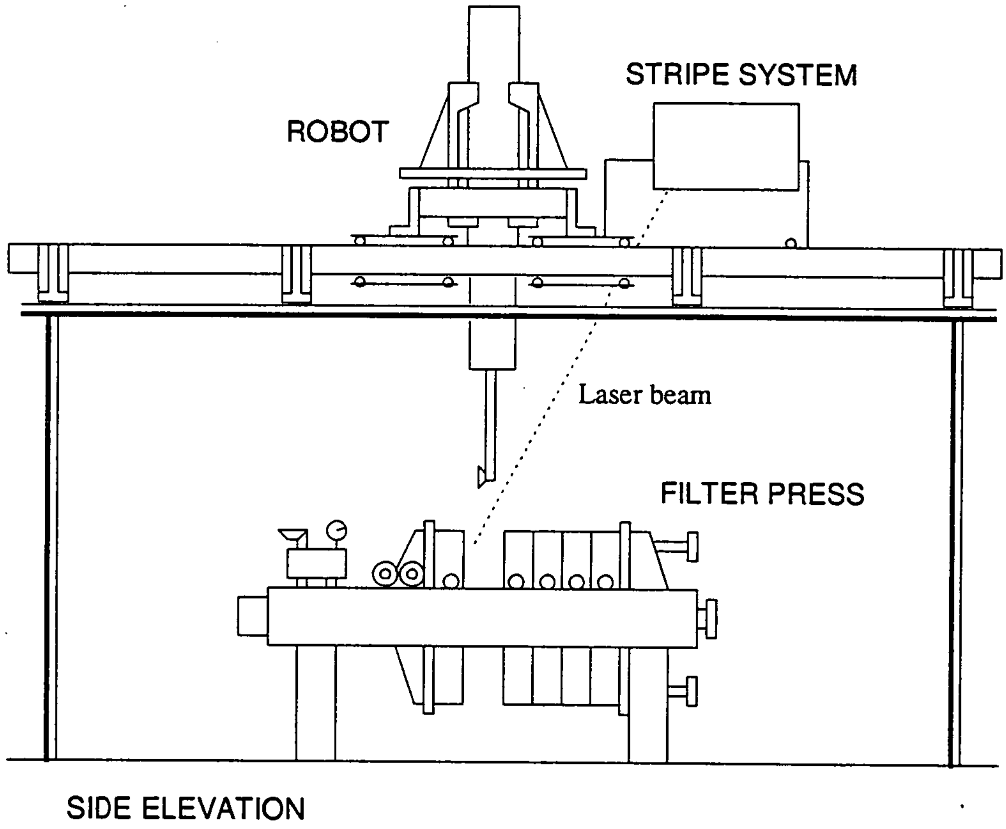

Figure 3.6: Mounting position of STRIPE system

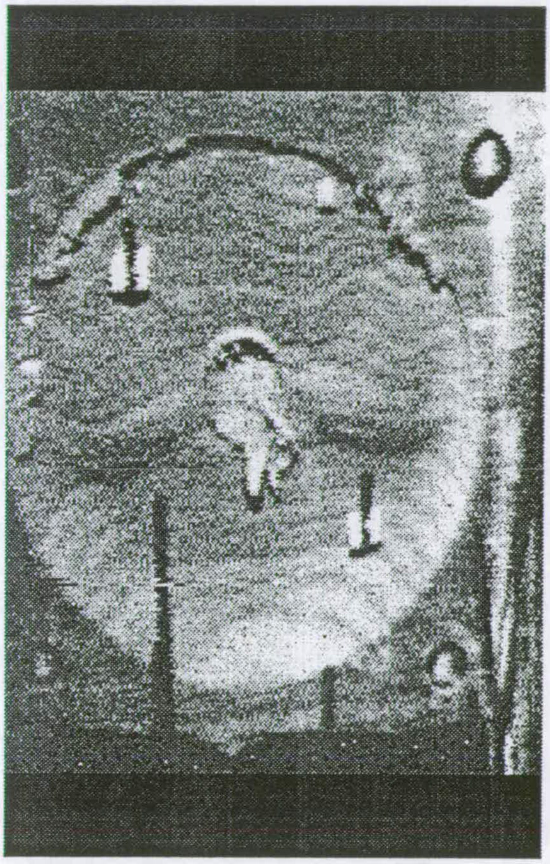

Figure 3.7: Typical greyscale image yielded by vision system

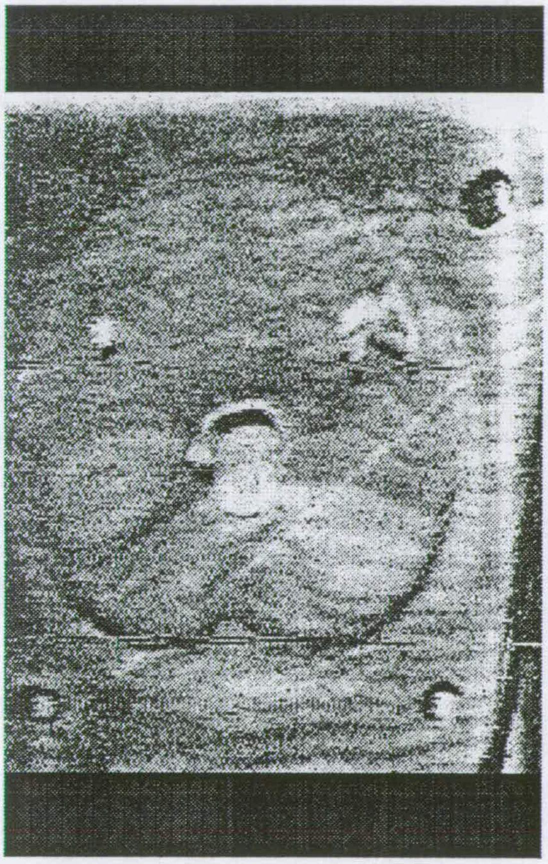

Figure 3.8: Example greyscale image yielded by vision system

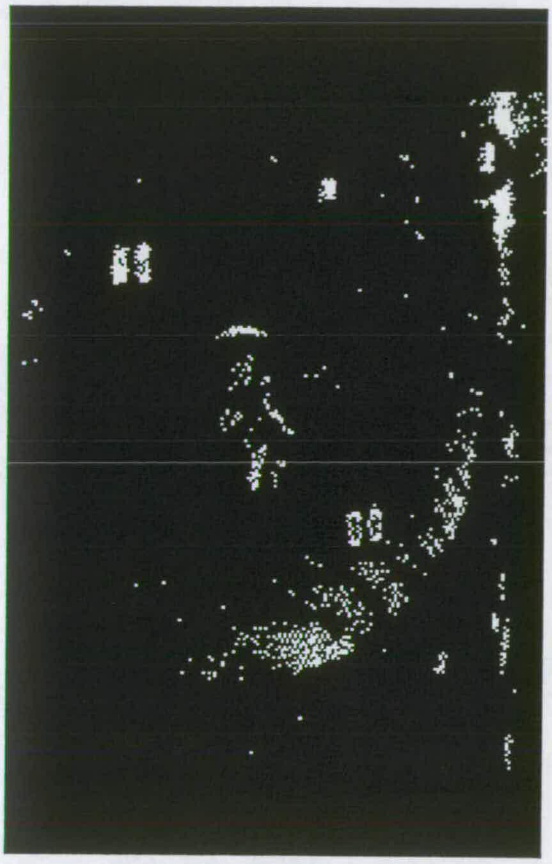

Figure 3.9: Thresholded image (binary from greyscale)

Figure 3.10: Eroded image (noise removal)

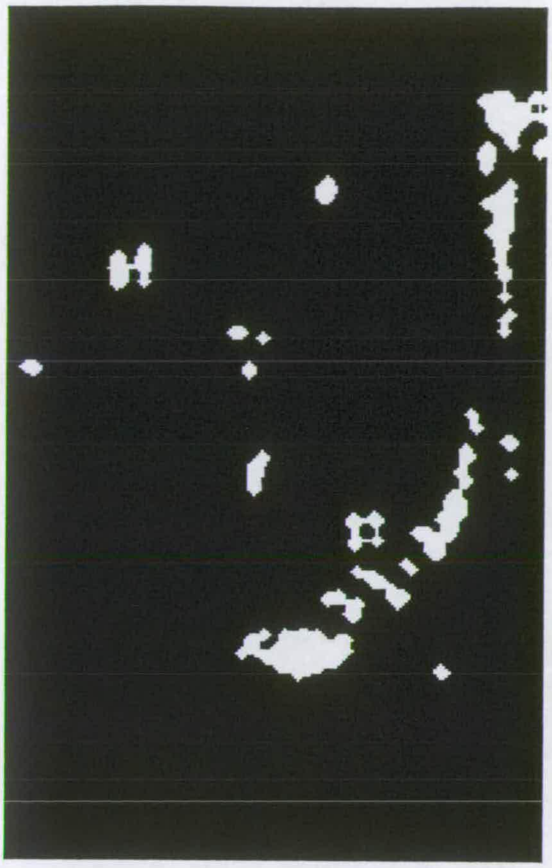

Figure 3.11: Dilated image (final image, used for data extraction)

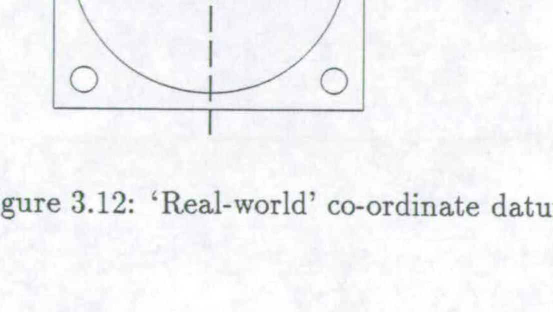

Figure 3.12: 'Real-world' co-ordinate datum

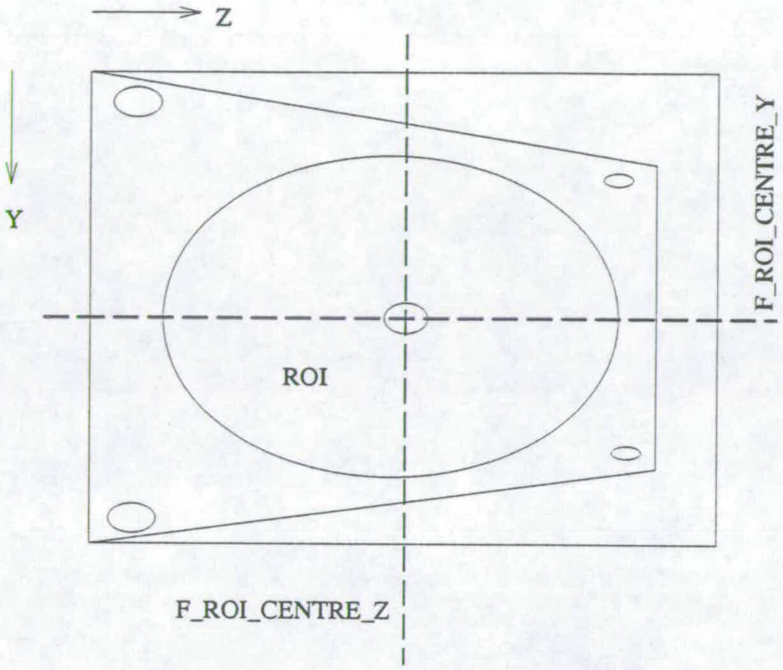

Figure 3.13: Co-ordinate conversion reference

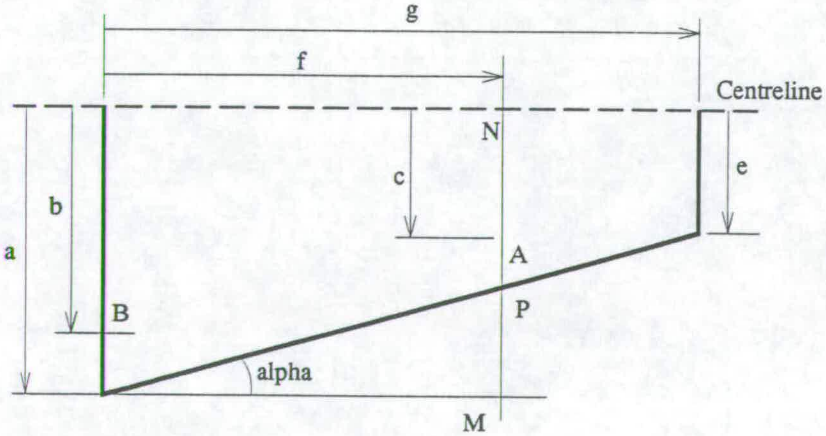

Figure 3.14: Co-ordinate conversion trigonometry

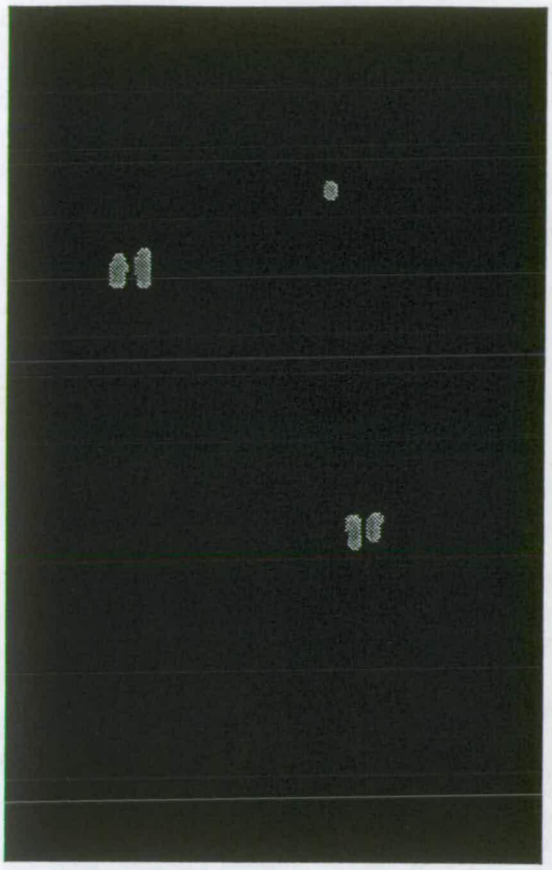

Figure 3.15: Cake deposits identified in image (White areas)

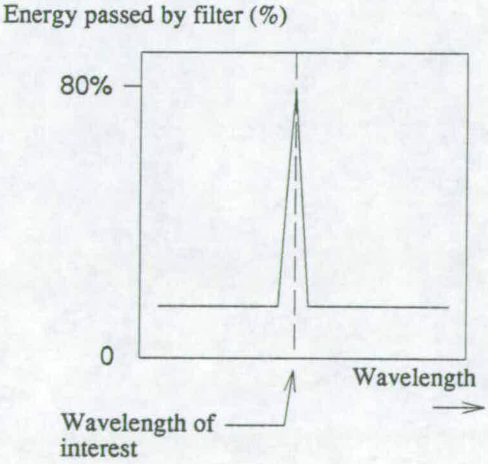

Figure 3.16: Characteristics of a narrow bandpass filter

Chapter 4

Deposit Removal

4.1 Approach

As mentioned earlier, observations of manual cloth cleaning practice showed that very simple and direct methods suffice. This indicated that relatively simple methods could be considered for automatic filter cake removal.

Scraping filter cake deposits off filter cloths was thought to be the best approach. The nature of this scraping function has a great deal of influence in the choice of a suitable robot. Much thought was directed at this problem; the first aspect considered was the direction of scraping.

As shown in Figure 4.1, it is possible to scrape a filter cloth in many directions, e.g. horizontally, vertically, radially and circumferentially. All these scraping directions have advantages and disadvantages.

Radial scraping offers the prospect of configuring the system such that the scraping device is always moving away from the slurry feed hole in the plate. There is a large, circular cloth seam in this region, hence the possibility exists of a full-width linear scrape damaging it. Always starting radial scraping from the centre of the plate, thus riding over the seam, is one way of avoiding damage to the cloth; always starting outside the seam area and moving radially away from this position is also an option; another is to ensure that the scraping path never passes through an 'exclusion zone' round the seam.

One disadvantage of scraping radially is the possibility that the scraper may become fouled. This would be caused by dislodged cake falling onto it when the scraper is moving upwards. Another, more important disadvantage, is due to the geometry of radial scraping. Areas of cloth near the slurry feed hole would be subject to multiple-passes of the scraper as it addressed areas close together near the circumference of the filtration recess, i.e. overlapping areas would be scraped close to the plate's centre, thus increasing cloth wear, something which must be avoided.

Virtually all filter press plates are externally rectangular, with gasketing faces bounded by horizontal and vertical edges and which may require either horizontal or vertical scraping to free them of cake. Circular circumferential scraping is really only advantageous for the inside rim of the circular recess of a small filter plate. As stated elsewhere, large filter plates usually have square or rectangular recesses. Nevertheless, as the plates in the research filter press had circular recesses, incorporating a circular scrape option in the solution was appropriate and proved to be important in the development of a scraping philosophy (Section 4.4).

Several scraping devices were considered, e.g. pneumatic actuators mounted on the lower end of a Cartesian (x y z) robot's vertical output shaft; double scrapers, similarly mounted, moving horizontally in opposite directions; chain-driven devices; air jets and jets or sprays of water. Many of these ideas were rejected almost immediately, e.g. water is totally unsuitable in a situation where it will drain onto the dry discharged cake. Air jets were also discounted; the possibility of cake being blown over everything in the vicinity of a filter press is neither a selling nor a safety feature. Other air-based systems may be of use in this respect, however. Air knives are available [32] which produce high velocity, precisely controlled blades of air capable of removing surface contamination and coatings from a range of materials and shapes. Such devices are typically static, mounted above a conveyor belt on which the product travels. It may be possible to mount an air knife such that it can be brought to bear on, and travel the height of, a filter cloth.

With a robot scraping in a carefully controlled pre-determined manner the cake should be discharged where it is meant to be, into a discharge hopper. The more complicated proposals involving chains and motors mounted at the end of the robot arm were felt to be too problematic and likely to require development in-house rather than being bought off the shelf, and were rejected accordingly.

After considering many scraping path options and their implications for the robot's specification, it was decided to adopt a best of all worlds approach. A robot capable of moving the scraping device horizontally, vertically, radially and circumferentially, was defined (with a suitable control system) as the most desirable solution. The flexibility offered by such a system, e.g. local, full, linear and circular scraping, was considered to be ideal for research purposes and justified the increased cost over a more basic system. The costs of robots investigated during the course of this work ranged from approximately £2k to £145k. The following section introduces relevant aspects of current robotics and details the process which led to a machine being commissioned this work.

4.2 Robot Specification

The word robot often brings to mind bright orange, one-arm machines welding or painting motor cars. As defined by the Robot Institute of America, "a robot is a reprogrammable, multifunctional manipulator designed to handle material, parts, tools or specialised devices, through variable programmed motions for the performance of a variety of tasks" [33]. Like many products of topical interest, robots come in shapes and sizes often unrelated to their popular image

Industries which have benefited from the application of robots include; semiconductor, pharmaceutical, manufacturing, automotive, electronics, food and drink, textile and chemical [34]. Within these industries the range of tasks fulfilled by robots is extremely large and varied. Some of these applications are; electronic assembly, e.g. fitting surface mount components, laboratory testing of products or intermediate compounds, machine loading and unloading, injection moulding, laser cutting and welding, arc, spot and gas welding, surface coating, testing of electronic components and assemblies, grinding, deburring, product handling, palletising, product sampling, dispensing, inspection, marking and quality control [35], [36].

Several recurring themes are encountered when reviewing the application of robots. These include; relieving human operators of tasks which are dangerous, onerous and stressful, require a high degree of concentration for long periods of time and are, therefore, subject to possibly costly mistakes; reducing product contamination, increasing quality and improving product consistency are also very common goals among those installing robots, as well as the inevitable economic incentive [19].

The requirements of the robots used in the diverse applications mentioned above are very different. Some, in the semiconductor industry for example, do not require to lift large masses, merely light components, but do require to work to very high repeatabilities. In contrast to these requirements are those of palletising or machine loading robots; here the need is more likely to be to move considerable masses, e.g. 500 kg [37], but not necessarily to the same degree of accuracy or repeatability as in electronics assembly[1]. The speed of operation will also vary with the application. Very high end effector speeds are possible, e.g. 10 m/s, but this is unlikely to be appropriate to very heavy lift applications. Similarly, low speeds with smooth motion may be the requirements when moving chemicals or

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[1] In robotic terminology Repeatability is the ability of a robot to return to a point in space which it has been taught by previously driving the manipulator manually to this point. Accuracy is the ability of a robot to arrive at a calculated point in space [38].

delicate components.

Other differences in the robots used in the foregoing applications will be found in their configuration. A defining characteristic of a class of robots is its number of degrees of freedom, or axes; these terms are synonymous when the robot's joints are linear or revolute, i.e. each having a single degree of freedom. A robot typically has between two and six axes, although more are possible. The configuration of these axes is usually in a classifiable arrangement, depending on whether they are linear or rotational, whether the robot is floor-standing or overhead and on what co-ordinate system is used in controlling it.

Robots can usually be classified as one of the following types; articulated, Cartesian, polar, gantry, SCARA and pick and place. Commercially available robots of each of these types were considered for this application, but most were rejected as being unsuited to the requirements of the research, or (as in the case of the gantry robot offered by Cincinatti Milacron for approximately £145k [39]) too expensive.

Pick and place robots can be extremely simple devices, sometimes being powered by pneumatic or hydraulic components rather than electric motors, but are of limited application. Typically they can only move their manipulator, usually a gripper of some kind, between two positions bounding a fixed path. This lack of flexibility in programming makes this kind of robot unsuitable for filter press discharge duties, at least as such duties have been conceived in this work.

Revolute, articulated, jointed, elbow or anthropomorphic are different names for one type of robot. This common robot, i.e. a single arm device with elbow joints, usually floor-standing, was considered for the task of scraping filter cake. While this is a very popular type of robot in manufacturing industries, it was quickly rejected as being poorly suited to servicing filter presses.

This rejection is based on an assessment of the suitability of the robot to carry out relevant tasks and the ease with which it could be retrofitted to an existing application. A conventional floor-standing robot would require tracks to facilitate its travel along the length of a press or group of presses, thus creating a potential hazard for operators when they are required to enter the area. Also, the space available between existing parallel presses is likely either to be insufficient for a retrofitted robot to pass between them or too wide for easy reach into both presses.

SCARA (selectively compliant assembly robot arm) and polar or cylindrical robot types have essentially the same disadvantages for this application as the revolute robot.

The most efficient way of accessing a filter press without restricting floor space and with minimum restriction on press location, is from above. With the side bar type of press used in this research, overhead access is relatively simple since the filter plates are supported at their sides. Some presses, usually larger ones, may have their filter plates supported from a central overhead beam rather than at their sides. Further work would be required to address the problems of access to such presses; but it is thought that the techniques and equipment developed for the small side bar-type press will be transferable to larger overhead beam presses without too much difficulty. Section 9.2 considers this in more detail.

Whether floor or overhead-mounted, however, the jointed-arm robot suffers from the following fundamental disadvantage in this application: Any force exerted on a cloth-bound deposit by a scraper at the end of a jointed arm will, in general, generate significant turning and bending moments in the extended jointed structure, requiring quite massive and expensive construction in an arm long enough to reach across the filter plates in common use (up to 2 m in width) if proper control of scraping is to be achieved.

Accordingly, after deciding on an overhead press access approach, gantry robots were considered. Gantry robots usually have very stiff structures readily adapted to resist scraping forces with little deflection; they are large scale versions of the Cartesian robot, one of the most straightforward robot configurations. An interesting variant described as a semi-gantry robot is offered by Reis [40]; here the conventional Cartesian axes are mounted at the top of a single column, rather than in a frame supported at many points around its perimeter, thus simplifying installation. Taking advantage of the simplicity of the Cartesian configuration of the gantry robot, many manufacturers offer modular systems which can readily be built to order [41]. Usually resembling overhead gantry cranes, gantry robots may manipulate complete cars, or inspect whole aircraft [38]. Unfortunately, gantry robots seem to be of more specialised application than the popular articulated type robot; fewer companies make them and they are very difficult to source.

Drawing up a specification for a gantry robot it was clear that an X-axis (longitudinal) motion was required, to move the scraping device along the length of the press, a Z-axis (vertical) motion was required, to lower the scraping device into the between-plate gap, but the Y-axis (lateral) requirement wasn't so clear. The Y-axis corresponds to horizontal movement across the face of a plate and many ways of achieving this were considered. These included pneumatic devices mounted on the robot Z-axis, and chain-driven scrapers moving away from the axis, (see Section 4.1).

During a visit to Crocus Ltd. (robot manufacturers), Dr. Macleod suggested a novel alternative to the conventional linear Z-axis; a vertical member with a lower section rotating about its lower end in a plane parallel to the filter plates. With the robot mounted centrally above the filter press the whole of a plate face could then be accessed without the need for a separate Y-axis motion as such. This idea was eventually rejected; cost, complexity and the adoption of a different scraping philosophy all counted against it. A more conventional, linear, Y-axis was specified.

The final area to be addressed in defining the robot specification was the need to clean both faces of each filter plate. In robot terms this meant rotation about the Z-axis so that the scraper could work in turn on opposing plate faces in the inter-plate gap. A fourth axis, R, was thus defined and a pneumatically operated rotation device chosen to fulfil this requirement.

An important advantage of Cartesian co-ordinate robots such as the gantry robot is its equal and constant spatial resolution, i.e. the resolution is fixed in all axes of motion and throughout the working volume of the robot. This is not the case with other co-ordinate systems used in robot design.

