Development of An Optical Technique for On-Line Measurement of the Thickness Distribution of Blow Moulding Parisons

by

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A thesis submitted to The Faculty of Graduate Studies
and Research in partial fulfilment of the
requirements of the degree of
Masters of Engineering

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Montréal, Québec

September 30th, 1991

On-Line Measurement of Parison Thickness Distribution in Blow Molding

Abstract

In the extrusion blow moulding process, the strength and weight of a hollow article, such as a bottle, is controlled by an open loop control process called parison programming. The article thickness is increased and decreased by opening and closing the gap of the annular die from which the parison is extruded. The die gap is regulated according to a gap-time profile which an operator determines during start up by trial and error.

An optical sensor has been developed which can measure the thickness profile of the parison on-line just prior to its enclosure in the mould. The device will help operators to program the gap-time profile for optimum use of plastic by providing rapid feedback on the formation of the parison. It also represents an important step toward the development of closed loop control for container thickness distribution.

The device determines thickness by striking the parison at an angle with a laser beam and measuring the separation between the beams that reflect from the outer and inner surfaces of the parison wall. A prototype was built and tested. The prototype uses three lasers at different angles and can make up to 250 point measurements during a one second scan. A personal computer uses specially developed software to reconstruct the profile of the parison wall from the raw data with an accuracy of ± 5%.

Résumé

Dans le procédé de moulage par extrusion et soufflage, la résistance mécanique et le poids de la pièce vide, telle qu'une bouteille, sont contrôlés par un module de contrôle en boucle ouverte appelé programmation de la paraison. Ce programme fait varier le profil en épaisseur de la pièce en augmentant ou réduisant l'ouverture de la filière annulaire d'extrusion pendant que la paraison est extrudée. L'ouverture de la filière est variée dans le temps afin d'obtenir le profil optimal de la paraison que l'opérateur détermine par essais répétés pendant la phase initiale de la production.

Nous avons développé un capteur optique qui permet de mesurer sur la ligne le profil en épaisseur de la paraison qui vient d'être extrudée, juste avant soufflage dans le moule. Ce dispositif pourra aider les opérateurs, par la connaissance immédiate du profil de la parison, à programmer la courbe ouverture de la filière vs. temps pour une efficacité maximale de la production. Il s'agit aussi d'une étape importante vers le développement d'un contrôle en boucle fermée du profil en épaisseur de la pièce.

Le capteur permet d'évaluer l'épaisseur de la paroi transparente en projetant un faisceau laser à un angle et en mesurant la séparation spatiale entre les deux faisceaux réfléchis aux surfaces externe et interne de la paroi de la paraison. Un

prototype a été réalisé et mis à l'essai. Ce prototype utilise trois faisceaux laser à des incidences différentes et peut collecter jusqu'à 250 mesures ponctuelles pendant une période de balayage d'une seconde. Un microprocesseur avec un logiciel spécifiquement développé permet de reconstruire le profil de la paraison à partir des données brutes avec une précision d'environ 5%.

Acknowledgements

I was very fortunate to have three excellent collaborators / supervisors involved in this Masters research Project. First, Dr. Paolo Cielo was instrumental in developing the optical aspects of the technique and evaluating the alternative techniques. Secondly, Dr. Andres Garcia-Pejon for his knowledge of the blow moulding field and the needs of the blow moulding industry. Finally, Dr. M. R. Kamal for his experience with closed loop control, and for making everything run so smoothly throughout the project. Thank you very much.

I would like to thank the Government of Canada and all those who administer it for providing the National Research Council of Canada and allowing me to freely use its facilities and consult the many talented people whom it employs.

At the National Research Council there are many people whom I have not yet mentioned whom I would like to thank for all of the problems that they solved (which I never could have) and for the blatantly brilliant ideas they came up with. They are:

Bruno Gauthier	For solving my toughest electronics problems with brilliance.
Mario Lamontagne	For suggestions that solved problems that I didn't even know that I had.
Marc Dufour	For C'i ,g all of those bugs that looked so obvious to him.
Roger Khayat	The first person I'd see when I had a mathematical formula that I

	couldn't solve, and for all those references.
Louis Charbonneau	For the various electronics and computer fix-its he perpetrated and for not yelling, "#@$%, une autre carte brisé!!?"
Robert Di Raddo	For sharing his experience in the field with me.
Claude Arnould Pierre Campana Antoin Pelletier Jean-Guy Allard Rigoberto Bermudez	For endless favours in the shop.
Gary Ng	For finding and removing a "time bomb" virus in my word processor two days before I finished this thesis.

As well, Yvon Bouthillier, Christian Bromhorst, Jean. F. Bussière, Blaise Champagne, Ghislain Chouinard, Christain De Grandpré, Alfredo Di Carlo, Denis Frayce, Patrick Girard, Louis-Paul Hérbert, Jean-Pierre Monchalin, Georges Salloum, Daniel Simard, Bernard Tremblay, Yvon Bouchard (Coreco), Claude Fedel (JML Optical).

Finally, I'd like to thank Neil Swan, my father, who volunteered to line edit this entire thesis.

The development of the technology described in this thesis was jointly and equally funded by The McGill University Department of Chemical Engineering and the Industrial Materials Institute of the National Research Council or Canada.

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CHAPTER 1

Introduction

Blow moulding is the process by which plastic bottles are made. The process is also used to make a range of other hollow articles such as storage tanks, sail boards, many toys, and even car bumpers. There are two main types of blow moulding processes (1): Injection Blow Moulding, and Extrusion Blow Moulding. The research work discussed in this thesis is applicable to the extrusion blow moulding process.

After a manufacturer has an extrusion blow moulding process running, his main concern is optimizing the strength and weight of the bottles. If the amount of unneeded plastic in a container can be kept to a minimum, this will a) save resin and energy, b) reduce the time consuming cooling step in the blow moulding cycle, thereby increasing the production rate, and c) lessen the burden on landfill sites and thus increase the product's acceptability to the environmentally conscious consumer.

The thickness of plastic containers which are made by extrusion blow moulding is regulated by a control process called parison programming (see Figure 1). To control the thickness at various points in such containers, the die-gap is varied during