Cylindrical co-ordinate robots consist of a horizontal arm mounted on a vertical column, which in turn is mounted on a rotating base. The horizontal arm moves linearly, the carriage carrying the arm moves vertically up and down the column and these two units rotate as a single assembly on the base. The working volume of this robot is, therefore, the annular space between coaxial cylinders. The resolution of the cylindrical robot is not constant and depends on the distance between the vertical column and the wrist along the horizontal arm. A typical resolution at the extent of the arm would be of the order of 3 mm [42] using a 1 m arm and a standard resolution digital encoder. This resolution is two orders of magnitude coarser than is regarded as the state of the art in machine tools.

Spherical co-ordinate robots have a kinematic configuration similar to that of the turret of a military tank. The arrangement consists of a rotary base and a telescopic arm able to rotate (elevate) about an axis normal to that of the base. The rotation of this system is usually measured by incremental encoders mounted on the rotary axes. The working envelope of this robot is, therefore, a thick spherical shell. The resolution of this robot system is poor, relative to a Cartesian co-ordinate system robot, because there are two axes of poor resolution; the system resolution varies with the extension of the linear arm.

The revolute co-ordinate robot has a relatively low resolution since it has three rotary axes; the system's resolution depends on the length of the arms. The accumulation of joint errors through this system also results in it having the poorest overall resolution compared to other types of robot discussed here.

Although the gantry robot used in this work has the best resolution of all those systems discussed, this was not the reason for its choice, as has been explained. The excellent resolution of this system is a bonus but not necessary, given the nature of the work. Since a fairly large diameter (relative to the system's resolution) scraping device is being wielded against filter cake deposits on the filter cloths of a filter press, the necessary accuracy and repeatability of the system are relatively low, certainly compared with those required for electronics assembly, for example. Position errors in the vertical and lateral directions of the gantry system of the order of millimetres would not significantly affect this work. Such a low level of accuracy, or repeatability would be wholly unacceptable in many other fields of automation, however.

If one of the other configurations of robot previously discussed had proven to be better suited to this application, then the work would not have suffered by the adoption of, e.g. a revolute system, even with its intrinsically lower resolution than the gantry robot actually used.

This unexacting demand on placement precision in the scraping application of a robot stems largely from the relatively large diameter of the scraper (50 mm to a filter plate width and height of 500 mm) and the nature of the scraping action. Since a relatively large area of each filter cloth is addressed by one pass of the scraper, the accuracy with which the scraper is placed is relatively unimportant. The size of the scraper makes up for poor positioning, within reason. Obviously if the scraper were grounded on the wall of the recess, i.e. the rim rising from the recess floor to the gasketing face of the plate, a problem might result. Given that the order of magnitude of any inaccuracy is measured in a very few millimetres, this is unlikely to happen.

Accordingly, the accuracy of the gantry robot used in this work was not quantitatively investigated. The experience gained with the robot was sufficient to indicate that the accuracy of the robot was well within that required by the work and effort was directed elsewhere, rather than proving the actual accuracy of the system.

The elements of a gantry robot with X, Y, Z & R axes, a controller allowing simultaneous multi-axis control, a suitably designed scraper and controlling software, represented a comprehensive system meeting all the scraping requirements.

One factor thought to be important at some stage in the success of this work involved sensing the scraping forces. Monitoring and controlling the forces being exerted by the scraping device would help reduce the likelihood of cloth damage occurring. Possible means to achieve such feedback and control are many and varied.

As a first approach to such problems of controlling scraping forces, the merits of a robot using steppermotors fitted with encoders were considered against the expense and greater flexibility of servomotors. It was decided to pursue the servo option as the potential benefits were seen as being great. Force feedback is relatively simply obtained using such devices, there was in-house experience in this area and this local knowledge was to be drawn upon in the course of the work. The flexibility of the scraper, i.e. its rigidity or ability to ride-over lumps and bumps on the cloth surface, was also thought to influence the ultimate success of the research. Using servos it is possible to vary the spring rate of the device through software, rather than physically. Such potential was deemed important in development work such as this.

4.2.1 Sourcing the Robot

Finding information on robot suppliers proved to be a very time-consuming task. There appears to be a lack of reliable published reference material to aid the robot hunter. The few publications that were found were out of date and often led to time being wasted rather than saved.

The British Robot Association (BRA) seems to have lost many members over the last few years. Many listed in the latest BRA publication available had gone out of business; of those still trading, all contacted had left the BRA due to dissatisfaction.

A list of potential suppliers was eventually compiled from a number of sources. Each company was contacted and asked for a rough cost estimate for a 4 axis gantry robot of the required dimensions. Eventually the choice was narrowed to two systems. Both were gantry robots based on standard components and built in a modular manner. After visiting the two factories the choice was clear. For a system to carry out the required tasks, one of the robots was twice as large and twice as expensive as the other. It was decided to buy the cheaper and more compact CAM Systems Ltd. robot. Table A.4 lists some of the companies contacted during the search for a robot to the project specification.

An order was not placed immediately for the robot controller; the Departmental Laboratory Superintendent, Matthew Rea, recommended that a brand new product was purchased which was due for launch at the time the robot would be delivered, some months after the robot order was placed. The new controller was the 3-axis version of a previously released 2-axis controller which gave it the advantage of being state of the art technology, built upon a successful foundation.

The author and Dr. Macleod visited CAM Systems Ltd. to see the final stages of assembly of the robot and to check, with the aid of a mock-up of the laser scanner box, that all would be well with regard to mounting the scanning system.

A number of weeks later the author and Matthew Rea visited CAM Systems again, this time to check and accept the robot prior to delivery to the University.

The robot was delivered in November 1990 and installed on the framework built for it (Section 5.3). CAM Systems had expressed concern over the rigidity of this structure when they were told of the intention to mount a laser optical system on the robot. It was explained to them that the laser would only be in use when the robot was at rest and that vibrations in the structure due to robot motion were not of concern in this way. These reassurances proved well founded as the imaging system did not suffer from vibration problems during system testing and use.

The robot was mounted offset from the centreline of the filter press. This was dictated by the minimum practicable overhang of the operator's elevated fixed platform consistent with the limitations of the site. As described in detail in Chapter 5 the operator's desk, computer, control equipment etc., are all mounted on this platform. Despite this non-central position, the robot can still address all those parts of the press which it is required to access. Figure 4.2 illustrates the robot and its axis details.

4.3 The Scraper

It is particularly important that a filter cake dislodging device:

1. Is able to address all areas of a filter plate, e.g. awkward angles in recesses, and
2. Does not damage the filter cloth it is acting on.

When addressing the plates used in this work which have circular recesses (large filter plates usually have rectangular recesses) it is obviously appropriate to use a circular scraper. The advantage of a circular scraper over, say, a straight-edged one, is that it presents a scraping edge to all possible cake locations, regardless of its direction of travel. If a straight edge scraper were used to dislodge deposits around the rim of the bottom of the filtration recess, a small chordal area of the recess edge would be left untouched. Figure 4.3 illustrates the difference in performance between straight-edged and circular scrapers.

Another major and more general advantage of a circular scraper is that it can be fixed rigidly to the shaft carrying it; that is, the only local movement required of it is 180° rotation about the robot's vertical axis, to address the other cloth forming the filtration chamber. A straight blade would require to be oriented by some relatively elaborate and possibly slow-acting mechanism during every scraping move to ensure it was appropriately angled to the direction of scraping.

Figure 4.4 illustrates the scraping head used on the demonstration system. Note the compliant mounting between the scraper and its carrier. This was added to further reduce the possibility of cloth damage, by allowing the scraper to be deflected by stubborn deposits, rather than forcing its way through them.

Considerations of cloth damage likewise influence the choice of scraper material; a sharp-edged metal blade, for example, would not be appropriate. The material used in this work was an off-cut of hard rubber-based anti-vibration material used in the departmental workshop as pads between machine tools and the floor. The tradename of the material is 'Tico' and it was used because it met the requirements devised for a filter cake scraper, i.e. it is:

- easy to machine to the required shape and size, and
- rigid enough to scrape filter cake deposits from filter cloths while flexible enough to deform under severe load, thus avoid damaging the filter cloth.

Figure 4.5 illustrates the scraping assembly, i.e. how the head shown in Figure 4.4 relates to the vertical axis of the robot.

4.4 Scraping Logic

As stated earlier, (subsection 3.7.1), the only area of interest on a filter plate for this work was the floor of the filtration recess. The following explanations of scraping actions, therefore, only apply to this area. It would be a simple task to extend the coverage to the whole of a filter plate.

'When to scrape' has already been established. If an object is identified as a significant cake-fragment, it is scraped. It should be understood, however, that a number of checks can be added to the image analysis procedure to limit the number of objects identified for scraping. The area, perimeter, circularity and centroid location are a few of the measurements which can be used to accept or reject an object as a scraping target. The most obviously useful of these characteristics is area, since this can be compared to a reference threshold value and the object ignored if its area is smaller.

How a filter cake fragment is scraped off a filter cloth depends on its location. The location of the fragment is taken from the data supplied for each object detected by the image analysis program. This data yields the centre Z, centre Y, minimum Z, minimum Y, maximum Z and maximum Y for each fragment. These values allow a bounding rectangle to be applied to each fragment to aid visualisation. Figure 4.6 illustrates this.

It was necessary to designate one part of each fragment, or rectangle as it is represented after image analysis, as the target for the scraper. Which point on or in the rectangle is targeted potentially affects the success of the scraping operation. If a very low point (large Z value) is used the scraper may become unnecessarily fouled, affecting subsequent scraping moves. The accuracy of location of the fragment rectangle must also be considered when choosing a target point. One consequence of the STRIPE system working at a very small angle to the vertical filter plates is the exaggerated apparent depth of each detected object.

This lengthening results in Centre Z and Maximum Z values for each rectangle which are slightly larger than they should be. The most accurate 'real-world' co-ordinates are, therefore, Minimum Z and all the Y co-ordinates. Minimum Y and Maximum Y were not felt to be the best scraping target points, hence the target co-ordinates used are, Centre Y and Minimum Z, i.e. the middle of the top edge of the fragment bounding rectangle.

This point was thought to be ideal for the first point of contact between the scraper and the fragments being removed. In many instances the cake fragment will be wider than the diameter of the scraper. Applying the scraper to the centre of such a fragment is thought to offer the best way of dislodging the whole fragment in one scrape.

It was observed many times during site visits that operators did not have to scrape the full extent of cake fragments. By using their experience they were able to apply the scraper in such a way that a small amount of effort on their part led to large deposits being removed from the filter cloths. Such judicious use of their scrapers was based on approaching the deposit at its highest point (but by necessity from the side of a press) and prising a portion of it off the cloth. The flexible nature of the filter cake (the majority of observations were of sewage sludge cakes) means that it rarely tears and breaks off the main cake mass, but starts a peeling action of the main mass as it falls. This self discharging action is an important factor in press discharge cycles; if every part of every cake had to be scraped manually discharge times would be significantly longer.

To some extent the scraping philosophy developed in this work attempts to take advantage of the cake peeling effect, hence the above mentioned choice of deposit target point. By making one scraping pass through each deposit it is hoped that the whole deposit will be removed. This approach saves a great deal of scraping and can be adopted with confidence if a post-scraping imaging scan is assumed. By imaging a cloth after all the deposits identified in the first scan have been scraped, the success of the scraping can be quantitatively assessed. At worst the situation may not have changed (though this is unlikely); at best all previously identified deposits will have been removed. Between these extremes are cases where part of a deposit has been removed. Here the peeling effect has not worked and only cake in direct contact with the scraper has been discharged. This will create a new image, with the 'new' deposits then being identified and addressed by the robot.

Targeting the top edge of each fragment implies that the scraper is always moving down the cloth to the target point. This is part of the scraping philosophy. Wherever possible, the scraper is brought to bear on fragments from above. This allows fragments to fall unimpeded into the discharge hopper, scraper fouling is minimised and control of the fragment's discharge direction is maximised. Furthermore, with vertical scraping the reaction to the scraping force is transmitted to the robot nearly along the axis of the scraper shaft, minimising bending stresses in the structure.

It is not, however, always possible to scrape straight down at a deposit's target point. The scraper must be 'grounded' on the cloth above each deposit so that its first contact with the deposit results in a prising action between the deposit and the filter cloth. Ideally, a simple vertical offset, equal to the scraper's radius, would be subtracted from the target point's Z co-ordinate to determine the point at which the centre of the scraper meets the cloth (the grounding point). This ideal grounding point for a deposit, however, may be outwith the filtration recess and on the raised sealing face of the plate. 'Straight down' scraping is then impractical. This problem is obviously not limited to circular-recessed plates, but the solution is complicated somewhat in this case.

A zone system was developed, whereby the grounding point of the scraper is chosen according to the position of the target point of the deposit and the nature of the scraping action. The zone system is illustrated in Figure 4.7.

Point A represents the centre of the filter plate, AB is the radius of the filter cloth seam round the slurry feed hole, AC is the radius within which a target point must lie if that deposit is to be scraped vertically downwards, AD is the maximum radius of the path of the scraper centre (beyond which the scraper would foul the rise from the recessed filtration area to the sealing face), AE is the bottom edge radius of the filtration recess and represents the limit of the scraping area, and AF is the radius of the top edge of the filtration recess, i.e. its outer rim in the plane of the filter plate's sealing face. The type of scraping move to be used is determined by which of these radial zones and which of the sectors WAX, XAY, YAZ, and ZAW the deposit occupies.

Vertical linear scrape

If a target point (TP) lies within the circle of radius AC a vertical downward scrape is possible, since subtracting the radius of the scraper still leaves the Z co-ordinate of the scraper-centre grounding point (GP) within the circle of radius AD. If the TP lies on the circle AC the GP is set to lie within or on the circle having radius AD, but with the same Y co-ordinate as the TP.

All vertical scrapes must be limited to ensure that the scraper does not foul the cloth seam round the feed hole, or run into the wall of the recess. The latter condition is met by limiting the vertical travel of the scraper centre to the length of a vertical chord of circle AD having the Y - co-ordinate of the target point.

If the scraper's path cuts circle of radius AB, the scraper would foul the cloth seam and must be further limited. An overshoot into the circular seam in the upper half of the plate is prevented by arranging the scraper's downward path, of given y co-ordinate, to terminate where it cuts circle AB. If the computed GP puts the scraper inside the seam circle AB, the GP location is corrected so that the scrape starts below the seam.

Circumferential scrape

A deposit with a TP outwith the circle of radius AC cannot be scraped linearly, since grounding the scraper 'above' the TP would foul the recess wall. A different type of scrape was developed for this situation, the circumferential scrape.

The circle with radius AD is the path followed by the centre of the scraper during a circumferential scrape. Where on the circle the scrape starts and stops, and in what direction it proceeds, are determined by the size and position of the deposit.

Two types of circumferential scrape are used, horizontal and vertical. Vertical scrapes are always carried out such that the scraper moves down against a deposit. Deposits with a TP within the areas WAZ and XAY, but outwith the circle of radius AC, (Figure 4.7), are scraped with a downward circumferential motion. Deposits with a TP within the remaining areas, WAX and ZAY, are scraped with a horizontal circumferential motion. The direction of scraping in this last case, i.e. clockwise (CW) or counter-clockwise (CCW), depends on which side of the plate's vertical centreline the deposit's higher point lies.

The method of calculating the GP so that the scraper does not land on the deposit prior to scraping is different from that used for linear scrapes since a subtraction from the appropriate Z co-ordinate is no longer valid. Instead of trying to land the scraper above the deposit it is grounded beside the deposit, i.e. the GP is calculated by subtracting a scraper radius from the Maximum or Minimum Y value, depending on which is nearer the centreline of the plate. The Z co-ordinate of the GP is then calculated to lie on the circle of radius AD at this Y value.

The Z co-ordinate of the end point of a circumferential scrape is calculated as for a linear scrape; the Y co-ordinate of the end point is taken as the Y value which will keep the scraper on circle AD when at the appropriate Z value.

4.4.1 Examples

Consider the deposits bounded by rectangles K, L and M in Figure 4.8. Each deposit will be scraped differently. K would require a CCW, horizontal, circumferential scrape, L would be a simple vertical scrape and M would require a CCW, vertical, circumferential scrape.

The target point for each deposit is also shown in the Figure as a cross in the middle of the top edge of the bounding rectangle. Calculating the grounding point for each deposit would be done as follows.

Grounding Point, Deposit K

The TP for deposit K lies outwith the circle of radius AC (Figure 4.7) and therefore cannot be scraped vertically downwards. The TP lies within the area WAX and is, therefore, accessible by a horizontal circumferential scrape. The vertical centreline of the deposit is to the left of the centreline of the plate, hence the GP will be to the right of the plate's centreline. This ensures that the scraper will be moving down through the deposit for the greatest possible amount of its travel. The Y co-ordinate of the GP is thus calculated by subtracting the scraper's radius from the Minimum Y value for this deposit. The GP Z value is found by solving the equation of the circle (radius AD) at this Y value. The resulting GP, scraping path, direction and extent are illustrated in Figure 4.9.

Grounding Point, Deposit L

The TP for this deposit lies within the circle of radius AC and can, therefore, be addressed by a vertical downward scrape. The Y co-ordinate of the GP is simply the deposit's Centre Y value, and the Z value of the GP is found by subtracting the scraper's radius from the Minimum Z value for the deposit. The resulting GP, scraping path, direction and extent are illustrated in Figure 4.9.

Grounding Point, Deposit M

The TP for this deposit lies outwith the circle of radius AC, but within the area WAZ. A vertical, CCW, circumferential scrape is therefore needed. The first co-ordinate of the GP to be calculated in this case is the Z value, i.e. the reverse of the process for a horizontal scrape. The GP Z value is found by subtracting the scraper's radius from the deposit's Minimum Z value, the Y value by solving the equation of the circle of radius AD to find the Y value at which the corresponding Z value lies on the circle. The resulting GP, scraping path, direction and extent are also illustrated in Figure 4.9.

4.5 Controller and Software

The power and flexibility of the software responsible for making scraping decisions and controlling the robot is an important factor in the success of the scraping function.

The robot controller used was the Programmable Multi-Axis Controller (PMAC) from Delta Tau Data Systems Inc. This powerful controller card has many useful features, including its own programming language, a 'user friendly' interface program, easy access to its thousands of variables and on-board memory for motion program storage. The card can communicate with external software for bidirectional passing of variable values (without the user running the menu-driven 'front-end') and uses variables in its motion programs thus allowing run-time flexibility, i.e. speeds and positions need not be preset in a program, they can be accessed and changed during robot operations.

The interface program was very useful in developing motion programs. The built-in program editor was used to code the programs prior to down-loading them to the controller's memory, and on-line help was available when things went wrong – a particularly useful command being 'why is the robot not moving?'. Instant access to the status of the motors, outputs and all other robot settings was also available through the interface.

The two most important features of the controller for this work were the facility for parameterisation of motion programs and its accessibility by external software. By using variables in the scraping programs rather than values, the scraping programming was greatly simplified. One program for linear scraping and one program for circumferential, or arc, scraping were all that was needed. The start point and end point of the scrape are passed to the appropriate motion program by the post-image analysis code. With this communication facility the PMAC can be accessed at any time, motion programs can be initialised and run, and information fed back to the user's software, e.g. robot position, outputs on or off, etc.

4.6 Plate Shifting Device

A common feature of all filter presses claiming to be automatic is a plate transfer device. This is a mechanism which sequentially moves filter plates away from the compressed stack of plates after filtration to facilitate cake discharge and cloth cleaning. On large presses, whether automatic or not, such a device is a necessity; a 2 m square filter plate is a very substantial component, typically having a mass of around one tonne and thus immovable by hand. Small presses (0.5 m square filter plates) are not so equipped since operators are expected to be able to move the plates manually.

Impressions gained from plant visits and operators' reports are that many plate shifting devices fitted to large presses do not work particularly well. With side bar presses it appears that the most common mode of plate transfer failure is that one of the pair of side lugs on a plate fails to be engaged by the shifting device. This leads to one side only of the plate being pulled away from the compressed stack, a dangerous situation since this 'crabbing' can in extreme cases lead to the filter plate falling out of the press altogether.

Although not essential for the development and evaluation of the scraping system, a simple, safe, plate shifting device was required for the development filter press in order that a fully automatic press discharge system could be demonstrated. Such a system is obviously required for small presses if operators are to be withdrawn from day-to-day operations. Given that small presses are not supplied with plate transfer devices, there is a requirement to supply retrofit systems to customers installing a robot discharge system such as proposed in this work. Effort was directed at designing a filter plate transfer system more reliable than those already in use on large filter presses and which would be simple to retrofit to existing installations.

The power, controllability and ready access to the side bar filter press of the gantry robot made it ideal in principle for shifting the filter plates. The first design approach, therefore, was to consider the robot pushing or pulling each plate in turn away from the compressed stack, using a specially designed appliance on the robot to act on each plate in turn. This approach was soon abandoned, since the frictional force opposing the sliding of plates along the side bars of the press and the distance of the robot carriage from the plates' lugs would result in unacceptably large bending moments acting on the robot. This difficulty is overcome by eliminating the friction force of the plate pins or lugs sliding on the press' side bars. Contact reaction between the plate lugs and the side bars is reduced by application of an upwards vertical, or lifting, force to each plate. This force is supplied by pneumatic cylinders suspended from the robot carriage. The plate lugs do not have to be lifted clear of the side bars of the press, although this did happen on the development rig; the intention is that the plate mass is partly borne by the cylinders, thereby reducing the frictional load opposing the sliding of the plates along the side bars. With the frictional force greatly reduced, or possibly eliminated, the main force acting on the robot as it moves a plate is simply a vertical load. The robot structure is well able to withstand such a load and since the lifting force is provided by pneumatic cylinders the robot's motors are not required to cope with greatly increased duties.

As illustrated in Figure 4.10, a hollow, square-section cross-member (A) is fitted between two of the robot's bogies and two square-section tube vertical members (B) extend downwards almost to press side bar level from it. Each of the vertical members, B, has another shorter but larger square tube telescoped outside it (C). The larger tubes, C, extend below the ends of the smaller ones, B, such that their lower ends reach below the level of the filter plate support lugs resting on the side bars of the press. The bottom of each larger tube is fashioned into a lifting hook which, in its default low, or down, position, clears the lugs during longitudinal motion of the robot. Two pneumatic cylinders (D), one per leg, act on the larger tubes, C, so as to lift these when air is supplied; when the air is removed, the tubes drop due to their own mass.

To move a filter plate, the robot moves the lifting lugs into position under the pins of the appropriate plate by moving longitudinally; air is applied to the cylinders, the tubes rise, collecting the pins on the hooks and so lifting or 'taking the strain' of the plate; the robot moves to the required position where the air is exhausted; the cylinders retract, the tubes and hence the filter plate drop and the plate is left in the required position.

It would be desirable to add sensing devices to the shifting lugs in production mechanisms to ensure that the pins are always correctly engaged and that slewing of the filter plates does not occur. Interaction between the shifting device and the machine vision system would also be possible, to signal when the plate was not travelling correctly. Such interaction may, however, be too complex and not really justifiable when simpler solutions are available.

One unexpected but important observation made during site visits was the occasional double shifting of large filter plates by automatic mechanisms. In some cases when the the leading plate was pulled from the compressed stack the plate behind it would also be pulled as the adhesion of the filter cake to both cloths was sufficient to cause this. The secondary plate did not travel the full width of the gap between the compressed stack and the discharged stack with the 'driven' plate, but nevertheless did move two or three inches away from the compressed stack. This has obvious implications for an automatic discharge system. As the inter-plate gap is reduced it will affect both the scanning and scraping actions. It is thought that the plate transfer mechanism described will avoid problems of double shifting because the shear force between a filter cake and the two filter cloths enclosing it, generated during plate lifting, should break the bond between the cake and at least one of the cloths and allow single plate shifting.

This argument is really only applicable to the retrofitted plate shifting mechanism described here. Plate lifting was achieved by accident rather than design. The intended action had been simply to apply a vertical force to the filter plates to reduce the friction loading between plate pins and press side bars. Had this been the result the potential advantage of a substantial shear force would not have been available. Some measure may, therefore, need to be taken to prevent "double shifting" of filter plates if this phenomenon is apparent in the operation of a non-lifting, plate shifting device.

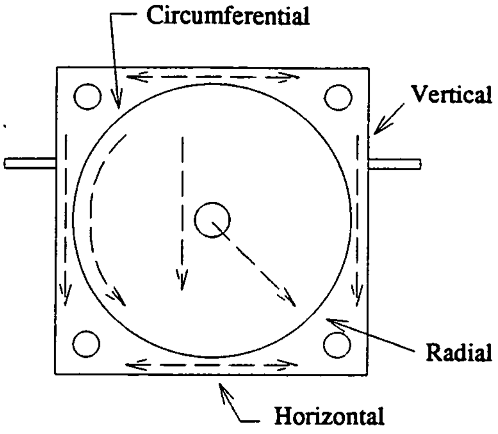


Figure 4.1: Possible scraping directions

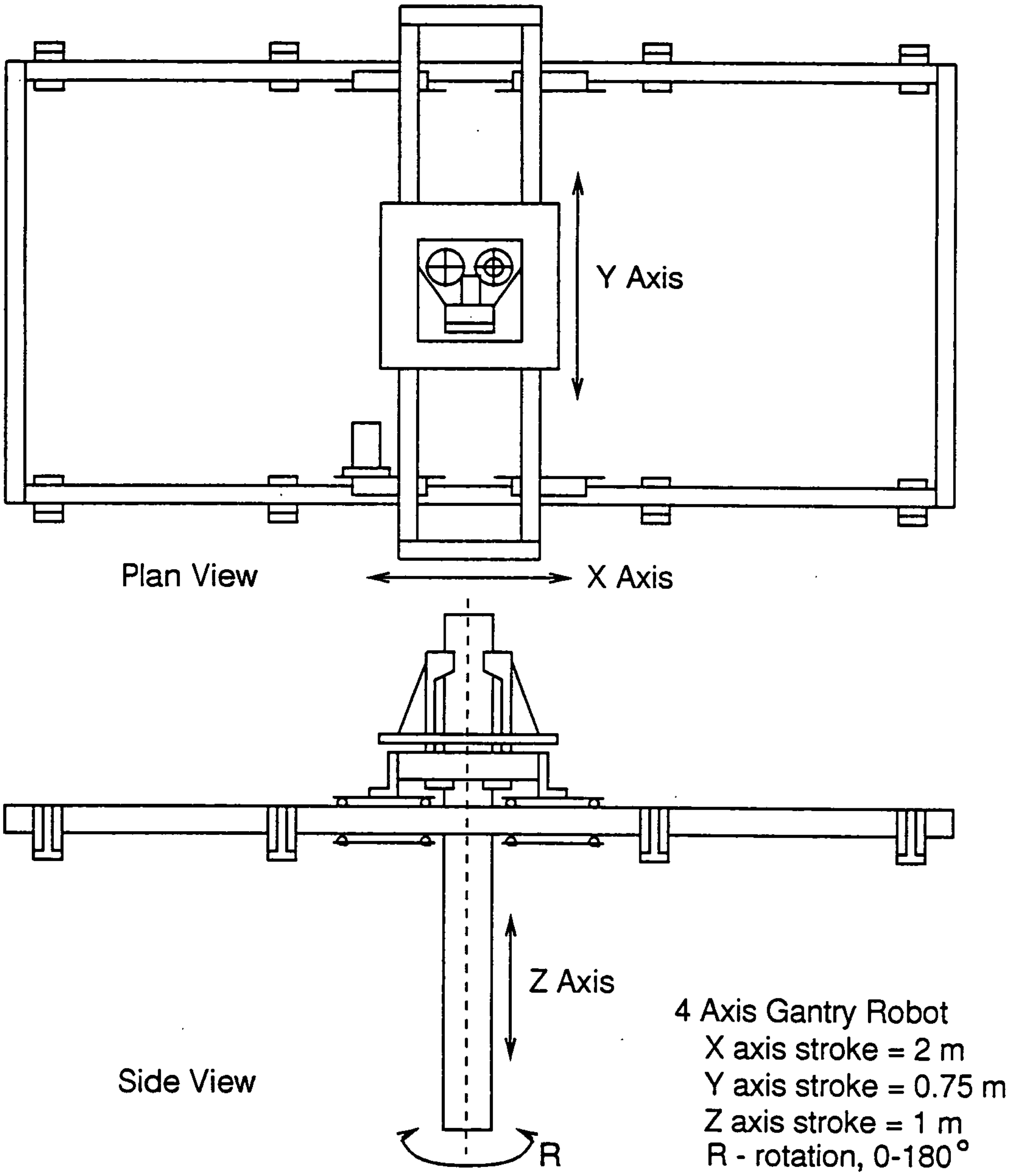


Figure 4.2: Illustration of 4 axis gantry robot used in research

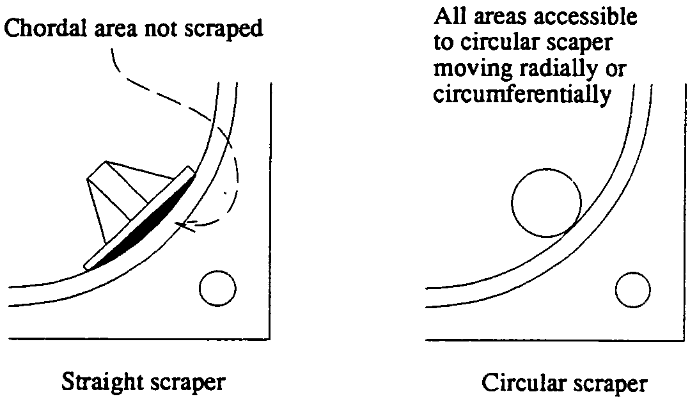


Figure 4.3: Advantage of a circular scraper

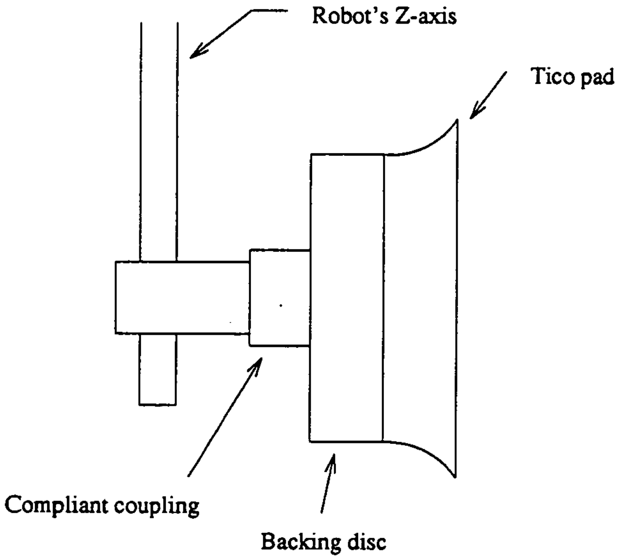


Figure 4.4: Scraper head

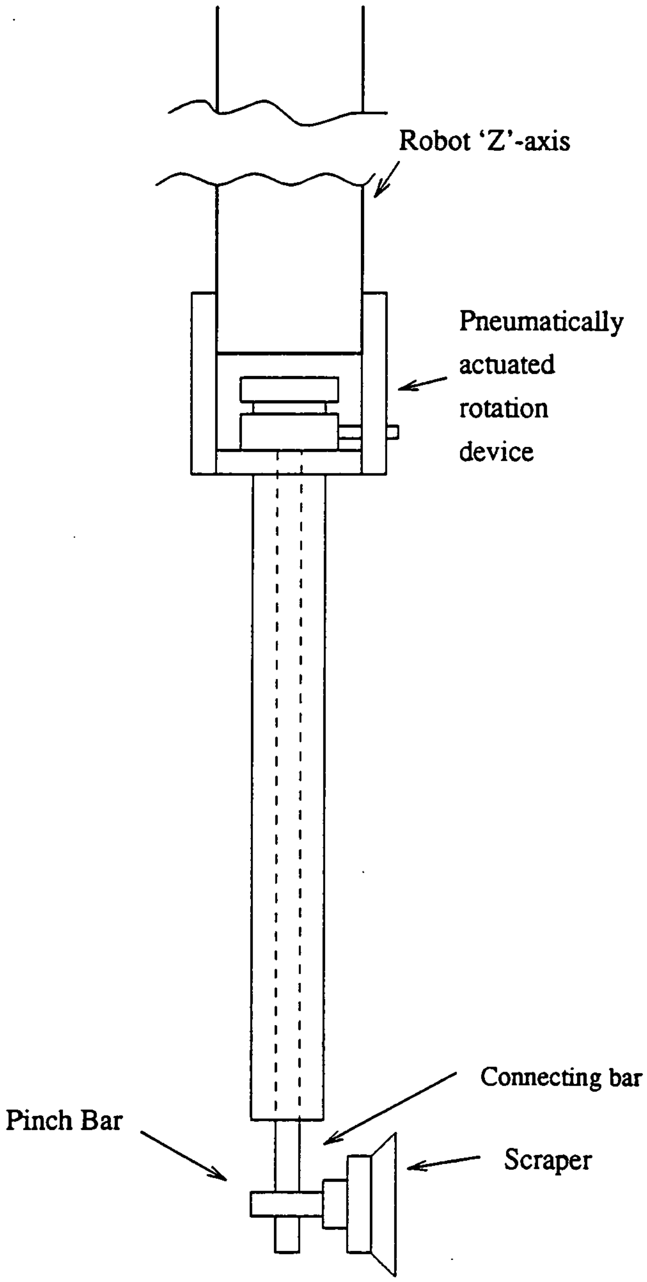


Figure 4.5: Scraper assembly

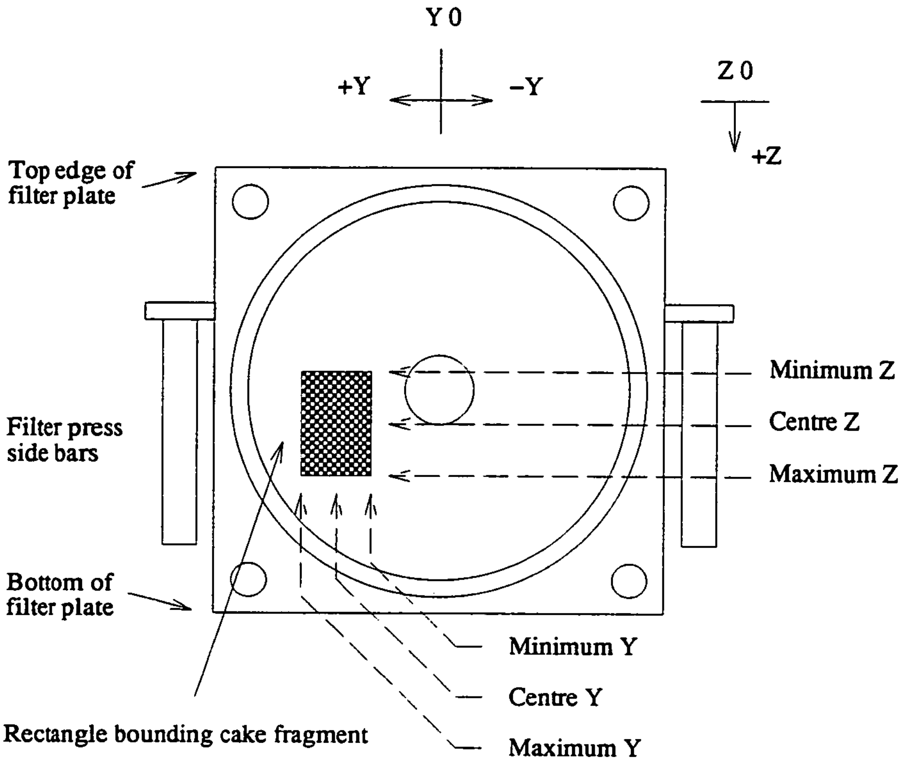


Figure 4.6: Rectangle bounding a cake fragment

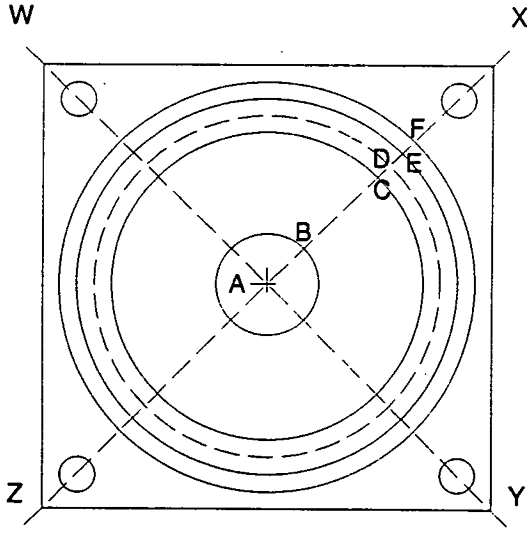


Figure 4.7: Zones for calculating grounding points and determining scraping moves

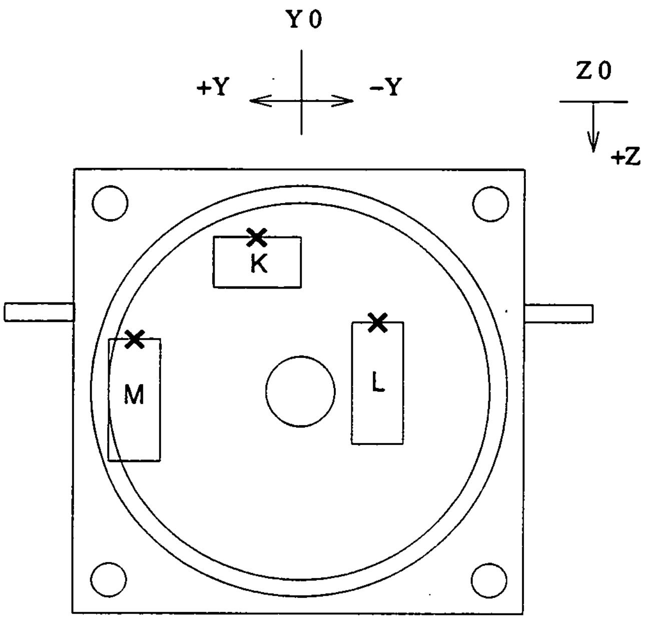
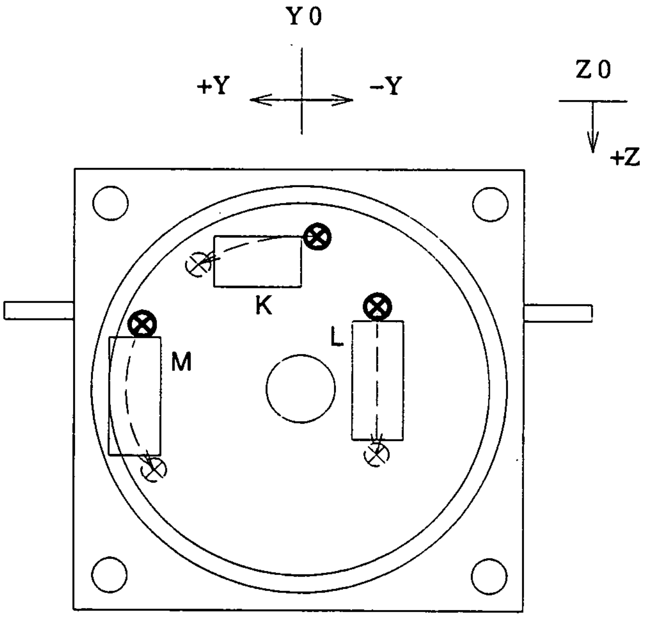


Figure 4.8: Scraping examples - deposit boundaries



K, L & M are the bounding rectangles of filter cake fragments

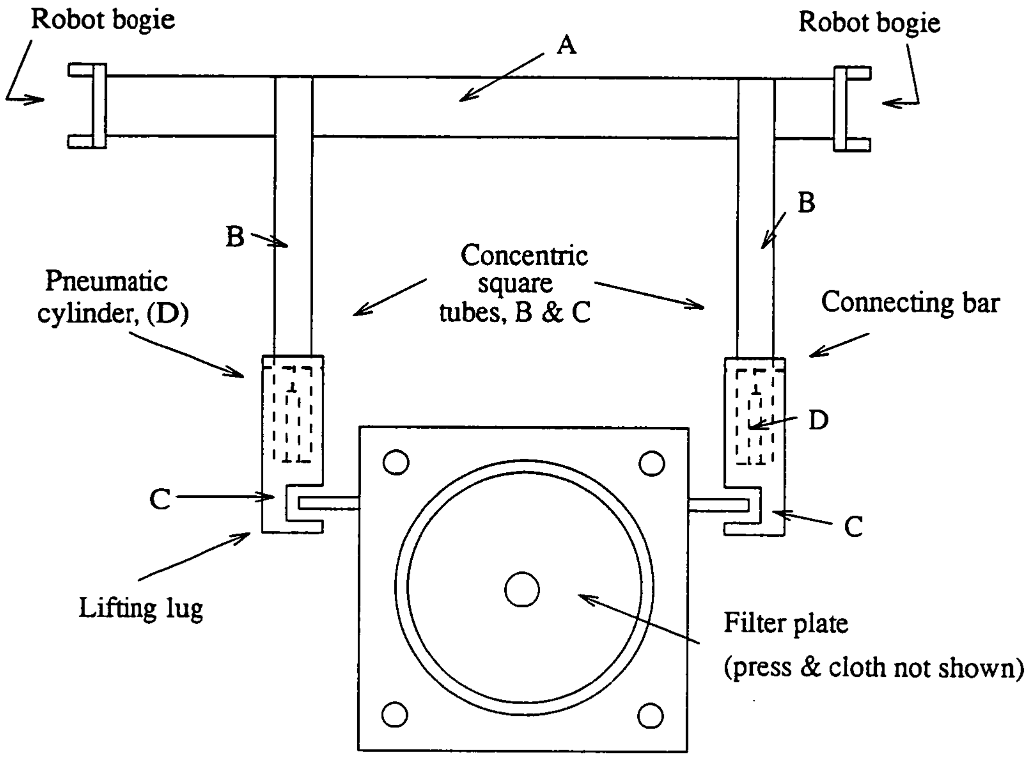
⊗ = Grounding Point of scraper

—> = Scraping path

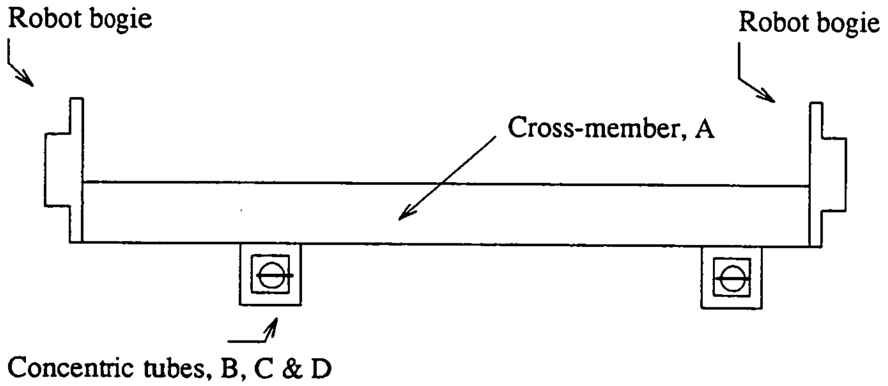
⊗ = End point of scrape

Figure 4.9: Examples - Grounding points and scraping paths

NOTE: Illustration is not to scale



FRONT VIEW



PLAN VIEW

Figure 4.10: Plate shifting assembly

Chapter 5

Equipment and Rig Layout

5.1 Filter Press and Associated Components

This project's concept required a robot to service a group of small filter presses. As discussed in subsection 2.1, the smallest filter presses of production interest have plates 0.5 m square, which may have the membrane inflation option described in subsection 1.1.1. The membrane plates do not have to be inflated, therefore both squeezed and non-squeezed cakes can be produced from the same press. By choosing a press equipped with membrane-type filter plates the capability to study filter cakes of very different moisture content at discharge is available.

After studying the cost of new filter presses, investigating the cost and availability of second-hand presses and consulting users about the possibility of the loan of a press, a 0.5 m square membrane plate equipped side bar filter press was acquired under a collaborative agreement with British filtration equipment manufacturers Edwards & Jones Ltd. of Stoke-on-Trent. The press was completely manually operated and did not have a core blow facility. It did have a cake washing facility, and used a single hydraulic ram to close the press and maintain the closing pressure on the filter plates during filtration.

Various items of equipment are required for the operation of a filter press, e.g.

a slurry feed pump, slurry and filtrate vessels, slurry mixers etc. The specification of these items is outlined below. Figure 5.1 shows the flowsheet for the filter press and its associated equipment as used in this work. The numbers shown beside each valve correspond to the numbers on tags attached to or very close to each valve on the press and its attached pipework. This simple system was extremely useful in quickly and accurately identifying valves during press operations. Despite initial concerns about the slurry supply line pressure gauge getting clogged with sludge, this did not happen. While it is true that valves 1 to 4, 6 and 8 appear to be a recipe for disaster, they are necessary for filter cake washing and press flushing operations. Great care was taken to ensure the correct state of all valves associated with the filter press before each operation was initiated.

An air driven diaphragm pump was sought for press-feed duties. These positive displacement pumps are suitable for pumping fluids with high solids content, as with slurries for example. Table A.1 gives details of the suppliers contacted. The chosen pump has a dry suction lift capability of 5 m, wet lift 8 m and can pump at up to 53 l/min.

The pressure and volumetric flow-rate of the compressed air in the air-line in the laboratory were insufficient to drive the diaphragm pump, so a compressor was purchased for this task. Please see Table A.2 for details of compressor suppliers contacted. The compressor chosen is a 2 HP, 50 l capacity, 6.8 cfm free air, 115 psi maximum working pressure, single phase, portable unit.

The compressor is also used to provide the air for membrane inflation, i.e. cake squeezing, at the end of filtration. Other compressor duties are: supplying air to the pneumatic cylinders in the filter plate shifting apparatus described in Section 4.6 and powering the small rotation unit housed in the robot's Z (vertical) axis to effect rotation of the scraper head mounted at the bottom of the axis.

Two vessels are used for filtrate handling; a small intermediate floor-mounted tank and a large overhead storage tank. The filter press is installed with the ram end higher than the fixed end plate end. The difference in height is very small, less than 20 mm, but is sufficient to create a gradient longitudinally through the press which allows filtrate to drain through the press by gravity. This filtrate drainage exits the press at the pipework end (both slurry in and filtrate out are at the same end of the press) into the floor-mounted intermediate tank. This tank is equipped with a level sensing device which controls a pump connected to a pipe from the bottom of the tank. As can be seen in the press flow-sheet diagram (Figure 5.1) the output from the pump is piped to the large overhead filtrate storage vessel. This tank is large enough to hold all the filtrate from one tank of slurry. The overhead position for the large tank was chosen for two reasons; lack of floorspace and convenience of gravity transfer of filtrate back to the slurry tank which is positioned directly underneath it.

A 205 l cylindrical polypropylene tank was purchased to act as the slurry tank. A bogie built from 'Handy Angle' with sides completely enclosing the tank provides the tank with protection from accidental impact, supporting points for various pipes and fittings, and a means of manœuvring the tank when it is full of slurry.

After considering various methods of slurry mixing and agitating, a pneumatic approach was adopted. Mechanical devices involving blades, motors and gearboxes were considered to be too expensive. A static agitating device using compressed air injected into the slurry through submerged nozzles was built and used to maintain the slurry in suspension.

The device consists of a vertical downpipe, 25 mm diameter, with a pneumatic coupling at its top end, and a cylindrical chamber, 75 mm diameter and 25 mm high, at its bottom end. Four 12 mm pipes are attached radially to the chamber, equally spaced round its circumference, in a horizontal plane. Along the length of the four radial arms are holes, drilled such that they all faced toward the bottom of the slurry tank. When compressed air is supplied via the top coupling it passes down through the vertical member, which also serves as the principal support for the device, and via the distribution chamber into the four radial pipes, exiting through the holes drilled along their lengths and out into the slurry.

The downpipe of the agitator passes through the horizontal support, and is held in place by two collars both of which are above the support; one is attached to the support, the other is screwed down against the fixed collar. Between the collars, and round the downpipe, is an 'O'-ring. When the two collars are tightened together the 'O'-ring is deformed and thus grips the downpipe. Although simple, this arrangement is extremely effective, the agitator is well supported and does not suffer problems of vibration.

The level of slurry in the slurry tank varies greatly during a filtration cycle, usually full at the start and almost empty at the end. The twin collar clamping arrangement for the downpipe allows the depth of the agitator, i.e. the vertical position of the four radial arms, to be varied very easily; although the device was usually left almost at its full depth at the bottom of the slurry tank during this work.

The pneumatic device was very effective as an agitator, i.e. maintaining the suspension of the solids in the bulk liquid, but didn't perform so well as a mixer, i.e. getting the solids and liquids into suspension. For this latter purpose a long handled wooden spatula was fabricated to allow the operator to mix the slurry thoroughly before, and if necessary, during filtration. The air supply used for the device was taken from the mains air available in the laboratory; although this didn't have particularly high pressure it offered a slightly higher volumetric flowrate than the compressor bought to drive the diaphragm pump. A higher pressure and higher capacity compressor would undoubtedly offer advantages in slurry agitation using the device described here.

G. H. Heath & Son (UK) Ltd. manufacturers of filter cloths, generously supported the research with a gift of four sets of filter cloths. The four types were;

- N° WWPP972, 100% monofilament
- N° WWPP728, 100% monofilament
- N° WWPP989, a monofilament/multifilament combination
- N° WWPP814, a staple/multifilament combination

Each cloth type results in different discharge characteristics for any given slurry – enabling a range of situations to be investigated.

To compliment the four cloth types, four kinds of slurry, which it was thought would give representative results for cake discharge, were identified. They were;

- Bauxite
- China clay
- Titanium dioxide
- Brewer's yeast

Companies were found who were prepared to gift quantities of these materials to the research as follows.

- B. A. Chemicals Ltd.
- E. E. C. International
- Tioxide UK Ltd.
- D. C. L. Yeast Ltd.

With a potential total of sixteen filtration and discharge options it was felt that a wide research base was available. Not all the cloth types are suitable for successfully filtering each slurry, however, and therefore in practise the total is less than sixteen.

Returning discharged filter cake to the slurry tank for the next filtration cycle is achieved with a wheeled hopper. The hopper sits under the press and collects the discharged solids. After discharge, the hopper is moved from under the press to beside the slurry tank and the filter cake transferred manually for re-slurrying. The hopper is a proprietary item described in the supplier's catalogue as a bar trolley, i.e. of the type often used as an empty bottle repository behind the bar of a pub! Very fortuitously such a hopper was found with exactly the right dimensions to slot under the research press. The hopper body is a one piece plastic moulding, like a bath fitted with four castors. The moulded nature of the hopper is particularly advantageous since it does not leak if any fluid drips from the press.