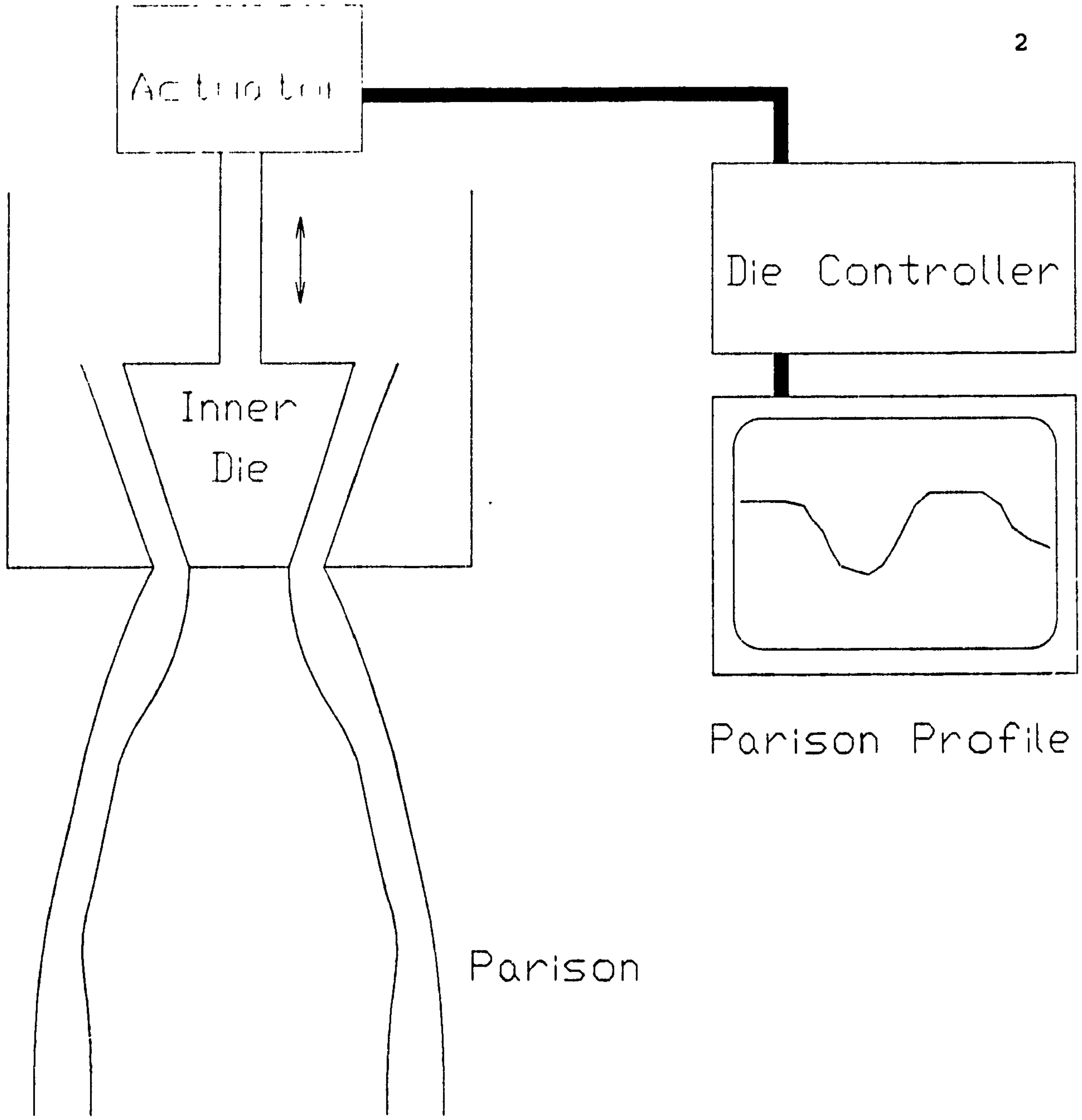


Figure 1 : Traditional Parison Programming system. Note how the thickness varies with the profile on the monitor.

extrusion according to a pre-programmed, gap-time profile. The gap-time profile is imparted to the extrudate, called a parison, which is then enclosed in the mould and blown into a bottle.

A major problem with parison programming is that an operator must create the gap-time profile by trial and error. The operator must cut open the bottle, measure its thickness at various points, and then edit the gap-time profile many times. This is a time consuming process. It is also difficult for an operator to predict how the gap-time profile will be distorted by swell, sag, and blowing before it ultimately becomes the thickness distribution of the bottle. A large safety margin is used to accommodate the uncertainty in programming the thickness distribution. As a result, containers tend to be made heavier than they need to be.

Any technology that can assist an operator in programming the parison profile in less time, with less experience, or with more optimum use of plastic in the product, will save the blow moulding industry money. Several good ideas have been pursued toward the goal of simplifying the parison programming part of the blow moulding process.

1.1 Review of Previous Work

Since parison programming was invented by Denis Hunkar in the 1960's, there have been a number of developments that simplify the job of setting up a profile for the operator. Hunkar made the gap-time profile easier to adjust through an array of sliding potentiometers. Other systems use computer programs to interpolate a smooth gap-time profile from a few given "master" setpoints. Some machines employ a device that uses a laser or an arrangement of photocells to measure the length of the parison for automatic control of the extrusion rate (2). Recently, Hunkar (3) presented "artificially intelligent" software for solving common blow moulding problems. Procedures have been developed to help an operator to program a profile more quickly by starting from the top and working down. Still, the fact remains that the most difficult part of setting up a profile, that of determining how the die gap should be varied as a function of time, is still left for the operator to figure out by trial and error.

Considerable effort has been put into the mathematical simulation of the parison formation, especially the phenomena of swell (4,5), and sag (6). The results have not yet provided the industry with a software product that will accurately calculate the required gap-time profile, given the die design, process operating conditions, and fundamental resin properties. This is due in part to the complexity of the problem and in part to the difficulty of characterizing the visco-elastic behaviour of a melt. A more practical approach to modelling parison behaviour involves the formation of empirical models. These models are fitted to experimental data. The need for such data has lead to the development of several techniques for measuring parison dimensions.

The first studies obtained experimental data using the pinch-off mould (or "pillow" mould) originally described by Sheptak and Beyer (7). This mould cuts a parison into "pillow" shaped segments instead of blowing it into a bottle. The segments are then weighed to determine the weight distribution of plastic in the parison. Kalyon et al. (8) improved the technique by photographing the parison just before it was pinched. This enabled the weight distribution to be separated into a thickness distribution and a diameter distribution. Swell modellers prefer to measure parison formation under isothermal conditions in the absence of sag. Utracki et al. (9) and Garcia-Rejon et al. (10) made such measurements by extruding the parison into an oil bath of the same temperature and density as the parison. Swan et al. (11) obtained these measurements by videotaping the bottom part of a cleanly cut parison in an oven.

The problem with empirical modelling is that a large investment in time and money is required to obtain the required experimental data for each specific process one wishes to model. Empirical models which are developed for a particular machine and resin, do not generally describe parison formation accurately on another machine or with a different resin. Thus, a generalized software tool for parison programming based on empirical models could do no better than produce a very rough first approximation of what the gap-time profile should look like.

DiRaddo and Kamal (12,13) developed an on-line closed loop control system for the parison thickness distribution. In their system, the length and diameter of the parison were measured using a camera hooked up to an image analysis system. The thickness distribution of the parison was inferred through the use of geometrical calculations, correlations relating diameter swell to thickness swell (14) and models that described sag (6). However, due to the difficulty of estimating the empirical parameters used in these correlations, one of the conclusions of the study was that a direct method of measuring the parison's thickness distribution on-line would have been preferable.

DiRaddo and Kamal have shown, however, that it is possible to develop computer algorithms for closed loop control of the blow moulding parison. Their program was able to maintain the parison dimensions at specified setpoints and suppress the effects of outside disturbances by constructively altering the gap-vs-time profile on-line.

1.2 Novel Technology

To improve upon current parison programming technology, the present work entails the design and construction of a device which makes on line measurements of the parison thickness distribution. The device utilizes recent advances in laser diode technology, linear CCD (Charge Coupled Device) sensor technology, and affordable fast computers to make an on-line scan of the thickness distribution along the length of the parison just prior to closing the mould.

A prototype device has been built that uses a measurement technique involving a beam of light reflecting from the inner and outer surfaces of the parison wall. Experiments demonstrate that the prototype can measure the thickness distribution of a polyethylene parison with a reproducibility of 5%. Two possible designs are provided for a possible second prototype. Both would be half the size, half the cost, and would incorporate optics for making simultaneous thickness and diameter measurements.

1.3 Potential Applications for New Technology

The parison thickness scanning sensor can provide an operator with rapid feedback on the formation of the parison. This feedback would help the operator to more quickly optimize the gap-time profile. It would also reduce the need to cut open the blown article in order to ascertain the thickness profile.

Now that the thickness profile of a parison can be observed directly, inflation simulation software (15-18) becomes useful for parison programming. With inflation simulation, one can estimate the parison thickness distribution required to produce a desired thickness distribution in the final blow moulded article.