5.2 Computing requirement

A Hewlett Packard Vectra QS20, 80386, 20 MHz PC (Personal Computer) was procured to provide the basis of the computing requirement for the whole project. The DOS operating system was used throughout the period of the research. The wide availability of software packages and add-in boards for PCs, coupled to the real-time nature of the DOS operating system were major factors in rejecting UNIX-based computers, e.g. SUN workstations, in favour of a stand-alone PC. Interfacing PCs with external devices, such as laser-imaging systems and robots, is generally accepted as being cheaper and more straightforward than with SUN-type workstations.

An 80387 maths co-processor, digital input/output (I/O) card and 4 Mb of RAM were added to the computer to enhance data acquisition and the performance of image analysis software. The I/O card reads the laser-generated image data into the computer while the extra memory and co-processor aid the storage and manipulation of this data.

Using the PC-NFS add-in card and software, the PC was linked to the departmental computer network, thus giving access to many more resources, e.g. laser printer, SUN workstations and increased disc storage.

The development of original software required during this project was carried out using the C programming language. Two compilers were required; one was available in the department, the other was purchased. The image analysis program was written in Microsoft C; all other programs were written using Borland's 'Turbo C'. Two dialects of the C language were used because at the time of ordering the image analysis package was only available in Microsoft C and a considerable amount of Turbo C code had already been written to control other items of equipment, e.g. the imaging system (acquisition).

5.3 Layout of Apparatus and Rig Structure

The main limitation imposed on the layout of the apparatus was the lack of space available for the rig in the laboratory.

The minimum floor space required for this apparatus is dictated by the size of the filter press and the need for access all round it. Added to this is the space required by an operator, operator's desk and any other equipment which must be floorstanding, e.g. the robot control cabinet. This space was not available in the corner of the laboratory given over to this work because of the proximity of a fire exit. In order to maintain access to this exit, the operator, a desk, and all computing and control equipment were located on a platform built over the exit route. The design of the structure can be seen in Figures 5.2, 5.3 and 5.4. These figures are scanned images of the original specification drawings created by the author for workshop personnel. The access gate to the main (lower) area is not shown in these figures, but all other salient features of the structure are illustrated. The elevated control platform was adjacent to, and integrated with, a substantial space-frame enclosing the press and all hydraulic and mechanical equipment, caged with mesh and a lockable gate.

This type of structure was thought to be ideal for an investigative project of this kind. The scraping robot is of the gantry, i.e. overhead, style, hence it is readily mounted on a spaceframe structure such as this. Also, because of the 'envelope' nature of the frame, mounting positions for other items of equipment, either at the time of original construction or later in the development phase when trying new ideas, are readily available. Moreover, the space frame, panelled externally with wire mesh, prevents accidental contact between people and the robot. Rig safety is discussed later in this section, and it is felt that the frame and cage design is a major contributor to this.

The need for a black-out is discussed in Section 7.2. Curtains were hung from the upper members of the robot-supporting frame extending round the three 'open' walls. A near-opaque fabric (tent groundsheet material) was used. A ridge-roof frame was built on top of the robot-frame to support the same type of material above the robot. With the exception of the operator's working area platform, the rig was thus entirely enclosed.

With curtains round the cage and a 'tent' roof above, the ambient light level inside is greatly reduced, as benefits the operation of the laser system. Inspection lights were fitted to the lower and upper areas of the rig, controlled by two-way switches, one on the platform and the other in the cage.

Preventing collisions between people and moving manipulators is one aspect of the safe operation of robots. The most commonly used and best developed electro-sensitive safety system for guarding robots is the photo-electric curtain [43].

Photo-electric curtains work by detecting obstructions in the paths of beams of light. An appropriate example of a filter press guarded in this way is that installed by Edwards & Jones Ltd. in Grimethorpe Colliery; this press is guarded by a Lightguards Ltd. photo-electric curtain [44].

Such devices are ideal for teaching situations as a physical barrier is not present, hence viewing of the guarded machine is unrestricted. One of the characteristics of these safety systems, however, is that they require a stand-off distance from the guarded machine. Working from the appropriate HSE guidelines [45] in the robotic discharge installation this distance would have been 1.2 m from the robot's working envelope. Unfortunately the restricted space in the laboratory did not allow such a relatively large distance. A further drawback of photo-electric systems is their high cost, as can be found in Table A.3. This guarding option was discarded for these reasons.

Warning notices relating to both the robot and the laser system are posted outside the cage in two prominent locations to advise of the dangers inside the enclosure and to state that unauthorised access is not permitted.

The only entry to the cage is through a substantial padlocked gate, fitted with an interlock device which is wired into the robot's emergency stop circuit; this causes all power to the robot to be removed as soon as the gate is opened. This power removal approach is acceptable because the robot stops instantly and does not require power to maintain position when under load.

Provision was made for personnel being in the cage while the robot is under power. Although this situation was not required during this research it may be necessary or advantageous during future stages of development. An emergency stop switch was installed inside the cage and two other emergency stop switches are installed on the outside of the cage, positioned where people would be likely to be standing to observe the robot's operation (as long as the black-out curtains were open to allow such viewing). A fourth emergency stop in the robot's circuit is the main on/off switch on the robot's control cabinet situated on the elevated platform. Thus the robot can be stopped by personnel positioned above, inside and round the perimeter of the cage. This arrangement proved entirely satisfactory during this period of the work.

To reduce the likelihood of someone inadvertently stepping off the elevated platform, it was protected by a railing and a safety chain was fitted to the entrance. Although this must be engaged by a deliberate rather than an automatic action, it is felt to be appropriate for the situation. Notices at the platform entrance and on the platform advise that the chain should be engaged whenever personnel are on the platform. It would be a relatively simple matter to fit a self closing barrier in place of the safety chain if this was later judged to be more acceptable.

The access ladder to the platform is a proprietary item, following a standard gradient, i.e. the ladder is the correct length for the 2 m vertical interval. The only special specification for the ladder was the height of the hand rails. The standard height, i.e. offset from the plane of the ladder, of the hand rails was felt to be too small, and much longer ones specified. This decision proved to be a good one; carrying equipment to and from the platform is much easier and safer than if the standard hand rails had been used. Unladen access also benefits greatly.

To take advantage of the camera mounted in the laser system, i.e. to look at the monitor to get a different view of what was happening in the press, a spotlight was fitted to the robot. Initially it was mounted on the Y-axis carriage but was later moved to the laser mounting structure to provide better illumination of the filter plate faces.

Figures 5.5, 5.6 and 5.7 are pictures of the research rig. These have been included to provide a clear understanding of the configuration of the apparatus. Viewed in conjunction with many of the illustrations in this thesis, these pictures provide an accurate and valuable insight into the whole project. As is apparent from the foregoing description of the rig layout and equipment used, these pictures are not of the rig in its final form, but at an intermediate stage in its development. The STRIPE system, for example, is not present on the robot, nor is the imaging control gear on the elevated platform. Photographing the rig in its final form would have been problematic, given the all enveloping black-out over the structure, hence the use of earlier pictures.

The picture in Figure 5.5 is roughly equivalent to the illustration in Figure 5.3, i.e. it is looking at the front end of the rig. The picture in Figure 5.6 is looking from above the front left corner of the rig, and while obviously not an isometric view, is similar to the illustration in Figure 5.2. The picture in Figure 5.7 shows the operator's elevated platform.

The pictures are annotated to identify various items of equipment. The key to these items is as follows:

A. Rig frame structure and enclosing mesh

B. Operator's elevated platform

C. Filter press (0.5 m square membrane type filter plates)

D. Slurry tank

E. Bar trolley for filter cake collection

F. Main filtrate storage tank

G. Intermediate, small, filtrate tank

H. Air compressor (red item partially hidden behind cylinder in Figure 5.6

I. Four axis gantry robot

J. Robot control gear cabinet

K. One of four emergency stop buttons for robot operations

L. Computer

M. Access ladder for operator's elevated platform

N. Operator's desk

O. Warning notices (note space for laser warning signs)

P. Robot vertical (Z) axis lower extension (original item, not final)

Q. Padlocked and interlocked access gate to filter press enclosure

As can be seen in Figure 5.6 not all the filter plates have filter cloths fitted to them at this stage. Also note the robot's vertical (Z) axis extension (item P in Figure 5.6). This is the lower arm originally supplied by CAM Systems Ltd., and is very different to the final design of this part (see Figure 4.5 in Chapter 4).

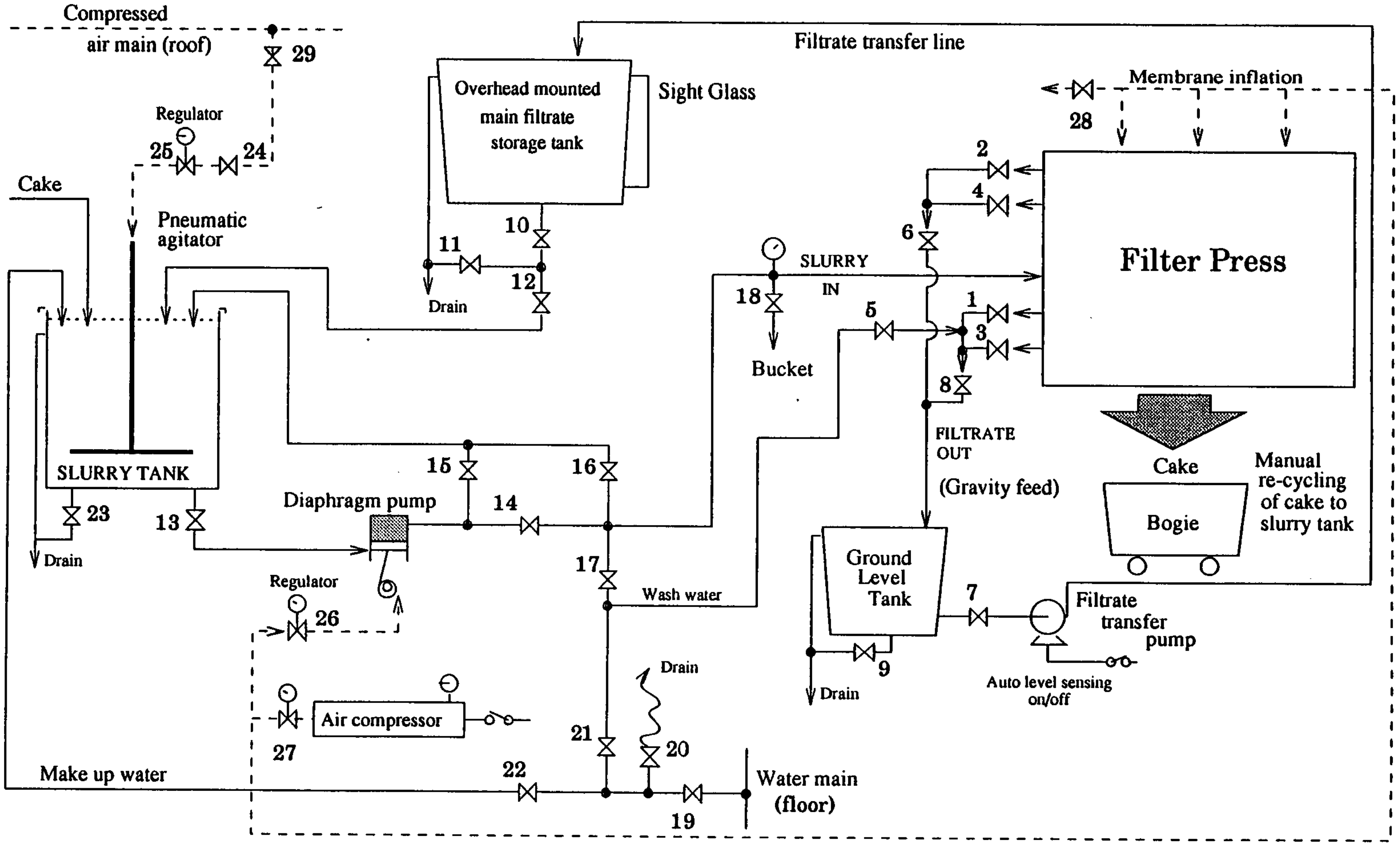


Figure 5.1: Flowsheet for experimental filter press

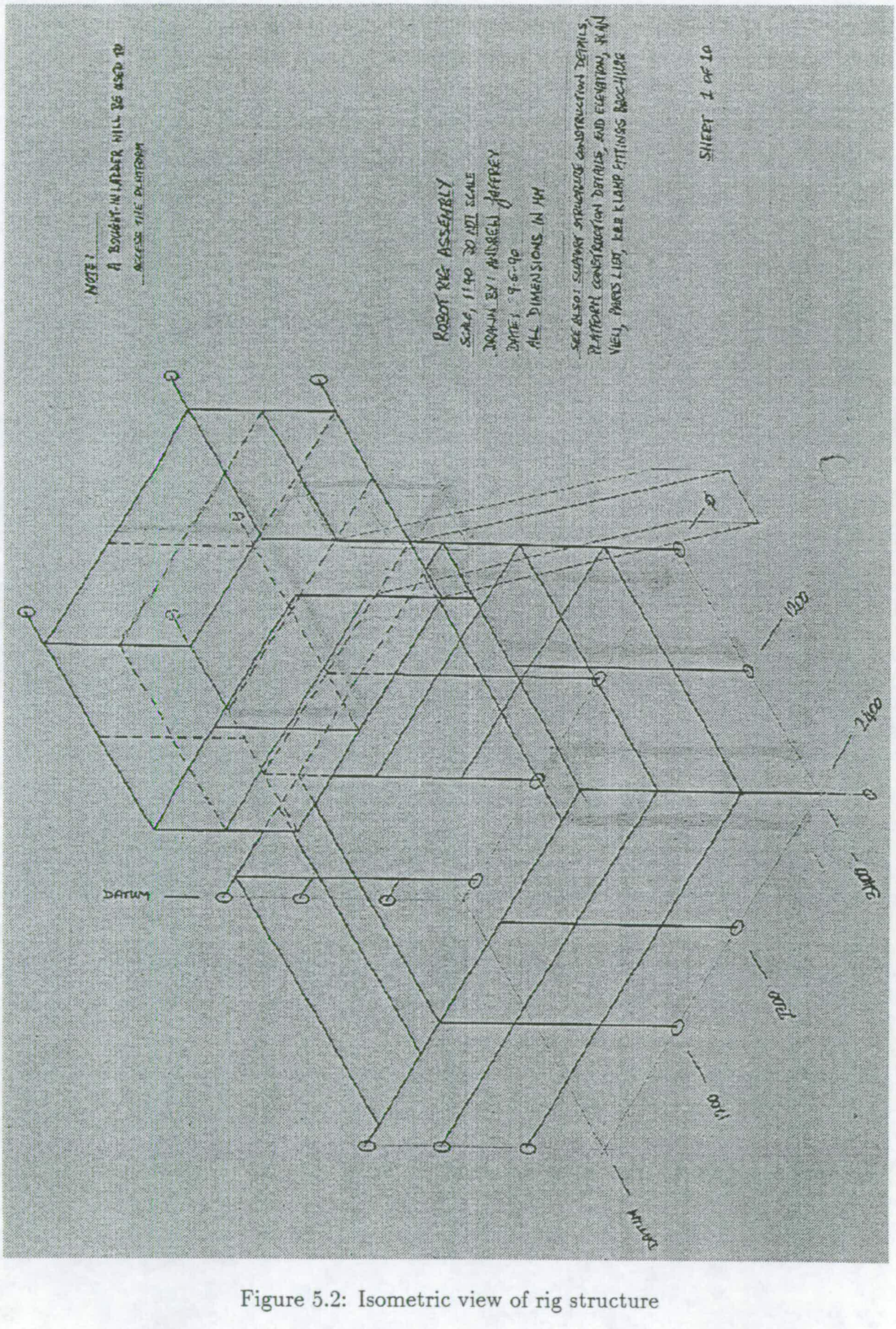


Figure 5.2: Isometric view of rig structure

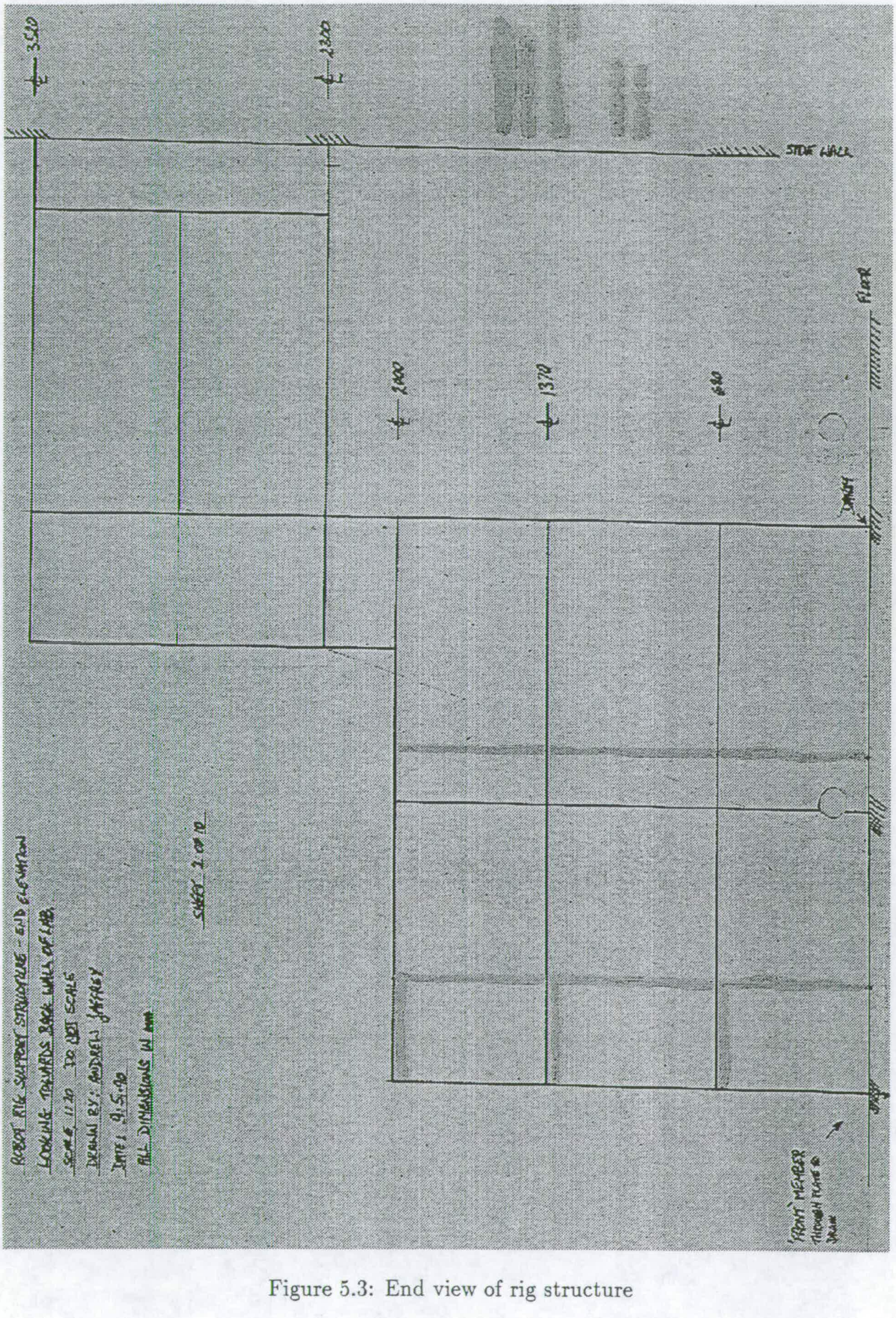


Figure 5.3: End view of rig structure

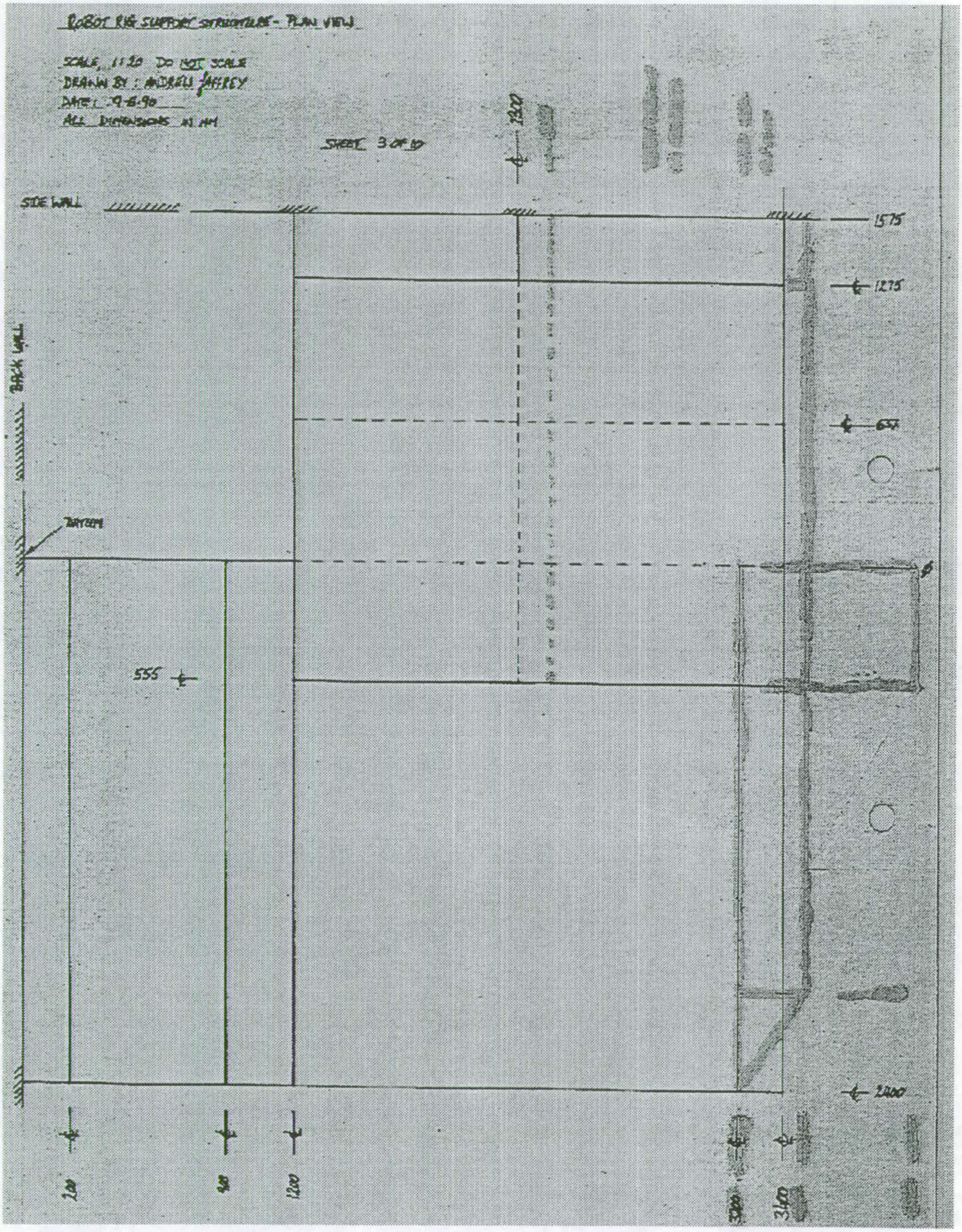


Figure 5.4: Plan view of rig structure

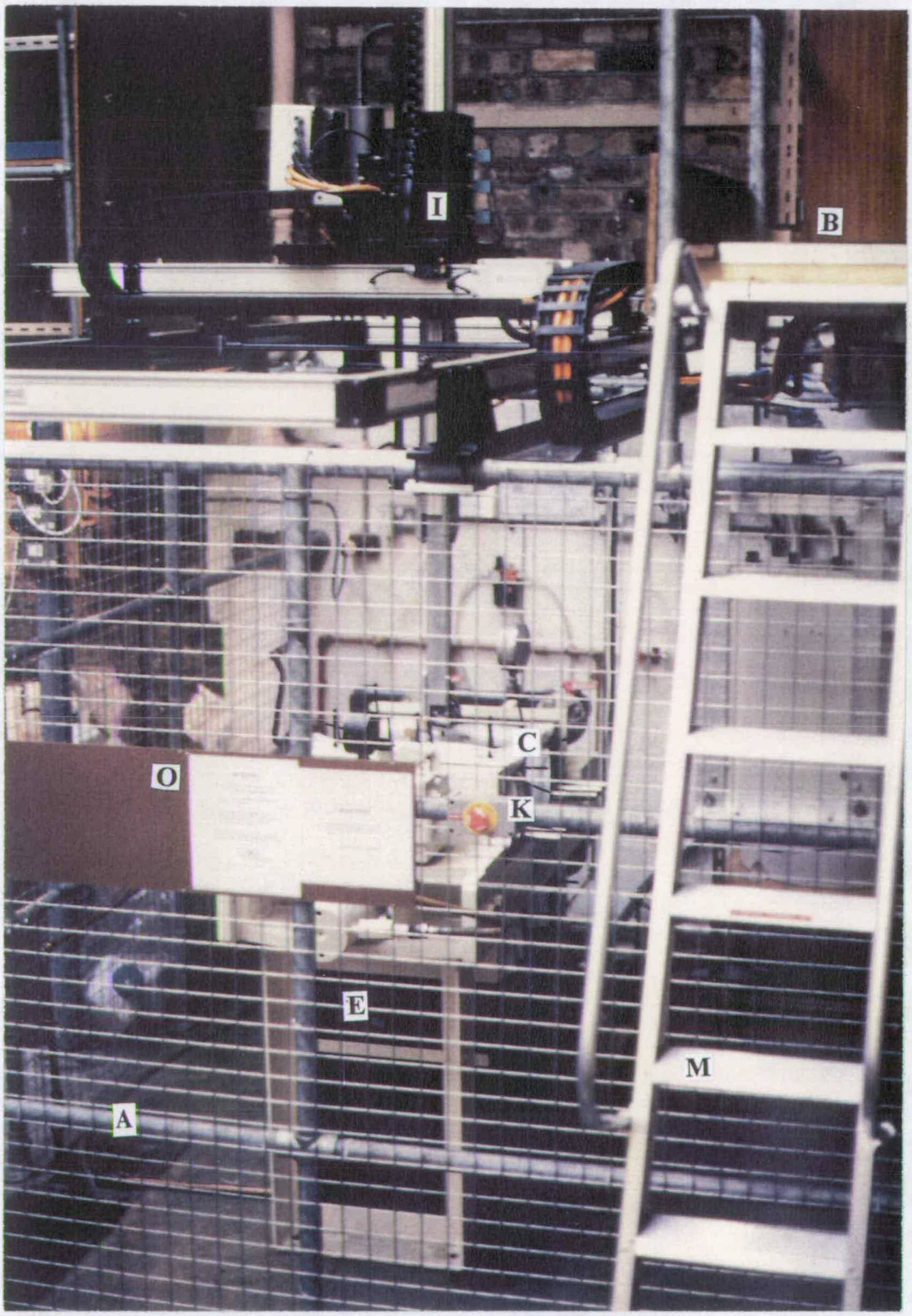


Figure 5.5: Picture of rig from front end

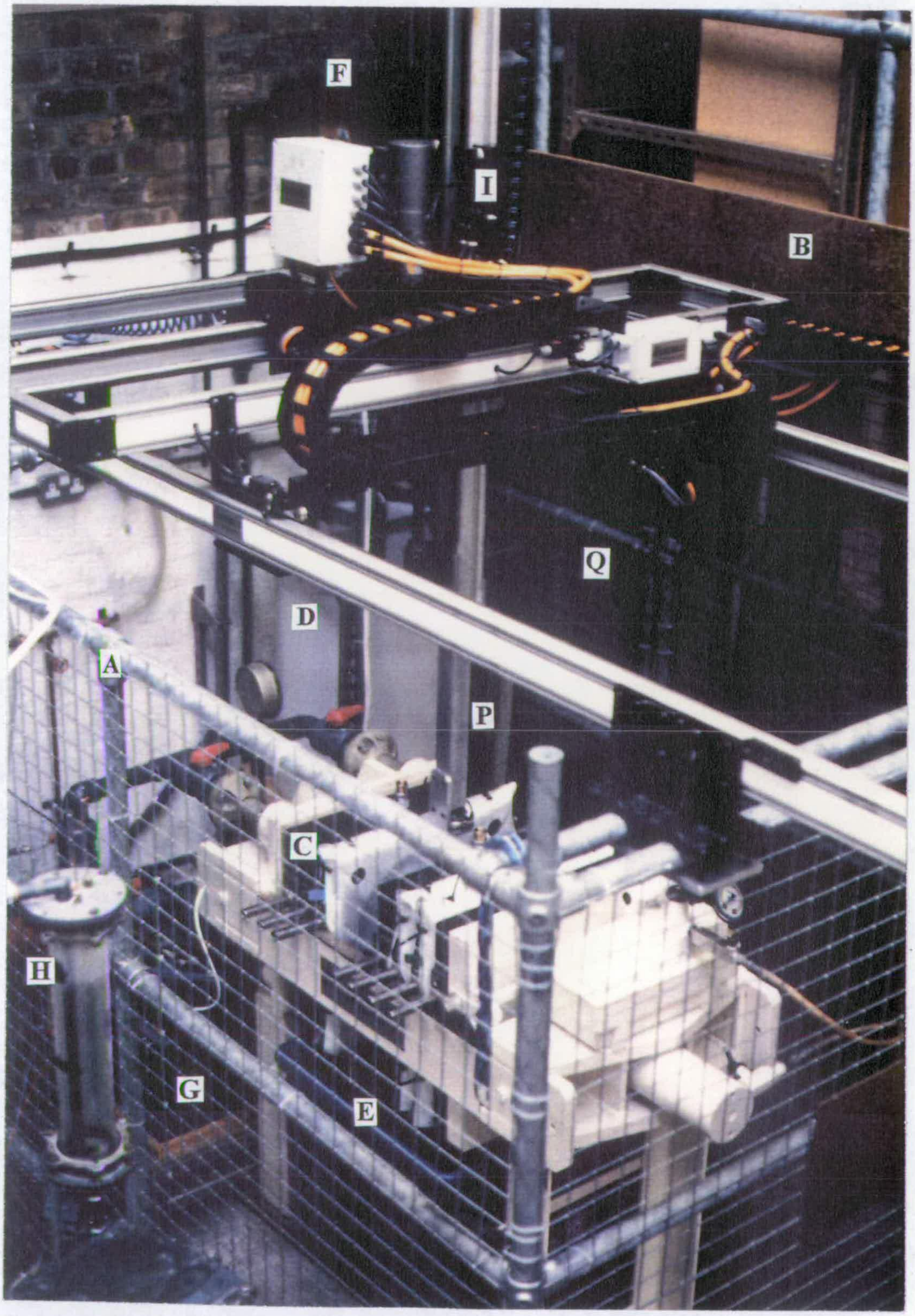


Figure 5.6: Picture of general layout of rig

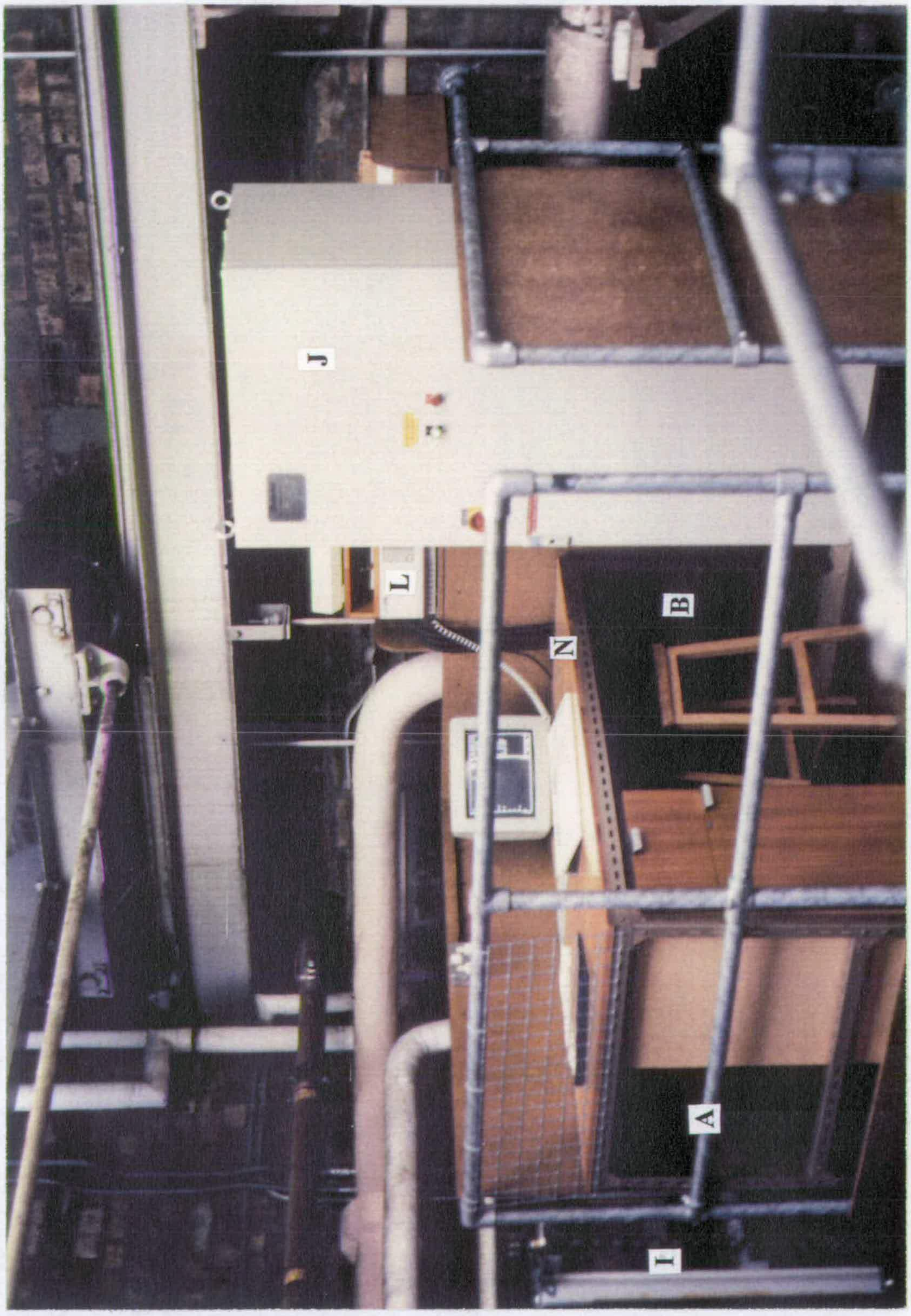


Figure 5.7: Picture of operator's elevated platform

Chapter 6

Software Control

In order to be used in this work the STRIPE system control software was converted from its original VME format to PC compatible code. This work was carried out by NEL. The PC version of the program is written in the Turbo C computer language, although it was necessary to add some lines of assembly language code at a critical point to speed up the acquisition of data.

6.1 Modular Program Design

Software control of the discharge operation is illustrated in Figure 6.1. Each of the basic discharge operations, e.g. scanning and scraping, is controlled by a specific piece of code which may also access or create data files for other pieces of code to use. All the separate pieces of code are joined by one piece of 'umbrella' code (discharg.c) which oversees the entire discharge operation. The user of the discharge system is aware of only one piece of code as calls to individual routines are automatic and transparent. This modular approach to system operation is desirable from the point of view of software quality control [46] but came about in this instance as a natural consequence of developing code for each part of the automatic discharge system in turn. It would have been possible, once the whole system was coded and functional, to integrate all the separate pieces of code into one large program. Such a move would be a retrograde step, however, as it moves away from the quality advantages of modularity.

Developed individually, many pieces of code can be tested and validated before being incorporated, still as separate modules, in a large software project. The testing, validation, maintainability, clarity of reading and understanding of code written this way is infinitely better than the same multifunctional code developed all in one unit, requiring complex testing, debugging and validation procedures. Making and testing changes in software is much more efficiently achieved in a small, clear and easily understood modular piece of code than in a large, all-programming-done-here, piece of code.

Although the controlling code for each component of the discharge system was developed separately from all the others, the modules are ultimately linked together to form one executable file. Each piece of code is compiled to object code (one step short of fully executable code) and all these object files are then linked together as one executable. This procedure is a standard programming operation and is extremely simple to use when all the modules are written in the same language. For one routine to communicate with another all that is required in the code is a command in the appropriate place. The 'external' program is treated as just another function (in C, a subroutine in FORTRAN) which can be called like any function in the calling program. While this works well for same-language code it can be problematic if different languages are used.

As stated earlier, most of the programming for this project was undertaken in Borland's Turbo C V2.0. Also mentioned was the necessity of programming in Microsoft C V6 for one of the modules. The image processing and analysis code could not be linked to the rest of the automatic discharge control code because it was written in a different dialect of the C language. Fortunately a way round this problem was found, making use of the spawn facility in Turbo C.

The spawn function in Borland's Turbo C is used to create a child process which loads and executes the program specified as an argument to the function [47]. There are two ways in which the spawn function can operate; the parent process may be suspended until the child finishes, or the child overwrites the parent process in the computer's memory, destroying the parent process. Spawn functions are useful when it is necessary to execute a separately compiled and linked application from a module of a program and return to the same program module when the separate application terminates. The 'parent-to-child-to-parent' procedure was used in this work to allow the Turbo C code 'control' over the image analysis, Microsoft C, executable.

After the scanning operation, i.e. image acquisition, the main (Turbo C) discharge program calls the analysis (Microsoft C) program to process the image; when the analysis is complete control is returned to the main program which then moves to the next stage of the cycle and calls the scraping functions.

6.2 Example: Plate Shifting Program Module

One piece of code to be called is for the plate shifter. In the first instance this will open the filter press; thereafter it moves one plate at a time for inspection and cleaning by the other modules. Finally, it is called to close the press completely for another filtration cycle.

The values used for dead reckoning by the plate shifting code are stored in the PMAC card by the operator in advance of system operation. The PMAC can store thousands of values which are accessed by software calls in the motion programs. The '.ref' files shown in Figure 6.1 are ascii files containing the values used in dead reckoning (they are for human reference only); none of the programs actually access these files. The contents of opening.ref are shown in Table 6.1 by way of an example.

The first column in the table, 'q', is the PMAC variable number in which the value x is stored. The third column in the table indicates which plate each value refers to. The values of x are given in mm, so if plate three is to be moved to an open position it will be moved 148 mm (q27) from an x position of 879 mm (q23). The q variables are accessed by PMAC motion program mp-200.aj which is listed in Figure 6.2.

The file to_laser.dat is an ascii file with the dead reckoning values (which are read by the code) for use by the scanning code to correctly position the robot longitudinally for plate imaging.

The example in Figure 6.2 of a motion program illustrates many of the features of the PMACs language and versatility which were important in the success of the work. It should be noted, however, that this code is intended to fully open the filter press in one cycle, i.e. without any scanning or scraping of filter cloths between moves of filter plates. As such it is a slightly artificial example, although still a valuable one.

`Line` : 7 Just as PMAC variable values can be set outwith motion programs, so they can be set from inside such programs. In this case p15 is set to one, so that the C code calling the motion program can check that program 200 in the PMACs memory is actually running, the default value for p15 being zero.

Line : 8 The 'home' command is extremely useful, as the scraper at any location on any motion axis can be commanded to return to its home position with a single command. The axes 3, 2, and 1 in program 200 are the robot's Z, Y and X axes respectively, i.e. vertical, lateral and longitudinal. It is extremely important to home the axes in this order to avoid potentially damaging collisions between parts of the robot and the filter press. By retracting the scraper along the vertical axis first the danger of a lateral or longitudinal move being commanded while the scraper is at a Z axis location down between filter plates is greatly reduced. The Z, Y, X axis homing sequence proved to be a satisfactory safeguard when initiating motion programs throughout this work.

Line : 11 Given the investigative/developmental nature of this work it was thought appropriate to use robot speeds well below those which would be used in a production system; the f40 command sets the maximum move speed to 40 mm/sec.

Line : 14 The press opening program requires only that the X axis motor be 'on-line', so the Z and Y axis motors are switched off during the execution of this program. This was done mainly as a safety measure so that any mistakes in programming would cause as few problems as possible. m26 and m28 are the appropriate PMAC outputs which enable or disable motors.

Line : 17 As this was a research project it could not be guaranteed that the filter press would be in the fully closed position each time a system or sub-system trial commenced. It was more likely to be open at a random plate number. To accommodate this the press opening motion program can start at any plate number, supplied by the user; the block of code starting at this line determines the entry point to the plate shifting part of the program.

Lines : 34 to 57 Each four line block of code corresponds to the parameter setting for moving one filter plate. The actual movement commands are in the subroutine in lines 24 to 32. The required longitudinal position of the robot is commanded in the second line of each four line code block. This command positions the plate lifting lugs fitted to the robot under the filter plate's supporting pins. Note that the x position value is in each case taken from a previously assigned q variable. These values are those listed in Table 6.1.

It should also be noted that unless stated otherwise all such values are stored in, and used as, absolute values – as opposed to incremental. Absolute values are positions specified with respect to the robot's co-ordinate system datum, incremental values are distances specified with respect to the current robot position. All the motion programs listed operate using absolute positioning. The PMAC may be programmed using incremental values, or one motion program may use both incremental and absolute values as required.

Lines : 24 to 32 Once the robot has moved to the required position to engage the supporting pins of the desired filter plate the movement subroutine is called. The PMAC output m3 was assigned to the relay controlling the operation of the plate lifting pneumatics. If output m3 is set to zero the relay is de-energised and the air supply to the pneumatic cylinders is removed, allowing the plate lifting lugs to drop if raised. When the output m3 is set to one, the relay energises and the compressed air supply to the pneumatic cylinders is applied, thus raising the lifting legs.

Line : 28 Having lifted the filter plate the robot is commanded to move to a new longitudinal position. This position corresponds to the originally commanded longitudinal position to collect the plate, minus the absolute value representing the distance the plate is to be moved, q27.

Line : 30 Once at the required longitudinal position the air supply is removed from the cylinders, thus allowing the filter plate's pins to drop back on to the side rails of the filter press.

Line : 59 Control passes to the next four line code block to set up the variables to move the next plate. The sequence repeats until the final plate is moved away from the stack, at which point the x-axis motor is put off-line (line 65) and the 'program running' flag, which had been set to show to external interrogation code that the motion program was running, is set to zero to show conclusion of program execution.

Line : 67 The motion program is then terminated.

6.3 Display Features

Some attempt was made to add useful display features to the control code. A pictorial representation of a filter plate was developed for display during the scraping routines. Prior to each scraping move this picture is shown with a coloured rectangle added defining the extents of the deposit about to be scraped. Also displayed is a representation of the path the scraper will take, including the start and stop points of the scrape. All these details are taken directly from the main algorithms for deposit identification and removal, so are true representations of the system's calculations. As such, the display is not merely a pleasing coloured image but also is extremely useful in development work and debugging, since wrongly placed deposits, or scrapes in the wrong direction etc. are readily identified and logged for correction.

6.4 Emergency and Safety Management

In addition to the hardware emergency stops wired into the robot's control circuit, it was felt appropriate to include some provision for stopping the robot in an emergency from the in-house software controlling it. At each point in the sequence of events in the automatic discharge, regardless of which of the C programs is controlling or calling motion programs to drive the robot, the user can halt the action of the robot by pressing any key on the computer's keyboard. This action is arranged to call a specific routine in the in-house software which sends a series of commands to the PMAC regardless of whether a pre-programmed motion program is running, or a directly commanded move from a C program is in charge of the robot at that moment.

The commands sent to the controller card are: ^A – abort all programs and moves, ^K – kill all motors and ^Q – quit all programs; these commands have the effect of stopping the robot and disabling all the robot drives and quiting all motion programs, so that were the drives to be reinstated the robot would not immediately start moving again. In addition to this sequence of commands, a further explicit disabling of each of the three linear axis motors is effected by setting each of the appropriate outputs to zero.

As has already been mentioned it is considered safe to "kill" the robot, i.e. disable its drives, effectively removing power from them, at any point of any operation. This is allowable because experience has shown that, unpowered, the robot can be moved quite readily along longitudinal (X) and lateral (Y) axes by hand. The Z-axis drive, however, when unpowered, effectively locks in place; therefore this is thought to be the only axis which may give problems in the event of an emergency. It should be noted, however, that such 'problems' did not arise during the whole of the research period. This is the situation with either hardware or software signalled emergency stops.

The only movement of robot axes which would result after an emergency stop, whether software controlled or hard wired controlled, would be due to reaction forces released when the robot motors were de-energised. Were the robot to run into some part of the filter press, for example, and this was observed by an operator who then effected the emergency stop before the controller's electronic protection prevented damage to the robot's motors, the driving force pushing the robot against the obstruction would be in effect until the instant of power removal from the servo motors. As soon as power is removed from the motors the force built up in the system will be released and the robot may move in the opposite direction to which it was being driven. The only time this would not happen would be if the scraper were being driven up or down the Z-axis (vertical) when it came into contact with an obstruction. In this situation recovery would be more complicated and would need to be effected by manual control of the robot from the computer keyboard (by a very experienced user of the robot) or by moving the obstruction, if possible. In extreme cases if a particularly unforseen set of circumstances occurred which made even manual recovery by computer control difficult, dangerous or impossible, then it would be possible to release the brake on the ball screw of the Z-axis by applying an electrical supply to the brake, which locks on when unpowered. Provision was not made to achieve this release expediently in an emergency since it was considered to be an extremely unlikely happening. Such an extreme set of circumstances was not encountered during this work and would be unlikely to occur in a future developmental installation of this nature, since robot movements should always be closely observed and be carried out using relatively low speeds. Whether or not such a set of circumstances could arise in an industrial application of this technique is a question outwith the scope of this thesis.

The remit for this work did not encompass the creation of a fully ruggedised, fully fool-proof piece of software, able to recover from all conceivable error situations. It was sufficient for this work to provide a means of safely disabling the robot if the need arose. This was achieved through software as well as hardware. The system operated effectively in all instances where it was tested deliberately. The emergency or safety facility was rarely needed in actual use of the robot, but when required it worked well.

This area of software development, like most others throughout the work, is admittedly lacking in formal safeguards. The pressure of time and the aims of the work dictated that effort be directed at overcoming the myriad problems associated with proving the concept of automatic, verified discharge of filter cake deposits from filter presses, not creating fully featured software.

```
Values used by PMAC prog 200 for opening the filter press.

These values for X put the plate shifter lifting lugs under
the plate pins(assuming the plates are correctly set for an
opening operation, i.e. closed).

              q        X       Plate
           ---------------------------
             21       750        1
             22       811        2
             23       879        3
             24       943        4
             25       1015       5
             26       1075       6
             27       148      Distance to move
```

Table 6.1: Dead reckoning values for opening filter press

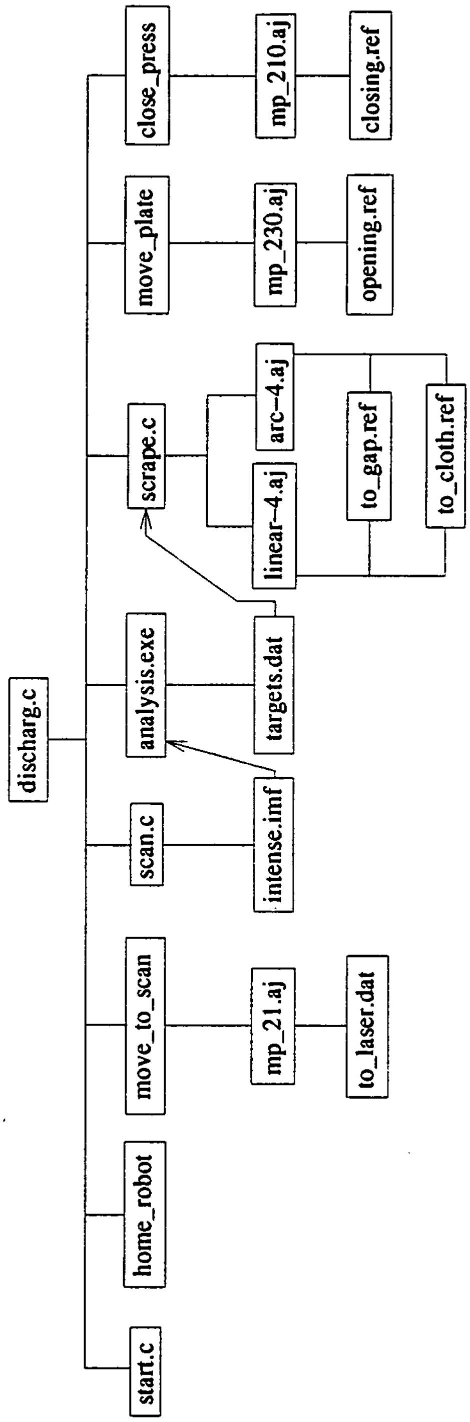


Figure 6.1: Discharge software overview

```
; Program 200 is the press OPENING, plate - shifting program
; All the distances are stored in the PMAC as Q variables

close
open prog 200
clear
p15 = 1                        ; set the 'program running' flag for C to see
home 3                         ; home the Z-axis
home 2                         ; home the Y-axis
home 1                         ; home the X-axis
f40                            ; set 40 mm/s as maximum move speed
dwell 1000                     ; pause 1 sec
dwell 1000
m26 = 0                        ; don't need Y
m28 = 0                        ; or Z motors on-line so disable them

if (p20 = 1)    goto 1         ; set '1st plate to move' variable in C and
if (p20 = 2)    goto 2         ; pass to PMAC in p20
if (p20 = 3)    goto 3
if (p20 = 4)    goto 4
if (p20 = 5)    goto 5
if (p20 = 6)    goto 6

n10                            ; movement subroutine
dwell 1000
m3 = 1                         ; lift plate
dwell 1000
x(p10 - q27)                   ; move across gap
dwell 1000
m3 = 0                         ; drop plate
dwell 1000
return

n1
x(q21)
p10 = q21
gosub 10

n2
x(q22)
p10 = q22
gosub 10

n3
x(q23)
p10 = q23
gosub 10

n4
x(q24)
p10 = q24
gosub 10

n5
x(q25)
p10 = q25
gosub 10

n6
x(q26)
p10 = q26
gosub 10
dwell 1000
dwell 1000
m24 = 0
p15 = 0               ; set the 'program running' flag to show it's finished
close
```

Figure 6.2: Listing of mp-200.aj motion program

Chapter 7

Performance

It may be reported with some satisfaction that all the mechanical equipment in the system functioned from the outset as designed and according to specification, with the following minor exception.

The operation of the pneumatic rotating unit, which turns the scraper about the vertical axis of the robot, was found to be unsatisfactory when supplied with laboratory air (at 2 bar pressure), but was entirely satisfactory when the air supply was changed and taken at 7 bar from the compressor used to drive the diaphragm pump. As foreshadowed in Chapter 3, all problems of performance centered on the vision system.