The development of a system for obtaining the feedback opens the door for the development of software to actually assist the operator in editing the gap-time profile. For example, such software might evaluate the effect of an increase in thickness in the gap-time profile on the length of the parison. Then, it would compensate by modifying the gap-time curve in such a way as to offset the effect. The software could incorporate models that empirically describe melt flow, swell, and sag, because the thickness sensor would provide the data on parison formation that is needed to fit these models to the specific blow moulding operation in question. In principle, a program could be developed to edit the gap-time curve automatically, in order to achieve the changes that an operator desires in the parison profile.

Eventually, these advances could be combined and developed into a much coveted closed loop control system for bottle thickness distribution. Closed loop control means continuous monitoring and optimization of the bottle thickness distribution. Thus, the effects of build-up inside the extruder head, day to day temperature variations, and market demanded changes in the resin or production rate, would be automatically adapted to by the control system. With tighter control, the large safety margin that is usually added into the container thickness could be reduced.

Figure 2 shows a strategy for combining the above elements into a closed loop control system. The strategy assumes that the thickness distribution desired in the final product is specified by the bottle's designer. There are two stages in the control process shown in Figure 2.

The first stage of the control process uses an inflation modelling computer algorithm (upper centre box). This algorithm calculates the thickness distribution that the parison needs at the start of inflation (middle right box) to produce a bottle that has the desired thickness distribution at the end of inflation (upper right box). The two upper left boxes provide this algorithm with accurate "before and after" information that the algorithm can use to verify and improve its predictions.

The shape of the parison is the manipulated variable in the first stage of the control process. However, it cannot be manipulated directly. It must be manipulated indirectly by varying the die-gap and die shape. The second stage of the control process regulates the thickness profile of the parison by manipulating the gap-versus-time profile which the die follows during extrusion. It also controls the extrusion rate.

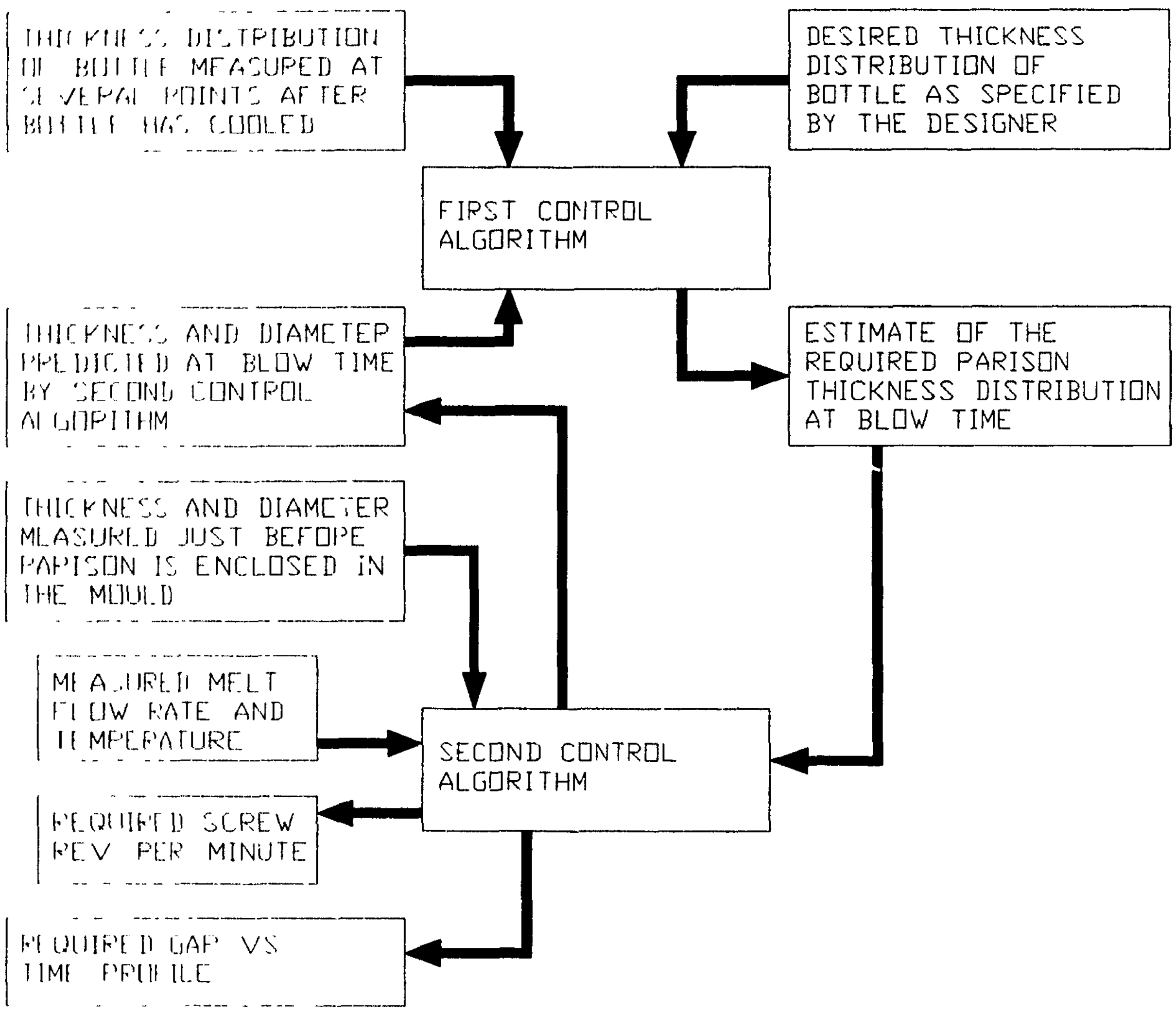


Figure 2 : The flow chart indicates how different elements of a closed loop control system could interact with each other.

1.4 Objective

The objective of the work done for this thesis was to design and construct an on-line, non-contact thickness measurement technique to determine the distribution of polymer along the molten parison during extrusion blow moulding. A number of possible measurement techniques were investigated. The technique chosen for development uses the principle of a beam of light reflecting from the inner and outer surfaces of the parison wall.

CHAPTER 2

Evaluation of Various Measurement Techniques

2.1 Selection Criteria

2.1.1 Criteria of Speed and Accuracy

In order to be useful, a measurement device would have to be able to obtain a thickness profile of a certain minimum accuracy. This accuracy would be determined by both the number of different point measurements made on the surface of the parison and by the accuracy of these measurements.

The typical cylindrically symmetric parison would require at least 20 evenly spaced point measurements along its length to map its thickness profile. Each measurement should be accurate to within at least +/- 5%.

If the parison were cylindrically non-symmetric, as would occur if ovalization technology were used to vary the die's shape, the same measurements would have to be made at least 3 or 4 times around the parison's circumference. This would add up to about 80 measurements.

All measurements of the parison must be made during the final 2 to 3 seconds of its formation - just before the mould closes around the parison. If measurements are made any earlier than this, it would be difficult to extrapolate for the parison thickness profile at the point in time when parison inflation begins.

To summarize, a parison measuring system could be required to make up to 40 measurements per second each with an accuracy of +/- 5%.

2.1.2 Technical Criteria

There are several criteria concerning whether a technique will operate within the restrictions of the blow moulding environment.

1) The technique must be able to cope with geometrical variation in a parison. The following list encompasses most of the variations that are found in typical blow moulding operations.