7.1 Initial Investigation of the STRIPE System

Shortly after the STRIPE system was first identified as applicable in this work an experiment was conducted to assess the ability of the system to detect lumps on filter cloths under realistic geometric constraints. A full account of this trial, made at Glasgow University and organised by NEL researchers in March 1990, is given here. The ability of the system to detect artificial filter cake targets on an actual filter cloth was investigated.

A small laser, fitted with cylindrical optics to generate a stripe of light, was mounted above two 0.5 m square filter plates set 150 mm apart in a discharging configuration. A CCD camera was similarly mounted, looking down at an acute angle at the cloth surface of interest. Using Blu Tak as a target the ability of the system to detect lumps on the filter cloth was investigated. The geometry of the set-up accurately reflected that encountered with a small (0.5 m square plates) filter press.

The stripe of laser light was horizontal when viewed on the vertical cloth face. For the purposes of the trial, this was moved up and down the face manually, instead of by the steppermotor driven mirror in a working STRIPE system.

Once the system was sufficiently well calibrated, the stripe projected onto the cloth was seen as a horizontal line on the monitor attached to the CCD camera. Variations in the gradient of the line across this screen indicated a change in the distance from the laser to the cloth caused by cloth irregularities such as lumps, bumps, holes etc., the STRIPE system having been developed as a range measurement device.

When a stripe encounters lumps and bumps on a filter cloth it is, when viewed from the appropriate direction, substantially deviated. The vertical deviation was demonstrated to be considerable when viewed from directions nearly normal to the incidence angle. When viewed perpendicularly, to the cloth, detection of such large deviations, and hence even of small protrusions from the cloth, would be very easy, though their interpretation as cake fragments rather than cloth wrinkles might be very difficult (Figure 7.1).

The overhead camera, however, viewing the cloth obliquely, does not register large changes in the stripe profile. Nevertheless it does show changes of gradient which correspond to changes in the distance from the cloth surface. The rate at which the position of a portion of the stripe on the monitor changes gives a local gradient which in turn can be related to the type of perturbation found. In general, a smooth gradient mimics the smooth gradient of a cloth bump, a sharp gradient, almost a step change, indicates the edge of a lump.

The deviations in the projected stripe caused by some target lumps of simulated filter cake were judged by the NEL staff present at the test to be suitable for range-finding calculations.

At the steep angles of illumination and viewing necessitated by the filter press geometry, however, the sensitivity of the STRIPE system was so seriously compromised that it seemed possible that it would fail to detect isolated lumps of cake of small but significant size.

7.2 An Improved System

A remedy was suggested by an important observation made during this experiment; this concerned the significant amount of light back-scattered by the fractured edge of a lump of material on the vertical face of a filter cloth when scanned from above.

As the cloth is vertical and the laser stripe is projected downwards at a small angle to the vertical, the amount of light back-scattered from the cloth and detected by the camera is small, as most of the incident light is diffusely reflected from the cloth and disappears from the camera's view.

The nature of lumps, however, is that a surface exists which is more perpendicular to the projected light and will, therefore, back-scatter a greater amount of the incident light. This difference in back-scattering would not be so clearly defined in an orthogonal system with the laser and camera acting normally to the surface. This localised increase in back-scattered light results in brighter segments in the viewed, and detected, stripe. Such variations in intensity can be related to the presence of deposits on the faces of the vertical surfaces under investigation.

7.3 Summary of Modified STRIPE Capability

It was apparent from this trial that two means exist for the detection of lumps (cake deposits), as distinct from bumps (cloth undulations).

1. The gradient of the stripe, as detected by the camera, increases sharply as it travels over the edges of a lump, the part of the stripe on the screen corresponding to the lump is offset slightly from the background stripe. When passing over a cloth bump however, the gradient appears to increase smoothly.

2. The intensity of the detected stripe changes as it passes over a lump, appearing brighter. This required investigation and verification as a valid, general statement; the use of Blu Tak on a filter cloth meant very different textures and materials for the fore and backgrounds for the scan. However, when a Blu Tak lump was made on a Blu Tak background there was still an increase in intensity for the lump relative to the background, confirming the generality of the observation.

   This aspect of using intensity as a means of distinguishing lumps from bumps was thought to be a unique extension of the STRIPE system and the possibility of patenting it (in collaboration with NEL) was investigated. This may be of significant long-term benefit.

The electronics of the STRIPE system were accordingly modified by NEL to detect the intensity of the observed stripe in addition to the deviation of the stripe. The STRIPE system, which in its original form had worked only with range information, in this modification yields intensity information also in relation to imaged objects on the cloth.

7.4 On-Site Test of Modified STRIPE System

In December 1990 a dry-run fitting and test session was held at the University Chemical Engineering laboratories for the STRIPE system. A frame was built to support the STRIPE apparatus on the robot in a position as near as possible to that calculated to give the most favourable viewing angles allowed by the press geometry. Filter cloths were fitted to some filter plates so that a scan of an accurately representative surface could be conducted. The scan was done simply by driving the stripe of laser light down the faces of the filter cloths to check that rotation of the scanning mirror, length of stripe etc. were adequate for this application. The result of the scan was not processed or stored in any way. The test proved to be very valuable, as it showed up very serious deficiencies in the scanning set-up. These were:

- The laser light wasn't intense enough,
- the ambient light level around the scanning area was too high.

These problems are related, since if the ambient light level is sufficiently low a relatively low intensity laser stripe will show up. The problem observed during the test was very poor detection of the laser stripe. The output from the STRIPE system's camera during scanning was viewed on a monitor. While the filter cloth was clearly seen, the laser stripe was not. The NEL staff present at the test indicated that the imaging performance of the system would be unacceptable in such circumstances, and that the likely causes were as indicated above.

7.5 Optical and Environmental Improvements

The first problem was addressed by NEL, the second by the author.

The test had been conducted using a STRIPE system configured with a powerful IR diode laser fitted with cylindrical optics, i.e. it generated a fan-like diverging flat beam. To increase the intensity of the beam, while actually reducing the system's laser classification to Class 2 laser use, the original laser was replaced by a less powerful, visible light, diode laser and the cylindrical optics discarded. The collimated output of the replacement laser was directed onto a small oscillating mirror to generate a stripe. This in turn was directed at the large scanning mirror which sent the beam down to the filter cloths. This arrangement is judged safer than the original because the laser power required to generate a bright stripe from a single point beam via an oscillating mirror is much less than that required to achieve the same stripe intensity via a cylindrical lens. A major safety benefit was also realised in the switch from an IR to a visible laser. The human eye's blink response is triggered by the wavelength used (670 nm), whereas it is not by IR. Subsequent setting up, alignment and use of the STRIPE system was made much easier and safer with the use of visible (red) light.

Abandonment of cylindrical optics in favour of stripe generation by oscillating mirror had other practical benefits. It is inconvenient to adjust the length of a stripe generated by an optical arrangement. Some form of zooming facility must be devised, often in a confined space not suited to the requirements of linear guides along which lens mounts must be moved. It is very easy to alter the length of a stripe generated by an oscillating mirror; adjustment of the mirror motor controller is readily achieved. The importance of this facility in this work is demonstrated in Section 7.7.

The ambient light level around the filter press was reduced by enclosing the entire rig in a 'tent'. A local tent repair company provided what seemed to be an ideal material; it was black/navy blue, nearly opaque, lightweight, waterproof and relatively cheap. A set of curtains made to drawings supplied by the author was obtained and hung round the inside of the rig 'cage'. These alone did not reduce the light level to a point where the STRIPE system could function consistently, and an upper tent or roof was added using the same type of material supported on a light metal frame high enough to clear the upper end of the fully retracted vertical arm of the robot. Once fully enclosed by this blackout the ambient light level round the filter press was greatly reduced and the STRIPE system was able to work more consistently and to a much higher standard.

7.6 Installation of Improved STRIPE System

The STRIPE system, modified as indicated above to register both range and image intensity of detected objects, was built at NEL and finally transferred to the research rig in March 1991. The output of this system was arranged to provide two simultaneous displays of the imaged field – a range map, in which objects are registered according to their degree of protrusion from the cloth, and an intensity map registering the regions of abnormal back scattered light intensity.

Much thought had gone into mounting the scanning system on the robot. The initial work addressed optimum choices of angles, fields of view, heights, path lengths, clearances and many other dimensions. Key questions were whether the box containing the modified STRIPE equipment could be mounted such that the laser and camera paths were not impeded by the robot and whether there was sufficient longitudinal robot travel to allow the laser system to address the two extremes of the press, i.e. the end plates. After these were satisfactorily answered, the question of the structure of the mount was addressed. The general solution was offered by the Laboratory Superintendent using the clockmaker's structural principle of parallel plates of material separated by pillars or similar suitable members. In this case two plates of Dural formed vertical, longitudinal (with respect to the robot's axes) side plates and two channel section members fitted laterally between them (see Figure 7.2). This arrangement offered a means of building a mount quickly and in such a way that provided a useful structure for future additions and modifications to the apparatus.

The setting up and adjustment of the scanner to give the correct field of view, focus, stripe width etc. proved to be a time consuming procedure. The original scanning mirror proved too narrow to give the correct field of view of the full width of the filter plates. Inadequate adhesive bonding of the mirror to its mount gave further practical problems. When these difficulties were overcome with the cooperation of NEL the correct field of view was established and the scanning system functioned satisfactorily throughout all ensuing experiments.

Initially all six control and data cables connecting the STRIPE system's scanning box to the controlling computer were bundled together for ease of routing so that they didn't interfere with the robot's travel. Unfortunately the signals passing through the cables interfered with each other; the bundle was divided into two groups of three cables, one group connecting to the leading edge of the box, the other going to the trailing edge. This separation of the cable groups successfully removed the interference.

To comply with University regulations the use of the STRIPE system's laser was registered and the author attended a laser users safety course for which he received a certificate.

A computer program, separate from the actual scanning and imaging code, was written to control the STRIPE system components and thus avoid having to conduct a time consuming scan every time a mirror angle or stripe or scan position required to be checked. This proved to be a very useful tool throughout the project and addressed the scanning mirror drive motor and the laser directly.

7.7 Evaluating the Modified STRIPE System

After delivery of the imaging system from NEL many tests were carried out to investigate the effect of various factors on its image quality and accuracy. The principal factors examined were the wetness of the scanned material, the orientation of the scanned surface with respect to the scanning system, the intensity of the laser stripe and the influence of optical filters.

7.7.1 Cake and Cloth Visibility

Test 1 compared scanned images of clean, i.e. non-caked, dry filter cloths with fresh, i.e. damp, filter cakes on damp filter cloths. The results of this test were very disappointing since the fresh cakes gave very poor images, whereas the clean dry cloths gave very clear images. The fresh cakes presented seemingly ideal 'detection' surfaces to the scanning system, being approximately 7 mm thick and having fracture surfaces in a horizontal plane, with the remaining cake deposits adhering to the cloth below this plane. The laser stripe was somewhat oversized during this test, i.e. it was longer than the width of the filter plate; the significance of this is discussed later in this Section. At the time of the test it was considered possible that the water content of the fresh filter cakes was in some way responsible for the poor images, i.e. their lacking clarity and positive information about the cake deposits.

7.7.2 Effect of Cloth Wetness

Test 2 examined the effect on image quality of wetting a clean, dry filter cloth. Although the cloth was clean, i.e. free of filter cake, it was discoloured from previous filtration cycles. Very clear images were obtained on scanning the dry cloth. The recess and slurry feed hole were discernible, as were some cloth undulations. The upper right quadrant of the filter cloth was then sprayed with water and another scan made. The image very clearly showed a reduction of information in the area sprayed with water, once again suggesting a reduction in system performance when scanning wet surfaces as compared with dry ones.

7.7.3 Effects of Wetness of Model Cakes

Test 2A investigated the effect of wetting two pieces of teaching chalk which were attached to a discoloured, but deposit free, filter cloth. A scan was taken with both pieces of chalk dry, after which they were sprayed with water and rescanned. This process was repeated until the chalk appeared to be saturated and disintegrating with further wetting.

The chalks used were respectively white and brown, the brown appearing to the eye to be very similar in colour to the discoloured filter cloth. Both pieces were attached high up on the filter cloth but still within the recess of the plate. After repeated spraying with water the brown chalk disappeared from the intensity image, while the white chalk remained discernible all through the test. Test 6 was similar to this one; the account of that test summarises thoughts and conclusions for both.

7.7.4 Effects of Cake Wetness

Test 3 examined the effect on image data of wetting partly dried filter cakes. Cakes which had been allowed to dry for a few hours after filtration were scanned, sprayed with water and rescanned. This was repeated a number of times. The purpose of this test was to try and establish a link between the degree of wetness of filter cakes and changes in image quality from the scanning system, as had been observed for non-caked cloths tested in this way. Once again the wetting was achieved by spraying water at the scanned area, but how much of the water was absorbed into the cake was unclear, i.e. the wetting may have been superficial, rather than deep within the cake as would be the case with fresh filter cake. This factor may have influenced the results of the test. These were that, in general, increasing cake wetness decreases image quality; but that in some instances the reverse effect is observed, i.e. that increasing the cake's wetness also increased the quality of the intensity image. This latter effect was usually quite localised and may have been due to water lying on the cake's surface, usually the upper fracture surface, leading to increased reflectance of the incident laser light and, therefore, to an increased image quality.

Test 3A was essentially the reverse of test 3, i.e. wet cakes were allowed to dry and scanned at a number of intervals. The plate faces used in this test were the two exposed when the first plate was moved to open the press for discharge. The first tests were carried out on the only filtering face of the first plate. The scan immediately after filtration identified the outline of the plate (implying the stripe was too wide) and some of the cake deposits, despite these being wet (a membrane squeeze was not applied at the end of filtration). Most of the deposits successfully imaged had definite edges, these edges being perpendicular to the filter cloth; not all the deposits were registered, however.

One particular deposit, near the bottom of the plate, showed up very well, not only on the intensity map display, but also on the range map. This was unusual, since very few objects had hitherto been registered on the range map (displaying data from the STRIPE system in its original form) as the orientation of the filter plates with respect to the scanner made this unlikely. The clarity of this deposit in the intensity display was due to a puddle of water sitting on the top edge; this result had been observed before in test 3. The surprise detection of this deposit (and only this deposit) in the range information display was thought to be due to its size. It was formed not simply by cake above it falling off, but by the cake above rolling off the cloth, i.e. the top part of the cake which fell peeled away from the cloth causing the rest of it to rotate off the cloth. The deposit (a very small slab of cake) fractured near its bottom edge as it fell leaving part of the remaining deposit – now the top part of the adherent cake – leaning out into the inter-plate gap. This leaning of the cake formed a ledge which was also in roughly the ideal horizontal plane. The ledge was approximately 20 mm deep which compares with a normally observed fracture surface depth of around 7 mm, so there was a greater than usual distortion of the scanned stripe, leading to the generation of range map information. These observations indicate how far the original NEL STRIPE system (giving range-map information only) falls short of detecting normal filter cake fragments in the circumstances of these tests. This first deposit to be clearly identified on the range map was three times the normal thickness of cake fragments.

In general on this first scan of the test the deposits at the top of the plate were drier than those lower down, but the image was good nonetheless.

Twenty-eight minutes after filtration was stopped the first face was rescanned after the cake had lost moisture by free exposure to the air for that time. Prior to this the water lying on the ledge of the bottom deposit was removed by dabbing with a paper towel; the deposit wasn't affected in any way other than having the water removed. The whole intensity image was much better defined than at first; more of the filter cake at the top of the plate was distinguishable, as was more of the circular recess. The bright patches at the bottom of the plate, associated with free moisture on the ledge of deposit there, had disappeared, although the ledge deposit was still detected.

Thirty-five minutes after filtration the face was rescanned. The intensity image again showed more of the circular recess in the plate and still exhibited good cake edges within that.

Sixty-five minutes after filtration the face was rescanned. The image of the edge of the recess was still completely circular, but while the top and bottom portions of the recess image were still useful, the middle portion had ceased to be detected satisfactorily, i.e. cake in this area was not found.

Seventy-six minutes after filtration and free air drying the exposed face of the second plate was scanned. The progress of the laser stripe down the face of the plate was observed on both the monitor showing the STRIPE system's camera output and directly from above the press and laser by eye. In both cases the stripe seemed to disappear for most of the scan. The range map did not register any data for the scan; the intensity map did show a faint trace of a deposit at the top of the recess, but did not show any other deposits, despite their presence with seemingly good upward facing edges. The top edge deposits were much drier than the middle area deposits, which were not detected. A section of the top edge deposit was removed to leave two deposits at the same vertical position on the plate where there had only been one long, horizontal deposit. The rescanned image successfully registered this change in the deposit.

The results of this test are confusing, since they seem to contradict the earlier observation that wetting a filter cake results in diminished imaging performance. This may support the caution stated in test 3 that spraying water onto a dried filter cake does not achieve the same cake wetness characteristics as those held by a fresh filter cake.

7.7.5 Effect of Angle of View

Test 4 examined the performance of the scanning system when the scanned surface was almost normal to the incident light, rather than at the acute angle normally resulting from the vertical orientation of the filter plates. A filter plate with dried deposits was lifted from the press and laid on top of the press so that it was almost horizontal (the pneumatic connections to the press' membrane plates prevented a true horizontal orientation). When the plates are in their normal vertical position only a few degrees of rotation of the scanning mirror are required to move the laser stripe from the top of the plate to the bottom. The scanner's parameters were not changed for this test so not all of the near horizontal plate's surface could be scanned, however the small amount that was scanned gave excellent results.

The range map produced was very good, as was expected given the now favourable plate orientation, and the intensity map was also good; the recess rim was clearly shown, as were cake deposits. The cake and cloth were then sprayed with water as in previous tests and the same limited area of the plate rescanned. There was a marked reduction in image information after wetting, again as observed in previous tests. This phenomenon is, therefore, not simply a function of the acute angle at which the system is normally required to operate.

7.7.6 Intensity Effects with Re-Wetted Cakes

Test 5 sought to determine the influence of stripe intensity on the scanned images of both wet and dry filter cakes. By adjusting the amplitude control of the galvanometer scanner the width of the laser stripe can be adjusted to be anything from a few millimetres long at the top of a filter plate to being in excess of the plate width. The stripe was set to be about 150 mm long and one vertical strip of a dry, caked cloth was scanned. The reduced width intensity image detail was excellent and the range map also showed useful information. The stripe was lengthened to approximately 250 mm, centred laterally on the plate and another scan taken. Again the detail was good, a cake edge at the top of the recess was clear, and the face of the filter cake was observed to be distinguishable from the clean cloth above it, one of the first instances where this was observed. When the stripe was further lengthened, to about 330 mm, however, the resulting range map was blank and the intensity map was of much poorer quality than previously observed in this test. The stripe length was reset to full plate width (480 mm) and the cloth and cake sprayed with water. The range map did not contain any information but the intensity map details were of a similar quality to those observed in test 3, i.e. relatively poor but just adequate for feature extraction. The stripe was shortened to 250 mm and the central strip of the plate rescanned. The range map once more contained useful data, and the quality of the information in the intensity map image was excellent. The very bottom of the filter cloth was distinguishable for the first time in a scanned image.

The very clear conclusion from this test was that a shorter, and therefore more intense, laser stripe when used for the scanning of filter cloths generates much more detailed images than longer, less intense, stripes, regardless of whether the cake and cloth are wet or dry. This was an important conclusion, but one based on dried cakes rewetted by surface spraying. See the account of test 7 for a repeat of this test on fresh filter cakes.

7.7.7 Colour Effects

Test 6 was essentially a repeat of test 2A with two differences,

1. six different colours of teaching chalk were used, and
2. the chalks were attached not to a filter cloth, but to the ram end plate, i.e. the metal plate which spreads the closing force of the hydraulic ram over the full area of the first filter plate in the stack and hence through the press.

White, brown, red, blue, yellow and mauve chalks were used. The chalks were scanned, wetted equally and rescanned. This was repeated until deterioration of the chalks became excessive. The chalks tended to disappear at different rates (number of sprayings) from the intensity images. Table 7.1 shows the relative ability of each chalk to be detected by the end of the test; 1 is very discernible, 6 indicates the chalk disappeared almost completely.

Strictly speaking this test is flawed, in that the result is assumed to depend solely on the colour of each piece of chalk. It is unknown if each chalk had exactly the same composition (with the exception of the colouring agent). The test did raise an important point, however; the colour of the laser light used in the developmental system may not be suited for use in some applications, particularly dyestuffs filtration, where the colour of the scanned surface may affect greatly the amount of reflected or absorbed light, and therefore the quality of the scanned image. This requires further investigation.

7.7.8 Intensity Effects with Fresh Cakes

Test 7 was a repeat of test 5 except that fresh filter cakes were used to examine the effect on image quality of changing the intensity of the laser light. Every face of filter cloth in the test press was scanned twice, once with a stripe width of 480 mm (full width) and again immediately after with the stripe reduced to 250 mm and centred laterally on the filter plate. Twenty-four scans were thus carried out, giving a good indication of the accuracy of the result.

It was observed that the shorter, and therefore more intense, laser stripes generated consistently more detailed and accurate intensity images than the full-width stripes; the range maps of the short stripes frequently contained useful data, whereas this was not the case for the long-stripe range maps. The very high quality of the data captured by the shortened stripe of fresh, wet, filter cakes dispells any long-term worries over reduced imaging performance of wet cakes – as had been implied in earlier test results. This was an important result.

7.7.9 Poorly Matched Optical Filter Distorts Results

Acting on this result test 8 investigated the use of a more powerful laser to improve imaging performance and also the effect of an optical filter on the same. The test was carried out in association with Mr Don Whiteford of NEL, a specialist in the use of lasers and their associated equipment. The first change made to the already modified STRIPE system was to replace the original class 2 laser with a class 3A laser. Since the class 3A is a more powerful and dangerous laser than the class 2 great care was exercised, particularly during the alignment stage of the conversion.

A scan of recently filtered material was made and an absolutely appalling result obtained; neither the range nor intensity images contained any information. It was also observed that the picture of the laser stripe on the monitor failed to show the stripe at all clearly; it was very dim, despite the stripe being very bright when viewed by eye from the vantage point of the operator's platform. The poor detection of the stripe by the system's camera was caused by the filter fitted to the camera.

The nominal wavelength of both the class 2 and 3A lasers was 670 nm, but the class 2 laser was nearer to this value than the class 3A. Gas lasers of a given type produce monochromatic light of exactly the same wavelength, irrespective of their power level or temperature changes. Diode lasers do not perform the same way. The wavelength of emitted light from a diode laser is temperature dependent, and may vary from its specified value. It is likely that the wavelength of the class 3A laser used in this experiment was emitting light around 675 nm, rather than 670 nm as was expected. The fact that the class 3A laser was an older diode laser than the class 2 may have contributed to the discrepancy in the wavelength[1].

The filter fitted to the camera was intended to pass wavelengths very close to 670 nm, and exclude others, as described in Section 3.7.4. The wavelength of the class 3A laser was apparently not close enough to the peak of the filter, so it was not detected strongly by the camera. The filter had been fitted to the camera by NEL at the construction stage of the system and was intended to cut down the amount of ambient light registered by the camera during scanning. Since the ambient light level around the research rig had been greatly reduced by the use of a blackout, the filter was thought not to be required any longer

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[1] These are the opinions of Mr. Don Whiteford of NEL

and was removed. The class 3A laser stripe was observed to be immediately very much brighter on the monitor, and the subsequent scan results were excellent. Given the effective doubling of the laser's intensity by removing the filter from the camera, the class 2 laser was reinstated to see if it would, after all, be intense enough to generate acceptable images. It was. Scanning still damp filter cakes from hitherto unexposed chambers from the earlier filtration yielded very good images. It is ironic that the use of a narrow bandpass optical filter, as outlined in Section 3.7.4 as an aid to system performance, proved to have quite the opposite effect in this instance. The narrowband pass filter was left off the camera for the remainder of the project work.

7.7.10 Fully Caked Cloths

The discharge system failed to deal with fully caked filter cloths. The component responsible for this failure was the imaging system. When cloth completely covered in filter cake was scanned this failed to generate an image which would allow ready identification of this fact. This result was expected since it was stated at the outset that this particular circumstance would not be addressed in this work. Some ways of rectifying this failure are proposed in Chapter 9 however.

7.7.11 Overall Performance of Complete Discharge System

Time constraints severely limited the opportunities to try the discharge system on fresh filter cake. Although the actual filtration cycle was quite short, the time required to set-up for each filtration was considerable. Most of this time was associated with re-slurrying and mixing the feed for the cycle. The time required to set-up and run a filtration was usually four or five hours; preference was usually given to other development work than to filtration, the mechanics of which were of little importance to this work.

Most of the testing carried out of the discharge system to perform as an integrated system used paper targets rather than filter cake. Small pieces of paper attached to filter cloths such that a very small area projected normal to the cloth, simulating a fracture 'ledge' of filter cake, were found to be extremely good targets for scan-and-scrape development work and were very useful in developing the co-ordinate conversion functions for the image analysis code.

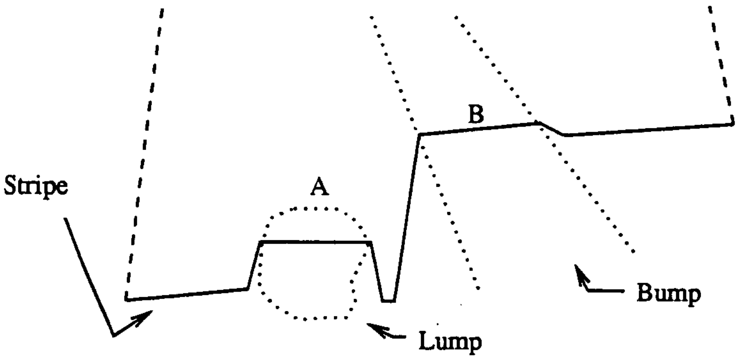
The discharge system was demonstrated to be able to identify, and drive the robot-borne scraper through, any such paper target placed within the filtration recess area of a filter plate.