    1) Curvature of membrane (rad. of curv. > 3 cm)
    2) Surface angle variation (theta < +/- 20 degrees)
    3) Distance variation from a fixed instrument (distance variation < 20 mm)
    4) Non-parallel surfaces (angle variation < +/- 5 degrees)

2) The technique should be applicable for cases where many of the material's properties are unknown.

3) The technique must work despite swell, sway, sag and downward motion of the parison.

4) The technique must be able to operate with a parison temperature as high as 350 C.

5) The technique should not cause distortion of the parison.

6) The technique should not visibly mark the parison.

7) The technique must not interfere with the operation of the machine.

8) The measuring technique should not require placement of components inside the parison or physical contact with the parison as sticking and fouling may occur.

9) The parison may have rough inner and outer surfaces. There will be surface scattering and may be some degree of internal scattering if optical techniques are employed.

2.1.3 Subjective Criteria

There are other somewhat subjective criteria which influence the suitability of a technique in a qualitative fashion. These criteria are listed below.

1) It is desirable that the apparatus occupy a small amount of space in the vicinity of the parison.

2) It is desirable to obtain a large number of measurements before the mould closes in order to achieve better parison dimension control.

3) The technique should be suitable for use with a variety of materials, additives, and colours.

4) The technique should be both inherently reliable and easy to maintain.

5) Ideally, the apparatus should not be expensive.

6) The technique should not waste polymer in order to measure it.

7) The technique must be safe.

2.2 Evaluation of Measurement Technique Alternatives

In the course of this research a number of techniques for measuring a parison were investigated. The design ultimately selected for development to the prototype stage uses a beam reflection technique. It is discussed in detail in the next chapter. This section will describe all of the other proposals and explain why they were not chosen for further development. Since some of the proposed ideas are not without merit, but were rejected for reasons of cost or lack of resources, they may be viable choices for future development.

2.2.1 Mark Tracking

Mark tracking requires the use of a device to repeatedly mark the polymer as it is extruded, right at the exit of the die. The marks are tracked with an image analysis system, and, at the same time, the diameter profile is measured. By analyzing the movement of the markings, the swell and sag of the parison can be accounted for without the use of empirical correlations or simplifying assumptions. In theory, the thickness distribution can then be obtained geometrically.

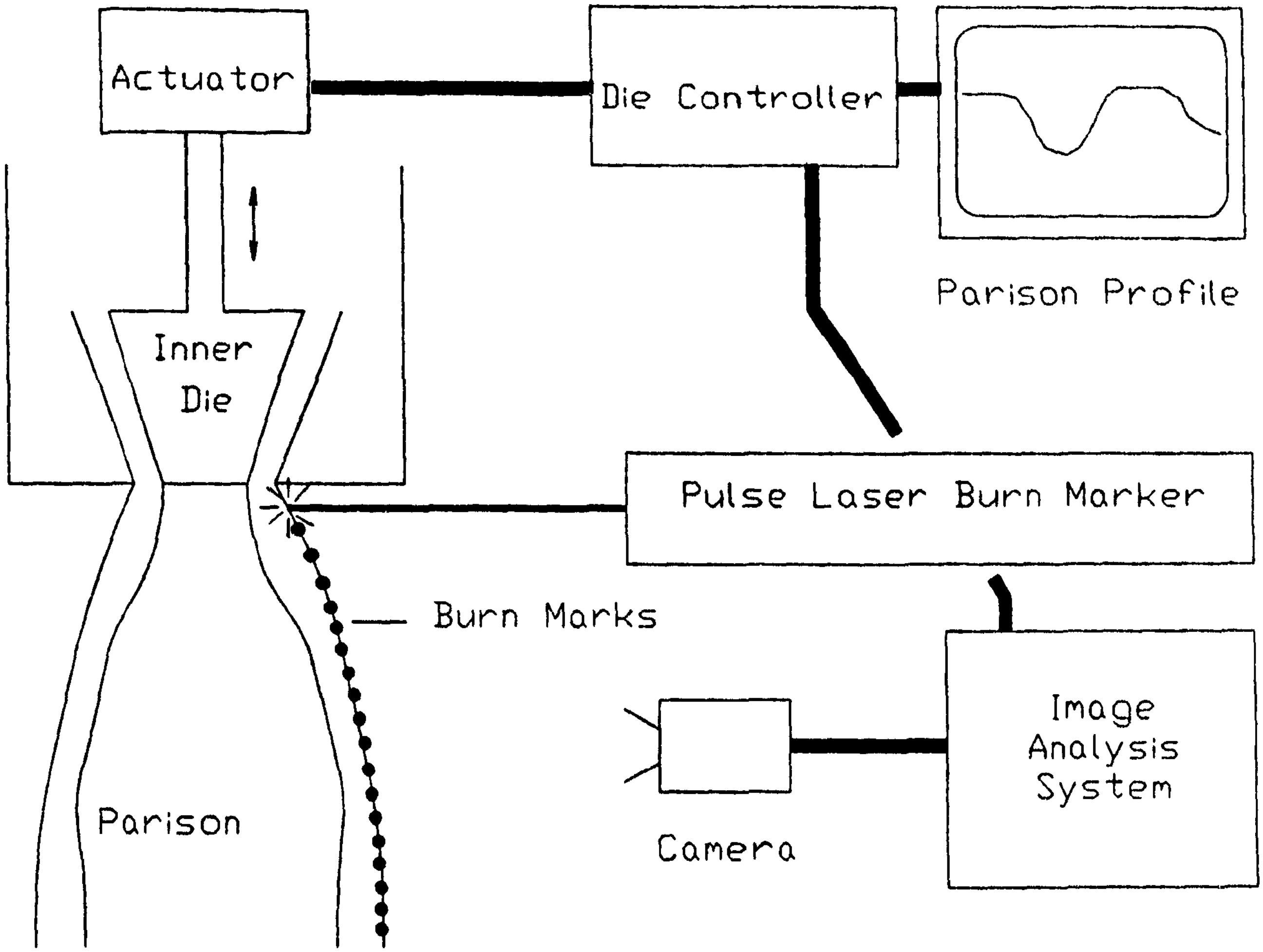


Figure 3 : Mark Tracking System. The pulse laser burns marks in the parison. The camera films the movement and the image analysis system calculates the swell and sag from the spacing of the marks.

As far as is known, this is an untested idea; there may be some practical problems. Firstly, it is difficult to mark a soft, hot, moving parison with the type of precise markings that would be needed. One technique that may work involves the use of a high power pulse laser to burn marks on the surface (see Figure 3). This type of equipment is commercially available but very expensive. Secondly, in continuous extrusion, expensive equipment is needed to obtain the exact flow rate ($35,000) necessary for the calculation of thickness. Finally, as mentioned above, the selection criteria require that no visible markings should be applied to the finished product.

Some ideas have been suggested for applying invisible markings to the surface. A pulse laser could be used to create a warm a spot on the parison (instead of a burn mark) which would then be tracked by a thermographic camera. Another suggestion involves the application of an ink which either disappears in time or is visible only in the ultraviolet or the infra-red.

2.2.2 Thermal Response Time

In the thermal response technique the response of the material to a thermal input is monitored. The technique is not applicable to blow moulding due to the unknown and variable thermal properties of the polymer and the very long response time (of the order of 100 seconds for 3mm of thickness).

2.2.3 Capacitance Techniques

Two conducting plates separated by a distance are capable of storing an electrical charge. The capacitance of the plates is a measure of the storage capacity. Placing an object between the plates will affect the capacitance in a manner dependent on the dielectric constant and the thickness of the object. By placing the plates of a capacitance measuring device on both sides of the parison wall, its thickness could be found (provided that the dielectric constant of the polymer is known). However, since it is not desirable to place part of the measuring device inside the parison an alternate layout of the plates was considered.

A special type of capacitance probe (19) drawn in Figure 4 could measure the thickness of the parison without the need for a plate inside the parison. Unfortunately, the probe would be highly sensitive to the distance between itself and the parison. It would not produce consistent readings unless it was placed exactly the same distance from the parison for every measurement. Exact placement would be virtually impossible without the probe firmly contacting the parison.

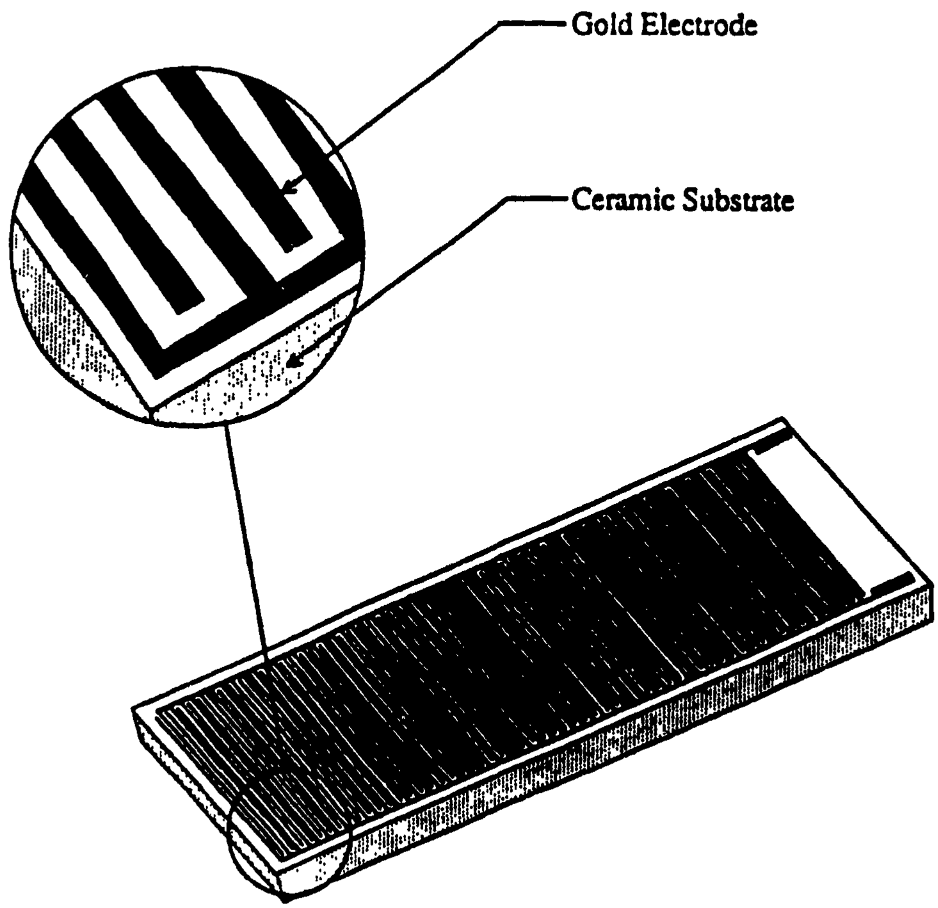


Figure 4 : Illustration of a capacitance probe. The capacitance will depend on the electric frequency and the mass, distance, and dielectric constant of material in the probes vicinity.

Another difficulty with the capacitance technique is determining the dielectric constant. To do this we considered placing a capacitance probe inside the extruder head. Unfortunately, for some polymers, the dielectric properties change significantly with temperature - especially near the freezing point. The value of the dielectric constant at a particular field frequency might no longer be valid after the parison was extruded.

2.2.4 Radar Reflection

In this technique the time required for a radar pulse to reach, reflect off, and return from an object is measured to obtain the distance. As the radar pulse travels at the speed of light, the time scale in measuring parison thickness would be in the order of 10 picoseconds. Modern electronic devices can not generate pulses or make accurate measurements of such short times. So far, the best thickness resolution achieved with optical radar devices is in the order of 1mm (20). To measure a 2mm parison to within 5% a resolution of .1mm would be needed.

2.2.5 Ultrasound Reflection

This technique is similar to radar reflection except that slower sound waves are used instead of radar waves. Ultrasonic thickness gauges require that a small piezoelectric transducer device be placed flush against the object that is to be measured. A drop of oil (or special liquid couplant) must be used to provide a conduit for the sound waves to pass from the transducer to the object. The ultrasound will not efficiently bridge an air gap. The device measures the thickness by measuring the time required for the sound to pass through the object and reflect back to the sensor.

Typically, about 2 or 3 seconds was required for the commercial instrument that we tested (21) to return a stable value for thickness of a solid piece of plastic. This is too slow for an on-line measurement system. As well, firm contact with the same point on the parison for this length of time would distort it. Some sort of mechanism would be needed to apply the oil to the sensor; this would complicate, and thus, reduce the reliability of the apparatus. Due to all of the above factors, using a directly coupled piezoelectric ultrasound transducer had to be ruled out. However, a number of ultrasonic transducers could be placed at various points inside the mould to measure the wall thickness of an article after inflation.

It is possible to make non-contact ultrasonic measurements (22). A sound wave can be initiated in a material without contact in at least two ways. The first is with an air coupled ultrasonic transducer. Air coupling is not as good as coupling with oil at the required high frequencies so this method may not perform very well. The second method uses a high power pulse laser to vaporize a layer of molecules on the surface of the parison (or just heat them very suddenly) consequentially creating a shock wave. Vaporization occurs quickly enough that the parison would not be significantly burned, distorted, or heated.

The reflected sound waves could be detected by any of a number of non-contact optical systems which use laser interferometry to measure minute displacement of the material's surface (23).

This non-contact technique was not developed further due to its anticipated cost and the anticipated size of the apparatus. The major limiting factor was the $50,000 U.S. cost of the pulsed laser, and the nearly $200,000 cost for the interferometric detector.

2.2.6 Nuclear Back Scatter

This technique (24) measures the amount of beta or gamma rays which are backscattered by the nuclei in the polymer melt. The amount of backscatter is a function of thickness. This technique is best used for films of 0.1 to 3.5 mm, but thicker measurements can be made with X-Rays. There are a number of shortcomings of this technique. Firstly, the time required for measurement of thickness at a point is long. Secondly, the cost is relatively high; one sensor unit on the market is listed at $12,000 for example. Thirdly, there is danger from nuclear radiation exposure. Fourthly, the instrument must be placed very close to the sample. The amount of backscatter is strongly dependent on the sample to sensor distance, thus additional equipment would be needed to compensate for the swell and sway. Fifth, the equipment requires frequent recalibration as the gamma or beta ray source decays. For these reasons backscattering techniques were not among the best alternatives.

2.2.7 Ellipsometry

Ellipsometry uses the polarization properties of light to study various properties of materials. It has been used to measure the thickness of very thin films (around 1 micron) to a high degree of accuracy. However, in order to measure a parison, microwaves having a wavelength around 5mm would have to be used. The equipment needed to make and detect these waves is expensive, too large, lacks spatial resolution and requires equipment on both sides of the sample.