The total scanning time of one face of a filter cloth was approximately 30 seconds. Of this, only 4 seconds or so was actual laser-on, image acquisition scanning time. The greater part of the time was required by the STRIPE system to initialise itself, home mirrors etc. While the actual scanning time was felt to be acceptable, the overall period for one scan was considered too slow for application of the existing system outwith a research and development environment.

Scraping times depended entirely on the location of the scraper head when a scrape was commanded. For the first deposit to be addressed after image analysis the time will be greatest, since the robot's longitudinal position is set for scanning, thus placing the scraper some distance from the scanned surface. The subsequent longitudinal move of the scraping head is the greatest required for any deposit on one cloth face. Assuming the scraping head was already positioned in, or directly above, the plate gap under consideration when the scrape was commanded, the scrape would typically take around 10 seconds. This time can be reduced by increasing the move speed of the robot, but was considered ideal in a development environment.

White	1	Mauve	4
Red	2	Brown	5
Yellow	2	Blue	6

Table 7.1: Results of colour effects test



Orthogonal view of filter cloth showing deformation of straight, horizontal stripe by lump A and cloth undulation B.

Figure 7.1: Deformation of stripe

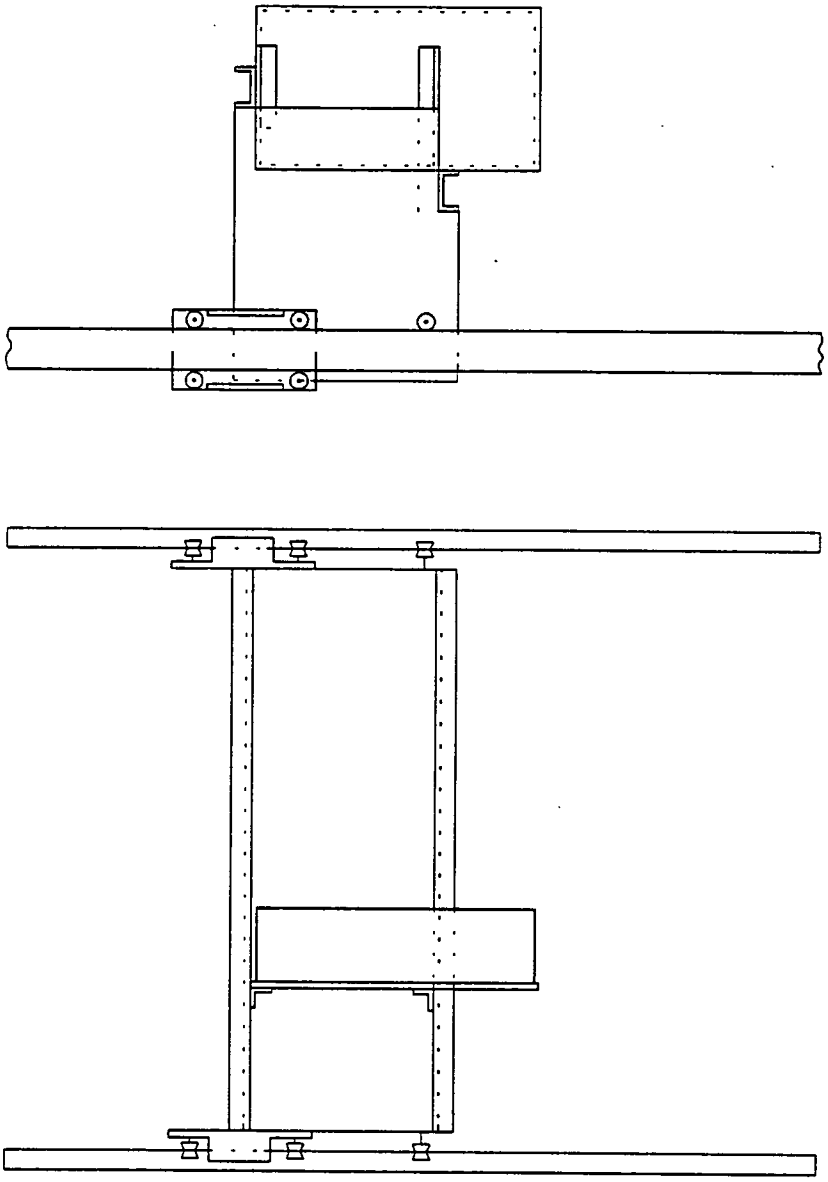


Figure 7.2: Mounting arrangement for STRIPE system

Chapter 8

Discussion

Many industrial contacts were made during the course of the work; e.g. suppliers of robotic and machine vision systems and users of industrial filtration apparatus were visited while searching for suitable equipment. Described in detail later, these contacts led to collaborative work being undertaken and confidentiality agreements being signed, in particular with Edwards & Jones Ltd. and NEL.

One of the reasons for conducting this research was to reduce discharge related risks to operators working with filter presses, i.e. to increase plant safety. Contact with plant managers, however, showed that they are (or at any rate were at the time of these enquiries, 1989-1990) more interested in the financial benefits to be gained from the use of truly automatic discharge equipment for filter presses. This is not to say that plant managers are uninterested in safety issues; their response to this suggestion is that they do not operate unsafe plant in the first place, i.e. any risks associated with the current operation of filter presses are deemed acceptable.

By eliminating the need for an operator at the discharge stage of a filter press' operating cycle, however, a significant labour cost saving can be made. This is particularly attractive to plant managers. Productivity increases may also be realised, although in the context of filtration this seems to be of secondary interest to managers.

Discussion with senior representatives of B. A. Chemicals Ltd., Burntisland, indicated that a very short payback period for a retrofitted automatic filter press discharge system was possible. A figure for this period has not been given because the discussion was not based on costed figures for the manufacture of the automatic system. It does indicate, however, that the savings derived from the use of a fully automatic discharge system could cover the system's capital cost in a reasonably short time. At the time of writing the economic situation is such that many companies can only consider capital outlay if a project promises a short payback period, e.g. one year. On this basis, the author's discussions with operators and manufacturers of filter presses indicate that even in a harsh economic climate the automatic discharge system described here would be an attractive investment.

Filter press manufacturers stand to benefit from the development of automatic, verified discharge technology. The filter press manufacturing industry is very competitive, hence any advantage one maker can obtain over another is potentially very valuable. Offering a genuinely automatic cake discharge option as part of a manufacturer's range is one such advantage. As with all advances, the advantage to the first company to offer such a system would undoubtedly be short-lived, imitation being the most sincere form of flattery; but such imitation will only happen if the technology is proven and taken up by the market. If the proven automation of one manufacturer's filter presses leads to others offering similar products, the future of the filter press industry may, however, be strengthened; particularly if presses become viable in applications previously thought to be unsuitable or uneconomic.

All the work on this project stemmed from the premis that the way to remove discrete deposits of filter cake from filter cloths is to scrape each deposit separately. This approach minimises cloth wear, but does have a time penalty compared with dislodging actions which act on the whole cloth face at once.

From discussions with plant managers it seems that, within reasonable limits, an increase in discharge time of an automatic system over that achieved by a human operator would be acceptable to industry. This is a result of human operating practices, at shift change-overs for example. The continuity of work possible with an automatic filter press discharge system regardless of tea-breaks, shift changes etc., means that while the machine may take longer to complete its tasks, it could still achieve the same throughput per day as a human operator discharging a filter press.

If the work described in this thesis is taken to commercial reality it could have a significant impact on users and manufacturers of filter presses. In the opinion of a specialist consultant the availability of "A reliable system for operating filter presses automatically would be an all time winner with this labour intensive batch process..." [48]. The adoption of a verified discharge approach in place of current practices would have important financial benefits.

The automatic discharge system described in this thesis met the original goals of the work, albeit in a very different way from the initial concept of a central cloth discharge station. The system devised is thought to be more flexible and more beneficial to the future of solid/liquid separation, as well as being far more attractive technically and economically, than that proposed at the outset.

It has since been learned that, in the view of a prominent filter press manufacturing company, the most important part of this work is that relating to deposit identification. This attitude is supported by the company's view that scraping individual deposits is not the way forward for filter press design, but that whole-face actions are. Shaking filter cloths, or even having a scraper capable of addressing the whole face in one pass, are methods seen as the future of deposit removal. Such an approach implies significant cloth wear and delay at each whole-cloth shaking or scraping and thus requires that such operations be performed only when deposits are detected. It does, however, require only a sub-set of the deposit detection system developed in this research. If the whole face of a filter cloth is to be addressed for cake removal, then the actual location of deposits is unimportant; all that matters is the identification of the proportion of the cloth area coated with persistent deposits and hence potentially unproductive. If a face of cloth can be said to be x% covered in filter cake this can be compared with a pass/fail threshold, y%. If $x < y$, the cloth is passed, otherwise it is considered to have too much adherent cake to remain effective in the next filtration phase of press operation and the 'global' discharge action against it is initiated.

This approach of deposit quantity assessment leading to whole-cloth action has resulted in much further work being undertaken in the University's Department of Chemical Engineering, with the support of a commercial sponsor, but is not reported here because it is subject to commercial confidentiality and was initiated after the period of research described here.

Chapter 9

Conclusions & Recommendations for Further Work

The conclusions reached on this work are as follows.

1. Automatic discharge of filter presses without human intervention is shown to be possible through the application of a novel approach to the problem of filter cake discharge and by the use of a specially adapted STRIPE optical range-finding system from NEL.
2. Verification of the discharge of filter cake is seen as the key to the success of this research. Once the presence of cake deposits on a filter cloth has been established as persisting after gravity discharge, it is relatively simple to direct devices to remove them.
3. The crucial element in the verification of discharge is the acquisition of an accurate and readily interpreted image of the filter cloth surface. Once this is achieved it is a relatively simple matter to detect automatically any discrete filter cake deposits in the image. It is, however, a more complicated problem to identify cloths which are fully caked.

4. The more intense the laser light used to scan filter cloths the greater the detail obtained in the resultant image.
5. While the techniques described in this thesis are applicable to large filter presses, the equipment described here is not. The present work has revealed substantial problems of scale up. The following is a discussion of these and of how the verification of discharge from, and inspection of, large filter plates may be developed.

Future work can take two directions: refining the existing system, shown in principle to be applicable to small filter presses; and addressing the different problems associated with completing cake discharge from much larger filter presses (plates > 1 m square). The latter require a radically different approach from that adopted in the present research, chiefly because of the long times needed to scan and address patches of deposit on such large cloths using the principles developed here.

9.1 Improving the Discharge System for Small Presses

Some of the ways of improving the performance of the STRIPE system have already been outlined, but significantly increasing the scanning speed is not thought to be an option. The possible refinements all relate to improving the quality and consistency of the generated image. Any one of the following changes would make an improvement; taken together the system's performance should be much improved.

- Using a more powerful laser, or several class 2 lasers to effectively increase the output power of the system without incurring the safety requirements of, say, class 3A laser use.

- Using laser light of a wavelength not strongly present in daylight and fitting a narrow bandpass optical filter to the detecting camera would prevent light of unwanted wavelengths reaching the detection chip. Obviously the filter would have to be carefully matched to those wavelengths corresponding to the stripe-generating laser and its tolerances, given the detrimental effect an imperfectly matched combination had on system performance in this work. This would reduce the sensitivity of the system to ambient light levels, since very little of the ambient light would pass the filter.
- Specifying an automatic aperture (auto-iris) for the detecting camera would ensure that the amount of light admitted to the camera was always the optimum for generating the best possible images. This setting would be arrived at by trial and error, but once identified would be controlled either by the aperture system itself, or by a lightmeter in the area of inspection.
- Incorporating the histogram-based image thresholding technique described in subsection 3.7.4 is vital, and is probably at least as valuable as the previous two modifications listed here.

The foregoing changes would allow such cumbersome features of the present work as the blackout to be done away with, since such an improved system could work at relatively high ambient light levels.

In any continued use of the STRIPE system the role of the range map should be re-examined. This image was not used as a source of data during this work, partly because it rarely showed any data worthy of extraction and partly because it was unnecessary. The intensity map, particularly toward the end of the work, when better use was being made of the STRIPE system (after fitting the blackout, removing the camera's filter and shortening the stripe as much as possible), provided all the information necessary for discrete deposit identification. In view of this, further modification of the system should be considered, or even a new system designed, around the principle of intensity variation.

Investigations should be carried out (ideally on-site with production filter cakes and equipment) into likely problems of stripe absorption by different materials and for determining suitable laser wavelengths to overcome this phenomenon. Some of the tests reported in Chapter 7 indicate that some colours of filter cake are likely to reflect much less of the incident laser light than others, to the point where image generation using available light sources may be impracticable for certain filtered materials. This finding must be examined in further work using a variety of filter cakes and wavelengths of laser light, perhaps including those outwith the range detectable by the human eye.

To be of widespread and long-term benefit, one of the major limitations of the discharge system as it now exists must be overcome, i.e. its inability to cope with fully caked filter cloths. The stated aim of this work did not include the detection and removal of cake completely covering the filtration area of a filter cloth, just the ability to cope with discrete deposits. The problem of detecting fully caked recesses stems from the processing of intensity images to detect bright areas, which correspond to edges of cake deposits. If the cake is complete it does not have any distinct edges to preferentially reflect incident laser light, so the resulting image does not have any clearly identifiable cake features. A number of ideas were proposed during this work to address this important question, but they were not pursued because of a lack of time and the self-imposed remit. Some of these ideas will now be outlined briefly.

The problem is to create signals from the unbroken cake face which can be interpreted by the image analysis software to mean that the cloth is fully caked and that scraping is required. Two simple ways suggest themselves to achieve this; to place reflective lumps or latex patches on the cloth. A number of small areas of cloth within the recess could be coated with latex, as already mentioned for gasketing surfaces, so as to prevent filtration at these points. If cake did not form over these patches (say 20 mm square), but the cloth was otherwise fully covered, the analysis software would detect the appropriate number of 'edges' (below the patches) in the correct areas of the recess and automatically signal a full cloth scrape (or other appropriate action). It is, however, likely that although filtration could not occur at the patches cake, or slightly wetter material, would build up and cover them, thus rendering this device inoperable. If, however, instead of patches of latex, lumps of latex (or another, more reflective and impermeable material) were used, the likely performance is much improved. It is proposed to attach a number, say four, of these reflective protrusions to the filtration area of the filter cloth. Each protrusion could be, say, of 20 mm diameter and of a length perpendicular to the cloth equal to the depth of the plate's recess, i.e. the free end would be in the plane of the gasketing surfaces. The protrusions on adjacent plates should then butt together during press closure, as do stay bosses on large filter plates. If, at discharge, a cloth's image does not show the correct edges of these protrusions in the correct places, then the protrusions are probably surrounded by filter cake and a full cake is signalled.

Introducing such protrusions to a filter cloth obviously has ramifications for scraping actions, cloth cost and filtration capacity. If, as has been assumed in this work, a deposit-specific scraping philosophy is in force then it is a trivial matter to program protrusion avoidance into the scraping routines. The cost of filter cloths would inevitably be increased; only a careful study of the economics of the issue of automatic discharge of filter presses would determine how detrimental this would be, given the bonus of fully caked cloth detection and unmanned operation. The volume of filter cake lost per cycle due to the use of the proposed 3-D markers would be very small. The value of such a loss would almost certainly be recovered in savings achieved through automatic operation.

9.2 Automatic Discharge of Large Presses

The difficulties to be overcome in applying the type of automatic inspection developed here to large presses include those of optical access and scanning speed for the size of area to be inspected.

As discussed earlier (Section 3.5) to obtain a satisfactory resolution across the area of the small (0.5 m square) filter plates used in this work with the modified NEL STRIPE optical system, a stand-off distance of 1.5 m from the top edge of the filter plates was required. This large stand-off was necessitated by the depth of the field, as viewed from above at the small inclination to the vertical corresponding to the relatively narrow opening between the plates. A proportionately large stand-off would be required in dealing with all other sizes of plate, since the gap between the opened plates would not be larger (relative to plate size) than in the small experimental press. Hence a plate 2 m square would require a very large stand-off in order to achieve the requisite path length ratio (sensor to top of plate : sensor to bottom of plate) to detect small objects at the point furthest from the sensor. It is possible to achieve these large (many metres) pathlengths by passing the beam back and forth between mirrors. This would make the detection equipment much more compact and hence more readily incorporated in the design of new filter presses, or more easily retro-fitted to existing installations. The biggest problem with this approach is the size of the mirrors required. For a 2 m press, these mirrors would be large, cumbersome and expensive, liable to give rise to errors in the image if not well manufactured and maintained. Any faults in the mirror will distort the image. As stated earlier, the success of an inspection or verification system of this type is totally dependent on the quality of the image obtained of the area of interest. Hence any proposed component which compromises this is unwelcome.

While optical access to the filter cloths in the research press was not difficult, just inconvenient, such access to the cloths on larger filter presses may be a problem. Overhead beams, pneumatic connections (membrane inflation), cloth cleaning apparatus, plate transport mechanisms, safety devices; these may, individually or collectively, make unrestricted viewing of the whole of a cloth face very difficult.

The time required to obtain an image of a cloth face greatly affects the viability of the whole system. If it takes too long, automatic cloth inspection will not be seen as an attractive investment. The STRIPE system as used here is rather slow, typically taking four seconds to scan the entire 0.5 m square cloth. Scaled-up in proportion to the area scanned, a 2 m square cloth would require 64 seconds of scanning, which is unacceptable. NEL have advised that the STRIPE system's data acquisition rate cannot be significantly improved. For this reason alone a new approach is needed for large filter plates.

The foregoing points relating to plate size, scanning speed and access (unobstructed pathlengths) suggest a new train of thought when considering a new inspection system for larger presses. They all point to the desirability of inspecting, not the entire area of a filter cloth, but limited critical portions only. This concept is valid if key areas of a cloth can be identified as being of critical importance, e.g. the gasketing surfaces and the area immediately round the slurry feed hole. This way only a few relatively small areas on each plate need be inspected, which could in principle be done very quickly. If these were found to be free of adherent deposits, the next plate could be addressed.

This idea introduces a change of concept with regard to removing deposits. Whereas in the system developed here every deposit above a certain size is addressed individually, the approach now proposed suggests a 'clean' or 'fouled' signal for each filter cloth. If the latter, some mechanical means could be employed to address the entire cloth, thus dislodging any deposits. Such a device may shake the cloth, or simply scrape the full area of the cloth in one pass. Assuming the inspected areas are chosen with care, a fouled signal from any one of these would automatically stop further inspection of that cloth and initiate the mechanical system immediately. This way inspection time is kept to a minimum and mechanical action taken only if absolutely necessary, thus saving time and lessening wear and fatigue of the mechanical removal system.

This limited cloth inspection cannot work in isolation, however; another system is needed to supplement the inspection of critical areas. So far no thought has been given to the amount of undischarged cake remaining on the rest of the filter cloth. It is possible that the cake covering the critical areas might discharge correctly, leaving, say, 80% of the cloth still fouled. This situation would not be dealt with correctly on the scheme proposed above if the limited inspections returned a 'clear' signal. Obviously this is unacceptable.

A small fraction of the original filter cake left on a cloth until the next cycle is acceptable (provided it is not in a position where it will create a problem or a hazard, i.e. in a critical area subject to special monitoring according to the proposal above). This small loss of discharge per cycle will be compensated by the anticipated increase in cycles per week resulting from the use of a fully automatic discharge system.

What is needed, therefore, to supplement the proposed critical area monitor, is a system which monitors the amount of cake actually discharged by each cloth, or, failing that, by each pair of cloths in each chamber. If an accurate assessment of what has fallen off a cloth is available, a decision can be made whether a) to act immediately against the cloths or b) to initiate the inspection of critical areas which may give rise to acting against the cloths, or c) to pass the cloths without further action. A threshold value would be defined representing the unacceptable discharge quantity which would trigger action automatically. If, for example, this value was set to 70%, then if less than 70% discharge is monitored from a chamber, a), mechanical action, would be taken immediately and critical area inspection, b), would be done without. If more than 70% discharge was monitored, immediate mechanical action would not be taken, but b), inspection of the cloth's critical areas would be initiated, followed by appropriate cleaning action or by c), as required.

Such a discharge monitor would probably be mounted below the filter press and have a horizontal detection plane running longitudinally under the press. Cake fragments falling through this plane would be arranged to register a measure of the area of each. The total projected for all fragments associated with the currently discharging chamber could then be compared with that representing a full chamber discharge, and action taken accordingly.

One of the problems encountered in such discharge monitoring is the way cake falls from a press. According to numerous observations made by the researchers, discharging filter cakes behave as uniform sheets tearing or snapping under their own weight; i.e. virtually all cleavage planes are nearly perpendicular to the cloth surface so all torn fragments have the same thickness as the original cake. However, rather than falling in a vertical plane, in which the projected area of any fragment equals the area of cloth covered by it, the fragments tend to peel off the filter cloths and roll as they fall. Some fragments do fall in an 'ideal' way, but others do not and this may be a problem for a two dimensional, i.e. single plane, measurement system to deal with. There would be an inherent inaccuracy associated with such a system, aggregating projected areas of fragments in a vertical plane as a measure of cake area discharged; it is, however, possible that statistical analysis of measured values and actual discharge values for each application may allow a factor to be applied to the results to compensate for this.

A more accurate, but much more difficult, way of monitoring the discharge of filter cake would be by the use of three video cameras. Viewing the fragments falling from each chamber from above, laterally and longitudinally, an accurate measure of cake discharged should be possible, regardless of rolling or pitching of the fragments. This approach might require real time analysis of video pictures and would probably entail high equipment costs.

If the single detection plane scheme can be made to work accurately enough, e.g. to within ±5% of actual discharge, there is not a significant advantage to be gained by using such a 3-D video system, since neither measurement technique is capable of indicating exactly where each cake fragment fell from, i.e. gasketing surfaces, round the feed hole etc. This means that inspection of important areas of filter cloth is still necessary, however sophisticated the drop-discharge monitor.

The concept of acting against the whole filter cloth, even if only a small part of it is fouled, goes against the ethos of the work described in this thesis, but is in line with the feelings of some press manufacturers because it allows faster operation; for example instead of several robot scrapes, only one large scrape is used. If this is accepted, it opens the way for many other types of inspection technique. In particular, this allows consideration of systems which cannot output location information, but which can output details of the size of deposits, since this is all that is now of interest. If the answer to the question 'Is the total area of adherent cake less than the threshold value for action?' is 'yes', immediate action need not be taken; if 'no', action must be taken immediately. In the case when the answer is 'yes', there is still the problem of inspecting the critical areas before passing the cloth as acceptably discharged.

Two other ideas for detecting adherent cake are now outlined briefly.

1. A system using Moiré fringes. NEL have expertise in this area also [21]. A Moiré fringe imaging system could in a single viewing generate a very accurate topographical map of the cloth surface, and hence of any protrusions on it. The main problem with this approach, however, is likely to be the difficulty in interpreting this image. The surface of a filter cloth is usually far from planar, with undulations, peaks and ridges being typical of the features observed during site visits. These apparent perturbations may confuse image analysis software searching for lumps of filter cake in an

image. A classification system may be of benefit in interpreting such images. Such a system is 'taught' how to recognise 'good' and 'bad' images. The learning process consists of many images being input to the software, along with a statement of whether the image is good or bad. The software uses this knowledge to establish which image parameters should be investigated to distinguish between good and bad images. Such an automatic technique with many teaching images can be faster than a person performing the same function. This technique is not always the answer to problems of image analysis however.

2. One of the advantages of the STRIPE system, as used in its modified form in this work, is the ease with which deposits are detected in the generated image. With a minimum of image tidying and a thresholding operation the object detection functions can be used to search for deposits. This is an attractive sequence of operations since it is simple and quick. An image acquisition system which produces the same kind of easily interpreted image as the STRIPE system, but which acquires the image in a much shorter time would seem to be ideal for this application.

   It may be possible to develop such a system using a technique based on phosphorescence. Systems are currently available [49] which assess substances by measuring the decay time of energy radiated by the substance in response to a measured previous input of light energy. It is thought that a variation of this technique may allow an accurate measurement of the amount of retained filter cake on filter cloths. Assuming that the absorption and reflectance characteristics of input energy by filter cloths and filter cakes are different, it may be possible to construct an image based on the different phosphorescence characteristics of the cakes and cloths, i.e. based on detected energy emitted within a limited time. Patches of cake should behave differently to cloths and be highlighted in the image accordingly. Such a distinction in the image should be similar to the variation of intensity in the STRIPE image, and be processed as readily. It may not be possible to acquire an image of the entire cloth in one go, and this may not be desired if only critical areas of the cloth are to be inspected; but, if a full plate inspection is required, it may be possible to do this by adding together a number of images, each of a different area of the plate. If the image generating technique is fast enough this multiple imaging need not increase the cycle time unduly. Indeed, given the rate at which ever faster computer systems are being developed to have greater amounts of memory at low cost, it may be possible to generate several images simultaneously, thus avoiding a time penalty.

Among the obvious objections to such a proposal are: the cake material may not phosphoresce significantly; the amount of input energy which would be required to assess the phosphorescence of a 2 m square filter cloth may be infeasibly large; the detection of the radiated energy may be impractical with CCD cameras; there may not be a detectable difference in the energy radiated by cake and cloth. Any of these, or perhaps the cost of the components, may make this idea nothing more than an interesting research project, but it may be worthy of further examination.

An alternative approach might be to measure the phosphorescence or, more conveniently, fluorescence, of the filter cloth, assuming the filter cake does not have any. It may be relatively easy to treat filter cloths so that they fluoresce in U.V. light, as some synthetic fibres do. Staining of the filter cloth may, however, be enough to mask this effect. Further investigation of this idea is encouraged.