2.2.8 Spectral Attenuation

Spectral Attenuation (25) is an infrared optical technique. The amount of light transmitted through a polymer film is measured at two or more different frequencies with filtered detectors. One frequency is at an absorption peak in the polymer's spectra. The others are nearby, but on a neutral part of the spectrum where there is no absorption peak (see Figure 5). The amount of light transmitted at the absorption peak frequency is compared to the amount of light that would have been transmitted at that frequency if there had been no peak - just a continuous spectral attenuation due to scattering. A ratio, T_1/T_0, is obtained. To estimate the amount of transmittance before absorption, the neutral band transmittance (measured at the two reference frequencies) is extrapolated to the absorption peak frequency. By the Beer-Lambert Absorption Law, the thickness of the polymer film is proportional to the log of the ratio, T_1/T_0.

$$T_1/T_0 = \exp(-kt), \quad \text{where 't' is thickness}$$

The technique has been demonstrated to work rather well on polymer films up to .5mm in thickness. It is not known whether the technique can be adapted to parisons having ten times this thickness. A light source is required behind the film which must be measured; for measurement of parison thickness it would be possible

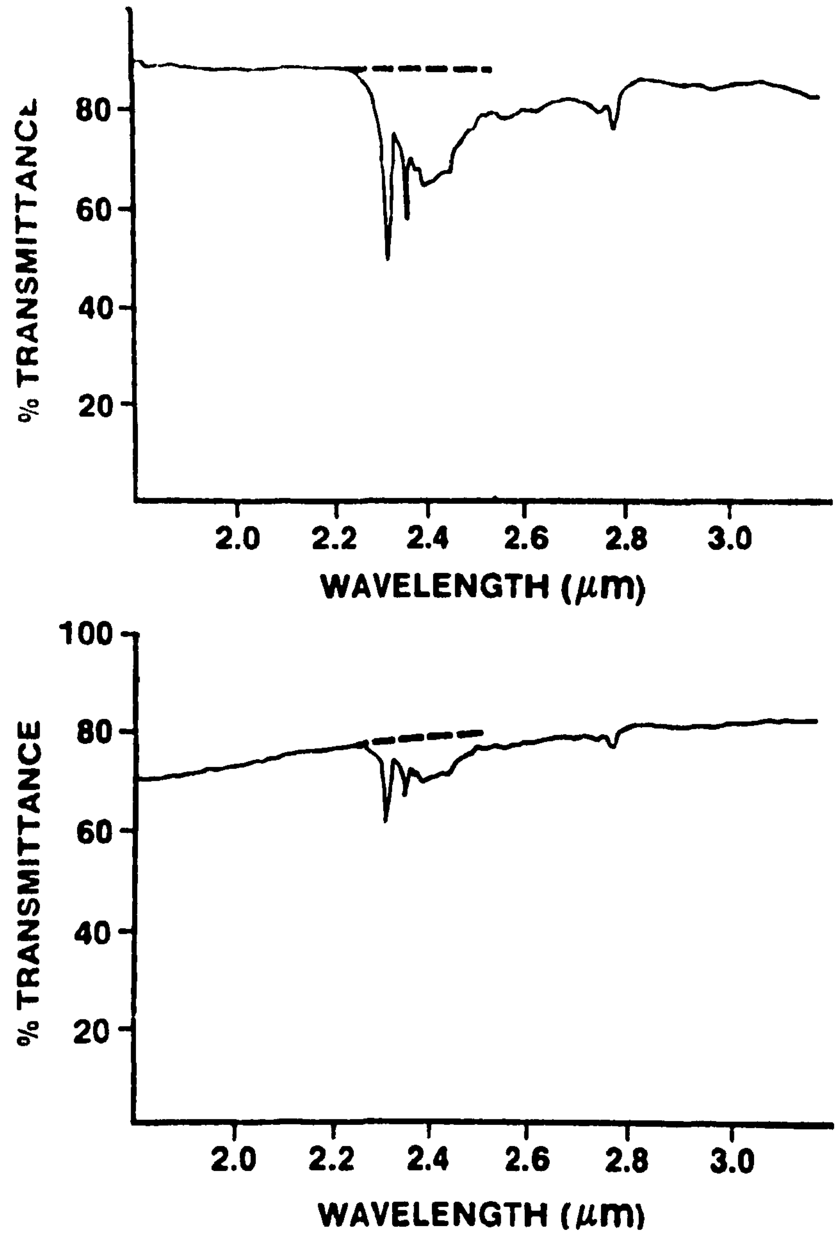


Figure 5 : Short-wavelength spectral distribution of the light transmitted through a clear plastic, 65 μm thick film (top) and a white-pigmented, 20 μm thick film (bottom).

to place the detector on one side of the parison and the light source on the other and thus obtain a measurement of the double wall thickness. The material being measured must be translucent for this technique to work. Choice of the best frequencies at which to measure spectral attenuation requires careful consideration of the type of polymer and the impurities in the polymer. This last reason was the strongest reason for not developing the technique. To be commercially practical, the device should not have to be specially modified and calibrated for every specific process.

2.2.9 Interferometry

Waves of coherent light from two separate sources will create interference patterns where they intersect (see Figure 6). Under the right circumstances these interference patterns can be detected and analyzed to determine the angle of separation of the two sources of light. A laser beam focused at an angle into a transparent film of polymer will reflect back off both the front and back surfaces of the film. The two reflections are two separate sources of coherent light and their separation can be found from the interference pattern that they form. The separation will be a function of the film thickness, refractive index, and several geometrical factors.

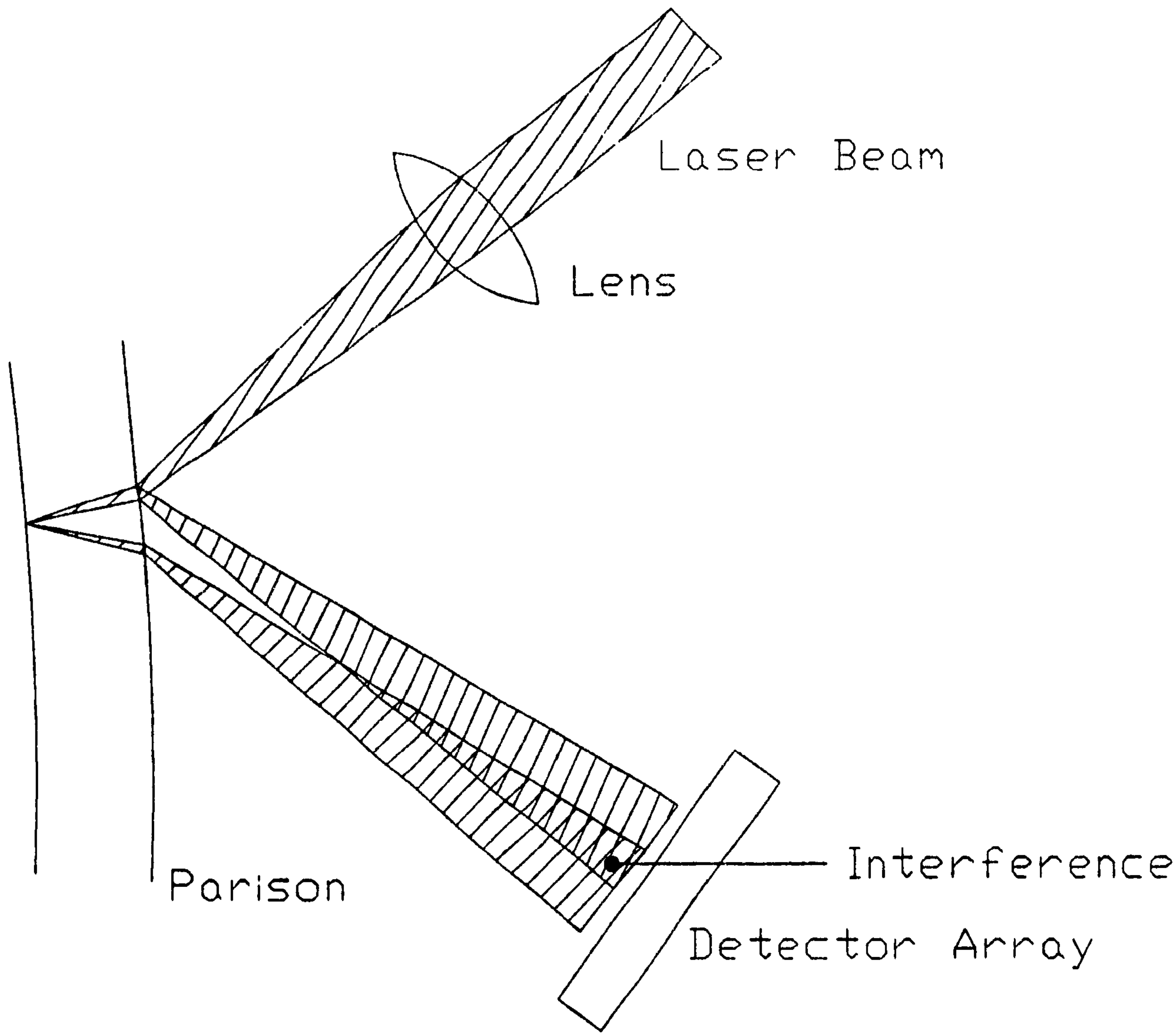


Figure 6 : Interferometry. The two reflected beams interfere where they cross.

Interferometry (26, 27) is especially sensitive to the turbidity and surface finish of the material which tends to obscure the interference pattern. With the use of Fast Fourier Analysis algorithms it may be possible to detect partially obscured patterns. In order to compensate for the unknown refractive index and geometry of the material, four measurements would have to be taken at different angles to gather enough information to determine the thickness, despite the unknown refractive index and geometry[1].

Optical bench tests were made with plexiglass samples roughened to resemble the texture of a parison. The interference pattern formed by the intersection of the reflected beams from a helium neon laser was observed on a screen. For smooth plastic a good pattern was observed. However, for the roughened plastics, the pattern was totally obscured. From these observations it was concluded that a study using fast fourier transform algorithms to determine if a faint modulation could be detected was not merited.

2.2.10 X-Ray Measurements

Using X-Rays, it may be possible to get the entire thickness and diameter distribution of the parison instantaneously.

[1] Research with the beam reflection technique discussed in the next chapter has shown us that it is very difficult to calculate the refractive index with the type of simultaneous solution we suggest here. Therefore, it might be preferable to have just three measurements and require that the refractive index be provided.

Theoretically, an X-Ray point source would be placed on one side of the parison, and a photoluminescent screen would be placed on the other. The screen would display the parison's X-ray shadow and could be viewed with a video camera. An image analysis system would interpret the diameter, length, and thickness. An X-ray system for examining electronics was used to view some plastic samples to see if the thickness could be observed. The results were qualitatively very encouraging.

An alternative smaller system could use an X-Ray sensitive linear CCD array. For example, reference 28 shows a 1 inch by 0.1 inch linear CCD array with a photoluminescent coating that glows when struck by X-Ray radiation. With the CCD a higher resolution could be obtained than with the screen, but measurements would have to be made one point at a time.

Figure 7 shows what we calculated the X-Ray shadow of a parison on a CCD chip would look like. The points in the profile where the slope is the steepest would represent the outer and inner edges of the parison. It is also possible that at each of these points there might be a sharp downward spike in the intensity profile. These spikes may occur because the X-Rays are at a high angle of incidence to the parison and might actually be reflected to the sides slightly. There is a program, called X-Ray, included in the software associated with this project that was used to calculate the intensity profile.

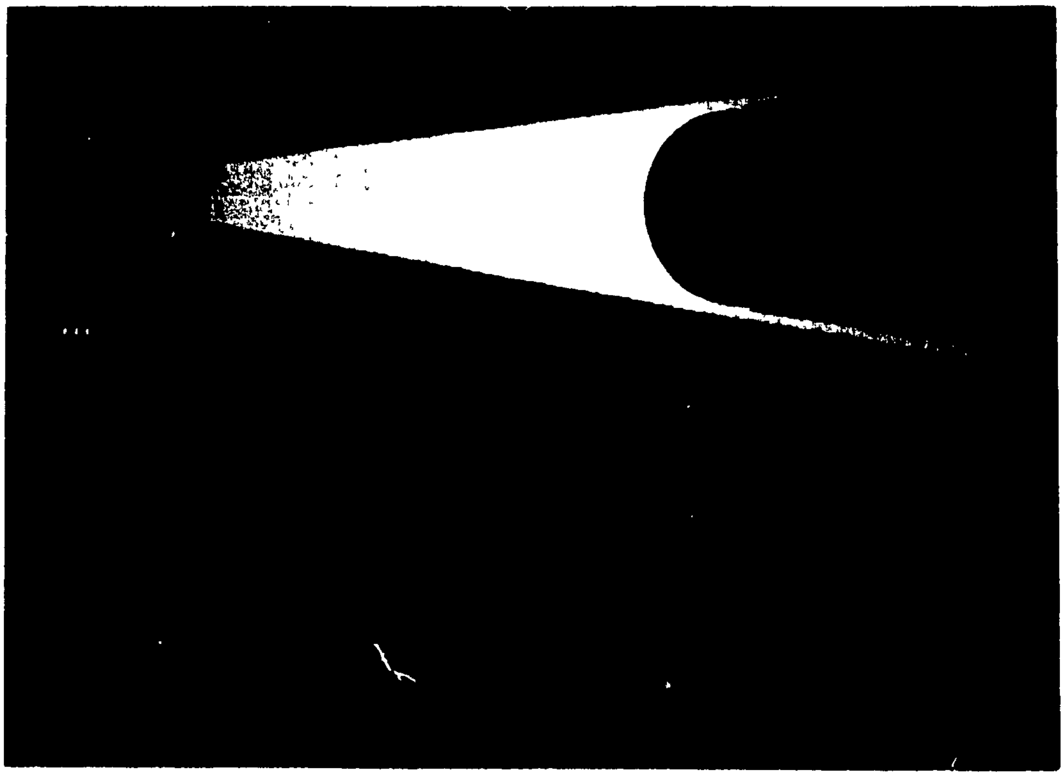


Figure 7 : The graphics output from the program X-RAY.BAS. Top: X-rays from a point source form a shadow as they pass through the parison. Bottom: The shadow's intensity profile.

Although the X-Ray techniques looked very promising, they were not developed because we did not have the resources to work with X-Rays. We also felt that they might be considered a health hazard if used in on-line control.

2.3 Proposed Technique

After careful consideration, the technique selected was one based on the principle of beam reflection. The details of this technique will be presented in the following chapter.

CHAPTER 3

Development and Evaluation of the Beam Reflection Technique

3.1 Description of The Technique

The measurement technique operates on the principle of beam reflection (29). A single narrow beam of light directed at an angle into a film of polymer can be used to measure thickness (see Figure 8). The beam is partially reflected back by the front and rear surfaces of the polymer film - thus generating two returning beams. A lens focuses the returning beams onto a CCD linear detector array which measures their separation. The separation is a function of the thickness, the refractive index, and the geometry of the object being measured. In Appendix 1 a simple equation describing this relationship is derived.

The prototype device was designed to incorporate three individual beam reflection systems (see Figure 9). The three beams all impinge near the same spot on the object, but from different angles relative to the surface. With the three beams, sufficient data can be obtained to determine the thickness, refractive index, and orientation of the part of the surface under scrutiny. In the program entitled "THICK.BAS", there is a routine called COMPS which orchestrates the solution from simulated data.