It is recommended that contact be re-established with Alex Yelshin to inform him of the work carried out on this project. It is probable that he would be able to make valuable comments on it.

Other methods of cake removal could be investigated, e.g. the air knife principle mentioned in Chapter 4. It should be a relatively straight-forward matter to mount such a system on the research press, or even a working press, to test its usefulness.

Regardless of which direction future work takes, one investigation which must be conducted is the chosen system's ability to operate successfully in a steamy environment, as is often encountered around discharging filter presses which have included a cake washing operation as part of the process cycle. The ability to work through clouds of water vapour may have an important bearing on the design of a successful monitoring system.

Some investigation of the requirements for system ruggedisation may be pursued. The internal protection required by the system, the materials used in its manufacture, resistance to EMI or RFI interference are all important factors which must, at some stage, be considered.

A worthy area of further work would be systems capable of detecting filter cloth defects during the discharge cycle. Tears, folds, creases etc. are all significant defects which ideally will be detected and signalled while the press is open, rather than during the pumping operation, when the failure of a cloth becomes more serious since it leads to more downtime for the cleaning of lines and transferring 'dirty' filtrate back to the slurry tank, as well as changing the damaged filter cloth.

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Appendix A

Equipment details

The following tables give brief details of the companies contacted while searching for items of equipment. Some comments are made on the equipment offered by them and/or the impression created by the company.

Company Name	Telephone	Date	Comments
George Meller (Nick Oliver)	01 579 2111	12.10.89	M1, Al pump £272
Kecol Pumps Ltd.	07462 4311	12.10.89	EB1-A, Al 1" £390
SSP Pumps Ltd.	0323 25151	12.10.89	Not allowed to quote. Must speak to Clyde Associated Engrs Ltd.
Clyde Associated Engineers Ltd. (Steve Ramsay)	041 954 0111	17.10.89	1" pump, Al £464 Cast iron £598 Polypropylene £680 Stainless Steel £911

Table A.1: Air driven diaphragm pumps

The pump chosen was the M1 Al pump from George Meller in London. Ordered 14.11.89, arrived 13.12.89

Company Name	Telephone	Date	Comments
S.I.A. (Graham Coats)	041 556 7301	27.10.89	8.2 cfm, 100 psi, £599 less 25% 17.7 cfm, 100 psi, £919 less 25%
Motherwell Bridge (Alistair Kirkwood)	0698 355711	27.10.89	If over 3hp (10 cfm) 3 phase High prices, e.g. £728 & £884
Norgren Martonair	041 954 5037	27.10.89	No longer deal in compressors
Brian Ferrier Pump Supplies Ltd.	031 553 4001	25.10.89	7.9 cfm (actual 6.8) 115 psi max £410 list, less 10%
DAK	0506 854821	25.10.89	All their's are too big for us
Compressor Services (Mr Noble)	041 889 8664	25.10.89	Ex hire, 7.84 cfm, 150 psi, £200 Compair E20, 13.70 cfm, £769 E25, 17.32 cfm, £1007
The Hydrovane Compressor Co	0527 25522	25.10.89	9.5 cfm, £680 22 cfm, £1490 without cooler 22 cfm, £1780 with cooler 19 cfm, £1950, 10 bar
Woodside Pneumatics (Bill Houston)	0236 56171	1.11.89	Hydrovane, 100 psi, 21 cfm. No receiver, £420 inc 3 month warranty. Reserved for 1 week
Fusion Equipment		25.10.89	Don't deal with compressors
Aircare (Paul Wynne)	0236 823720	2.11.89	8 cfm, ex-hire, 6 months, SIP, 50l £250/300 6 mnth parts & labour
Kerr	041 429 3368	2.11.89	Recon, 6 months warranty, 9 cfm, £550. Azenda, 20 cfm, £650. 10 cfm £682 less 20%, 12 cfm £845 less 25%
C.B. Nicol	0333 23161	2.11.89	E16, 15.2 cfm, 3hp, £695 - 15% Warranty agents for them
Airpower Systems (Derek Burnside)	0324 552599	2.11.89	SIP w/shop comp'r, 4 months ex-hire, 8 month warranty. 19.5 cfm 200l, 5.5hp, 150 psi, ≈£500

Table A.2: Air Compressors

An Azenda compressor from Brian Ferrier Pump Supplies Ltd. was chosen. Ordered 14.11.89, it arrived 23.11.89.

Company Name	Telephone	Date	Comments
L. C. Automation (Ken Davis)	0772 34951	1.11.89	
Siba Delta (92) Ltd. (Brian Robertson)	061 976 3636	1.11.89	£4/5k. Alt'ive is ≈£1.2k has to be 1.2m from robot
Lightguards (Services) Ltd.	0462 456611	1.11.89	
Proctor Brothers Ltd.	0532 430531	11.12.89	Supply custom solutions to problems. Very helpful, but for such a basic problem he suggested I contact LC Automation. They don't manufacture photo-electric devices, but buy in & include in own designs

Table A.3: Photo-electric curtains

It was decided not to purchase a system of this kind, mainly because of the expense, but also due to the barrier of the 'rig structure' which prevents access to the robot.

Company Name	Telephone	Date	Comments
ABB Robotics (David Bradford)	0908 319666	31.10.89	10% discount. ≈£40k
AB Robotics	091 510 9292	2.11.89	
AMTRAC (Bill Smith)	0282 415174	2.11.89	
Automation Technology	04862 29361	2.11.89	Build to order only. For good control of 3-axes, £12k, likely another £12k to finish package. Total ≈£30k, timescale ≈16/20 weeks
John Brown Automation (Mr Stone)	0203 473748	2.11.89	Don't do gantry systems, suggested Crocus Ltd.
CAM Systems Ltd. (Peter Christie)	0284 753097	2.11.89	Compact well engineered lightweight modular system, well suited to our relatively small working loads
GEC (Alan Wanstall)	0788 542144	6.11.89	
Hayes & Fordham (Mr Fordham)	0532 507090	6.11.89	
KUKA	0734 303500	6.11.89	
Norgren Martonair	0608 61676	6.11.89	Don't make, try handling division.
Reis Robot	0908 270042	6.11.89	Possibility of ex-demo robots being suitable for our purpose potential for a lower cost solution!
Sands Technology (David Sands)	0223 420288	6.11.89	
Time & Precision	0256 28428	7.11.89	
Cincinatti Milacron	021 351 3821	8.11.89	Very, very expensive!
Unimation (Peter Edwards)	0952 29031	8.11.89	Saw video of PUMA 700 Series
CGM Automation (Dave Ash)	0533 787405	8.11.89	Sent sketch, 8.11, no reply.
ESAB Automation	0264 332233	14.11.89	For welding
Crocus Ltd. (Nigel Clark)	061 487 1486	14.11.89	£28/30k, custom built. Heavy modular components, designed for quite heavy lifting duties.

Table A.4: Robots

The V-Plan robot from CAM Systems Ltd. was thought to be the most suitable of all the gantry robots investigated. Ordered 1.6.90.

Company Name	Telephone	Date	Comments
Vision Dynamics	0442 216088	15.11.89	
Pulnix	0256 475555	15.11.89	
Agema Infrared Systems	0525 375660	15.11.89	
Insight Vision Systems Ltd.	0684 310001	15.11.89	
Microsystem Services Ltd.	0494 41661	15.11.89	
Integral Vision Ltd. (Mr Magalhaes)	0234 327422	15.11.89	From 3 people's work at Cranfield on robot vision
Brian Reece Scientific Instruments	0635 32827	15.11.89	
Computer Recognition Systems Ltd. (John Thompson)	0734 792077	15.11.89	Expensive. Try again in future once successful. Claim to be biggest British specialists
Kontron Electronics Ltd.	0923 245991	15.11.89	
Quantel Ltd. (Brian Kercker)	0635 32222	15.11.89	
Sira Electro-optics Ltd.	01 467 2636	15.11.89	Expensive, one off basis
Syscon Ltd.	0223 420919	15.11.89	
Ultrafine Technology Ltd.	01 569 9920	15.11.89	
Industrial Monitoring Eq't (Mike Phillips)	0923 30323	22.11.89	
Airmatic Engineering Ltd. (Geoff Hutton)	050 981 2816	28.11.89	
Analytical Vision Systems (John Nottingham)	046274 2922	28.11.89	
Allen Bradley (John Macrory)	0908 71144	29.11.89	Too expensive
Alphr Technology	0462 675838	29.11.89	
Cambridge Consultants Ltd (Elizabeth Orme)	0223 420024	29.11.89	
Modicon	0256 460466	29.11.89	
Image Inspection	01 748 9898	29.11.89	
International Robomation Intelligence Ltd. (Roy Barnes)	0564 772054	29.11.89	
Joyce-Loebl (Ron Owen)	091 482 2111	29.11.89	
Planer Industrial	0932 786262	29.11.89	Couldn't do what we want
Smith Associates	0483 505565	29.11.89	Consultants only
Trivector	0767 82222	29.11.89	No vision now, try Cosense
Cosense (Mr Brookfield)	0223 844190	29.11.89	
NEL (Rob Rixon)	03552 20222	6.9.89	STRIPE range-finder. Not really a 'vision' system but should be suitable

Table A.5: Sensing systems

Company Name	Telephone	Date	Comments
Automatix International	0203 415644	16.9.91	All Macintosh
Computer Recognition Systems Ltd.	0734 792077	16.9.91	Library Not for sale
Davy M^{c}Kee	0202 537000	16.9.91	
Electronic Automation	00482 879641	16.9.91	Systems integrators
Foster Findlay Associates (Dr. John Foster)	091 273 1111	12.9.91	'C' library available
Matrox UK (Dave Humphries)	07933 614002	17.9.91	Write own libraries
Data Cell	0734 333666	17.9.91	Think they can do it
Brian Reece Scientific (Pete Hanson)	0635 32827	17.9.91	Very helpful; no 'C' yet
Vision Dynamics (Aran Wood)	0442 216088	17.9.91	Helpful, need framestore

Table A.6: Image analysis software

The software library chosen was the C_Images package from Foster Findlay Associates Ltd. in Newcastle.

Item	Description	Supplier details	Ordered	Arrived	Cost (£)
1	Filter press	Edwards & Jones Ltd. Whittle Road, Meir Stoke-on-Trent, ST3 7QD Tel : 0782 599000	12.9.89	5.10.89	2000 (3 year loan charge)
2	Air-driven diaphragm pump	George Meller Ltd. Orion Park, Northfield Ave Ealing, London, W13 9SJ Tel : 01 579 2111	14.11.89	13.12.89	307
3	Air compressor	Brian Ferrier Pump Supplies Burlington St, Leith Edinburgh, EH6 5JL Tel : 031 553 4001	14.11.89	23.11.89	369
4	Four sets of filter cloths	G.H. Heath & Son (UK) Ltd Burslem, Stoke-on-Trent ST6 4QE Tel : 0782 575500	5.12.89	17.1.90	Free Samples (Worth ≈400)
5	HSE Robot Safety Booklet	Safety Services, Old College University of Edinburgh Tel : 031 667 1011	6.12.89	8.1.90	9.50
6	Cylindrical tank (for slurry)	Eastern Storage Equipment 2 Dewar Sq, Deans Ind Est Livingston, EH54 8SA Tel : 0506 413313	12.1.90	31.1.90	37.16
7	Trolley discharge hopper	Eastern Storage Equipment 2 Dewar Sq, Deans Ind Est Livingston, EH54 8SA Tel : 0506 413313	12.1.90	31.1.90	40.30
8	HP Vectra QS 20 80386 42Mb PC	Hewlett-Packard Ltd. South Queensferry West Lothian, EH30 9TG Tel : 031 331 1188	9.2.90	4.4.90	≈4000
9	Kee Klamp No. 7 tubes & fittings	W.H. Banks & Son Ltd. Duff Street Lane Edinburgh, EH11 2HS Tel : 031 337 2293	11.5.90	9.7.90	value 578.51 discount 15%
10	4 axis gantry robot system	CAM Systems Ltd. Moreton Hall Ind Est Bury St Edmunds Suffolk, IP32 7DF Tel : 0284 753097	1.6.90		≈20K
11	Co-processor (80387)	Technomatic 486 Church Lane London, NW9 8UF Tel : 01 205 9558	?	12.6.90	282
12	STRIPE Laser-based range finding system	NEL East Kilbride Glasgow, G75 0QU Tel : 03552 20222	.8.90		5700 (3 year loan)

Table A.7: Equipment list

Appendix B

Filter cloth materials and properties

Fibre	Strong acid	Weak acid	Strong alkali	Weak alkali	Solvents	Oxidising agents	Hydrolysis
Polyester	★★★	★★★	★	★★	★★★	★★★★	★
Polypropylene	★★★★	★★★★	★★★★	★★★★	★★★★	★★★	★★★★
Polyamide	★	★★★	★★★	★★★	★★★	★★★	★★
Polyaramid	★★	★★★	★★★	★★★	★★★	★★★	★★
Acrylic	★★★	★★★	★★★	★★★	★★★	★★★	★★★
PTFE	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★
Co-polyimide	★★★	★★★	★	★★	★★★★	★★	★★

Resistance of fibre to acids, alkalis etc.,... ★ Poor ★★ Fair ★★★ Good ★★★★ Very Good

Table B.1: Some filter cloth materials and their properties

Appendix C

Filter press manufacturers

The following is a list of filter press manufacturing companies (or UK agents for foreign companies) contacted during this research.

1. Alval, agent for Z.W.A.G. (Zschokke Wartmann), Switzerland
2. Charlestown Engineering, Cornwall, UK
3. CRB Filtration, agent for Rittershaus & Blecher, Germany
4. Edwards & Jones Ltd. Stoke-on-Trent, UK
5. Euro Technic, Stoke-on-Trent, UK
6. Eurofiltec, France
7. Fairey Microfiltrex, UK
8. Fairey Industrial Ceramics, UK
9. Fawcett Christie Hydraulics, agent for Purolator Filter GmbH, Germany
10. Flowtech, UK
11. KHD Great Britain, agent for Humboldt Wedag, Germany
12. Larox, Finland
13. Dr. M, Germany
14. Pannevis, Netherlands
15. Putsch, Germany
16. Schenk Filtersystems, Germany

17. Sillaford, agent for Trislot Systems and Bekaert, both of Belgium
18. Sparkler Filters, UK
19. Stella-Meta, UK
20. Stockdale, UK
21. VC Filters, UK

Appendix D

Previous Publication

The following paper was published by the Institution of Chemical Engineers in the preprint volume of papers presented at the IChemE Research Event, UMIST, Manchester, 9 & 10 January 1992. ISBN 0-85295-290-2.

(Reproduced here with the permission of the IChemE)

The Development of a Laser-Guided Robotic Discharge System for Filter Presses.

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Abstract

Robotic techniques for discharging filter presses are being developed in this laboratory. Our objective is to secure full, automatic, discharge without the operator intervention currently required to ensure complete detachment of filter cake from the cloths - a particularly desirable objective when the filtered materials are hazardous or subject to contamination, and where labour costs are of critical importance.

Means have been devised for optically identifying residual filter cake deposits on the filter cloths of a small production-scale press after normal gravity discharge has occurred. The images of such deposits are processed electronically to generate signals which guide a four-axis gantry robot to effect suitable scraping actions.

The imaging and robot systems are designed to serve a group of presses, consequently reducing the capital cost per press installed.

Introduction

The filter press is a batch-filtration device apparently first introduced in the 18th Century, which nevertheless retains today an important place as the filtration means of choice in many widespread process situations. More recent and sophisticated filtering arrangements operate continuously and more nearly automatically; but the filter press has at least two unmatched advantages: It allows filtration and subsequent solids washing to proceed in a totally enclosed system of minimum free volume; and - in the case of modern diaphragm or membrane presses - it offers a uniquely rapid, effective and low-cost means of dewatering the filtered solids by squeezing them in situ against the cloth by application of hydraulic pressure to the membrane bounding the other face of the cake. The filter press is thus particularly recommended for use with hazardous or easily contaminated materials, and in applications where the recovered solids must be dry before they can be further processed or disposed of.

All present filter press arrangements, however, require operator supervision of the discharge of the solids cake, whose removal from the cloth must often be completed by hand. Automatically sequenced presses are in widespread use; but operator intervention is invariably required for monitoring the cake discharge and, on occasion, completing it by removing adherent cake fragments from the cloth by manual raking or scraping. This labour is particularly expensive and uncongenial when the operator must wear protective clothing, either to isolate him from hazard or to shield the product from contamination.

Accordingly, we are developing and evaluating means of automating the monitoring and completion of filter-cake discharge from filter presses of otherwise orthodox design, with the object of extending the acceptability of these in process applications to which they are inherently best suited. This is admittedly a literal, apparently naive, approach to the essential problem of devising fully automatic filtration apparatus having the advantages of the existing filter press. It has, however, the merit, not only of building on existing and well established technology, but also of offering the prospect of equipment that may be retrofitted to existing presses and, indeed, made to serve entire groups of presses, with considerable prospective capital savings over more radical schemes of improvement.

Cake-Residue Identification and Removal

The direct replacement of the human operator requires the provision

1. of mechanical means of cloth scraping, activated and directed by
2. means of identifying and locating adherent deposits on the cloths.

Item 2) must itself comprise a) hardware (physical sensor) and b) software (image recognition and processing) components.

Figure D.1 shows the general arrangement of the physical parts of our system and their relation to the orthodox filter press (Edwards & Jones Ltd., Stoke on Trent) to which our apparatus is applied. The optical cloth-monitoring scanner is mounted on a servomotor-driven carriage running on overhead horizontal rails parallel to the long – or X-axis of the press. The scraper proper, one experimental version of which is shown in Figure D.1, can be brought up to the cloth-covered face of the plate requiring attention by the longitudinal (X-)motion of the same servo-driven overhead carriage as carries the optical monitor. The X-carriage forms one component of a computer-controlled four-axis gantry robot.

Cloth - Scraping Robot

This proprietary robot system (CAM Systems Ltd., Bury St. Edmunds) is shown in elevation and plan in Figure D.2. It allows the scraper head to be traversed horizontally across the face of the cloth by the motion of a second, Y-motion, carriage bearing the scraper assembly, and to be moved vertically in the same plane by means of a Z-motion ball-screw device mounted on the Y-carriage. A two-position rotary pneumatic actuator can rotate the scraper head about the Z-axis through 180° into alternative fore- or aft-facing orientations, so that the scraper can address either of the two plate surfaces exposed by the opening of the press and separation of the plates. The Y- and Z-motions, like the X-motion, are driven positively by servo-motors; so the scraper can be brought to any designated spot on the cloth-covered surface in response to Y and Z co-ordinate signals from the controlling computer and similarly can then be made to execute any desired scraping action.

For application to presses having no automatic plate-shifting mechanism, the pneumatically retractable telescopic legs of our novel plate-shifting mechanism project downward from the X-carriage so that, when extended, lifting hooks can engage the plate-lugs. On retraction, the selected plate at the end of the stack can be raised until its lugs no longer rest on the side-bars of the press, when it can be separated from the other plates of the stack by motion of the X-carriage.

A significant advantage of the overhead gantry configuration adopted for this robot system, in preference to, say, the more familiar jointed 'robot arm', is the ease with which it can be extended to cover a larger press or a group of presses. The manufacturers are experienced in installing systems many times more extensive than that supplied for our proving trials with a single small press, so the technology of this part, 1), of our automatic cake-discharge system is already well developed.

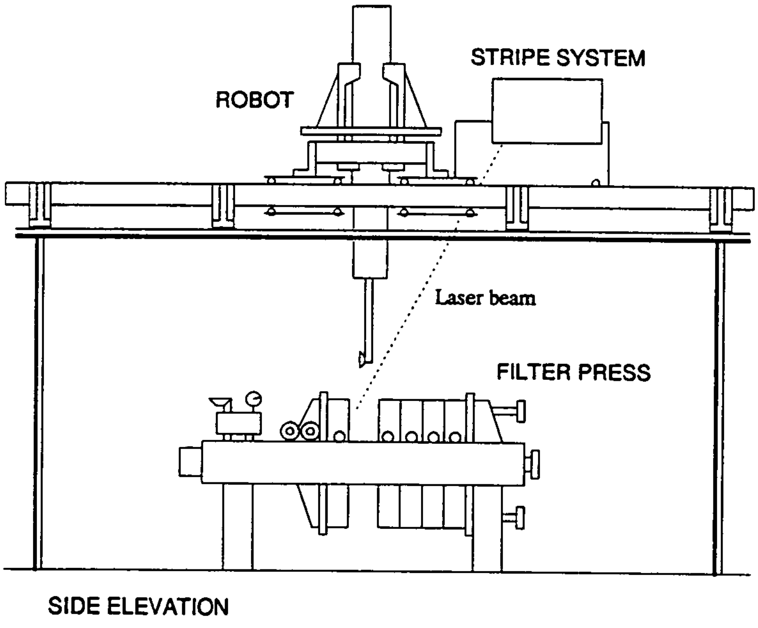

Figure D.1: Layout of Equipment

Plate-Scanning System

This is far from the case for component 2). Indeed, our major innovative task has proved to be the development of 2a), an optical system capable of detecting cake fragments adhering to a cloth inevitably stained to the same colour and far from plane, in the restricted viewing conditions imposed by the limited separation of the plates and the need to view them from above (their only unobstructed aspect). We have solved this problem for the small press in our laboratory, whose plates are 0.5 m square, with a modification of the established STRIPE scanning system developed by the National Engineering Laboratory. The original of this is essentially a triangulation system for registering protrusions from a smooth surface as deviations in the reflected image of a straight stripe of laser light scanned over the surface. Such a system is not very sensitive when the surface is illuminated and viewed as obliquely as the arrangement of Figure D.1 requires, and does not readily allow cake fragments to be distinguished from undulations in the irregularly stretched cloth. Our modification, for which patent protection has been applied, overcomes this difficulty by registering variations in back-scattered light intensity along the reflected stripe and between successive scanned positions. The abrupt edges of cake fragments, being more nearly perpendicular to the cloth surface and to the viewing direction than those of bulges in the cloth itself, backscatter the incident light much more intensely and are thus readily identified.

Although this system works well in our present application, we think it probable that its efficacy of detection and location will be inadequate when large plates (1 - 2 m square) are to be examined; and we are evaluating alternative plate-scanning systems more suitable for large presses and optically unfavourable environments.

Image Processing Software

This performs the vital function of interpreting the scanner-generated images. Objects (cake deposits) are identified and their size and location established. This information is passed to a decision program which decides the type of scrape to be effected and passes the appropriate instructions to the robot controller. Once the robot has completed its tasks another laser scan is made of the cloth to establish the success of the scraping operations; if necessary the robot can rescrape persistently caked areas.

Acknowledgements

This programme, including maintenance for A. Jaffrey, has been funded by SERC Research Grant GR/F/06098. We have also gratefully to acknowledge the interest and help of Messrs Edwards and Jones Ltd. of Stoke on Trent, who have leased one of their presses to us for the duration of the programme; of the

Director, and Mr R. Rixon of NEL, East Kilbride, Lanarkshire, for building and leasing to us the optical scanner to our specification; to G & H Heath & Son (UK) Ltd. for gifts of complete sets of filter cloths; and to the following for gifts of solid particulates obtained by filtration in their industries:

- B.A. Chemicals Ltd., Burntisland, Fife
- E.C.C. International, Cornwall
- Distillers Co (Yeast) Ltd., Menstrie

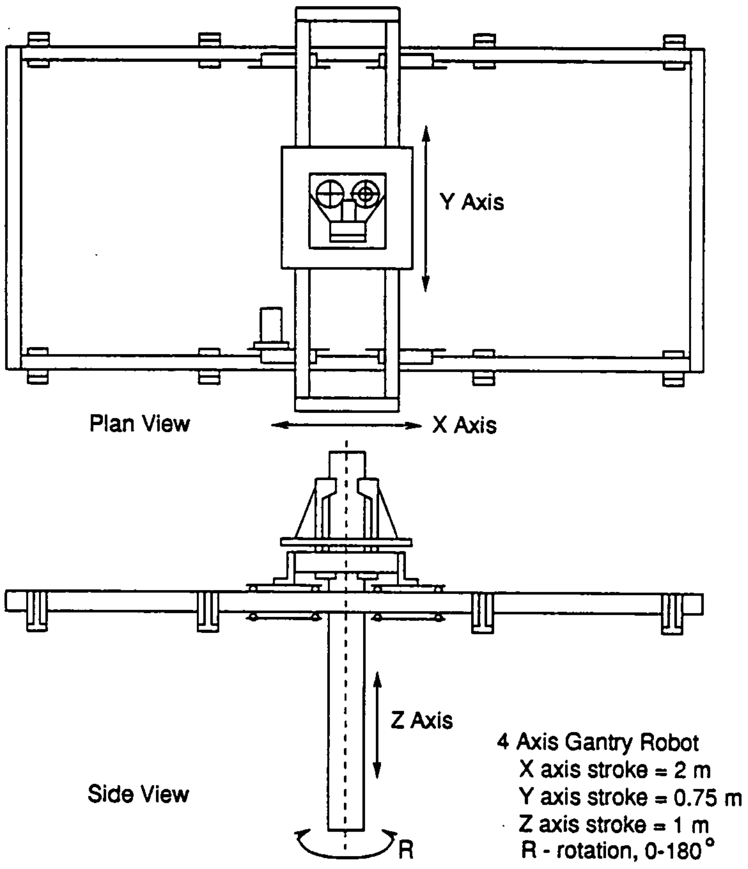

Figure D.2: Robot