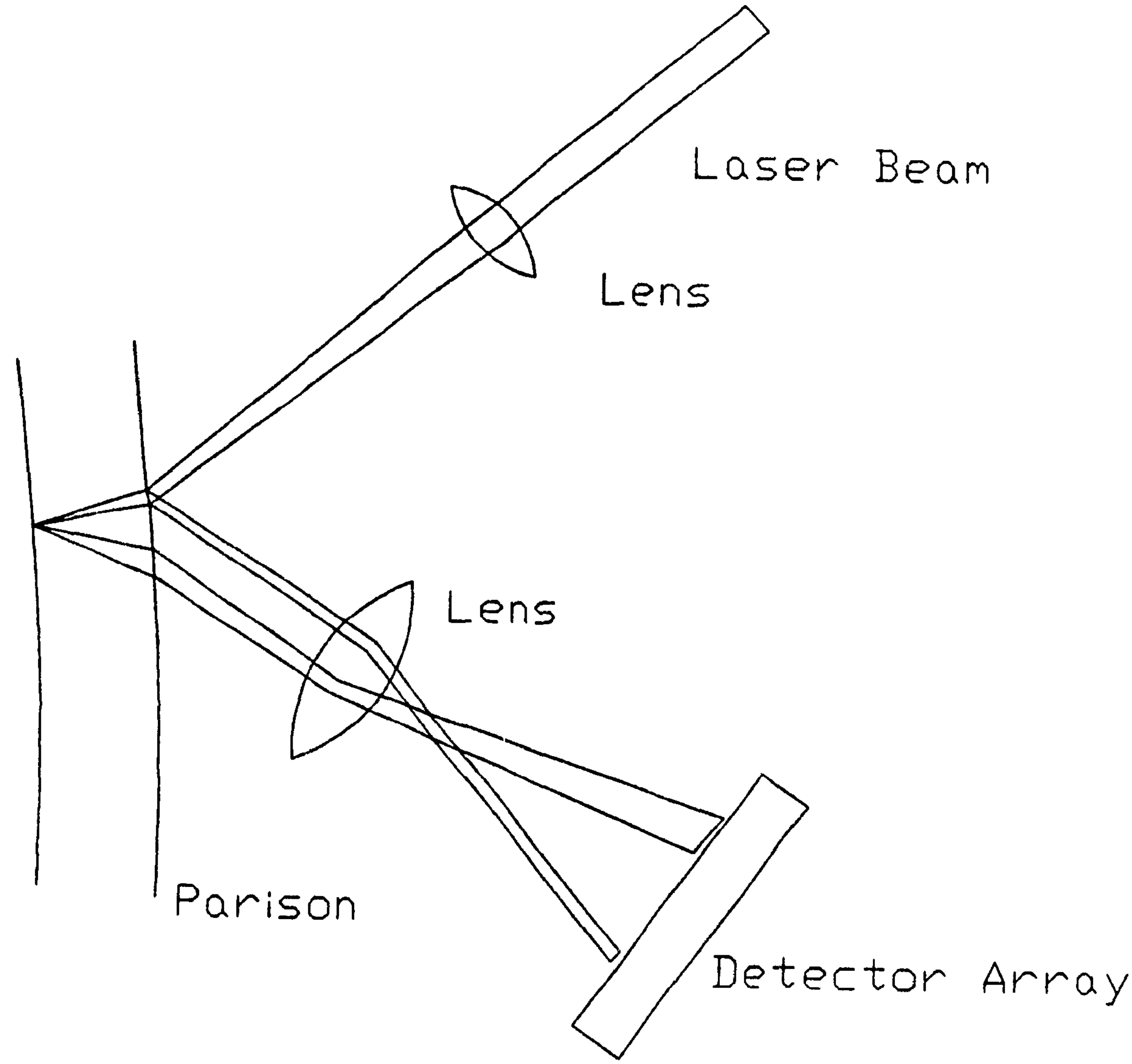


Figure 8 : The two reflected beams are focused onto a linear detector array which registers their separation.

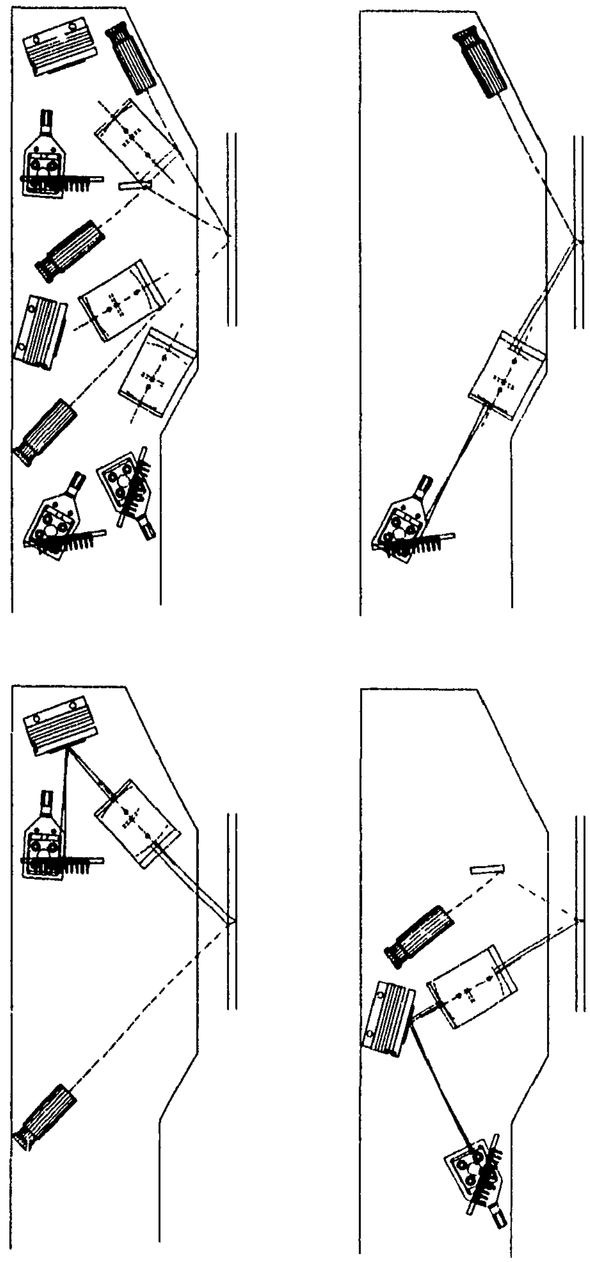


Figure 9 : Schematic of prototype device containing three separate beam reflection systems (top left). Systems 1, 2, & 3 are isolated in the other figures. Mirrors fold some optical paths to reduce the size of the device.

Unfortunately, during the calculation of the thickness, error in the original data obtained from the three reflected beams is severely compounded. The main problem is that it proves very difficult to determine how much the separation between the reflected beams is caused by an increase in the thickness and how much is caused by a decrease in the refractive index.

The lower right window in the photo of Figure 10 shows the results of calculations to determine the thickness and refractive index from simulated data. The thickness and refractive index values are estimated at the point where the dotted lines intersect (the cross hairs mark the spot). As the lines have nearly the same slope, their point of intersection is difficult to obtain accurately if there is a small amount of scatter in the raw data.

If the refractive index can be provided, then it is possible to reconstruct the thickness profile of the parison after scanning it with the prototype thickness sensor.

3.2 The Optical Characteristics of The Parison

To recap, parison thickness was to be measured by striking the parison with a laser beam, and monitoring the separation between the two spots of light on the parison surface which are caused by

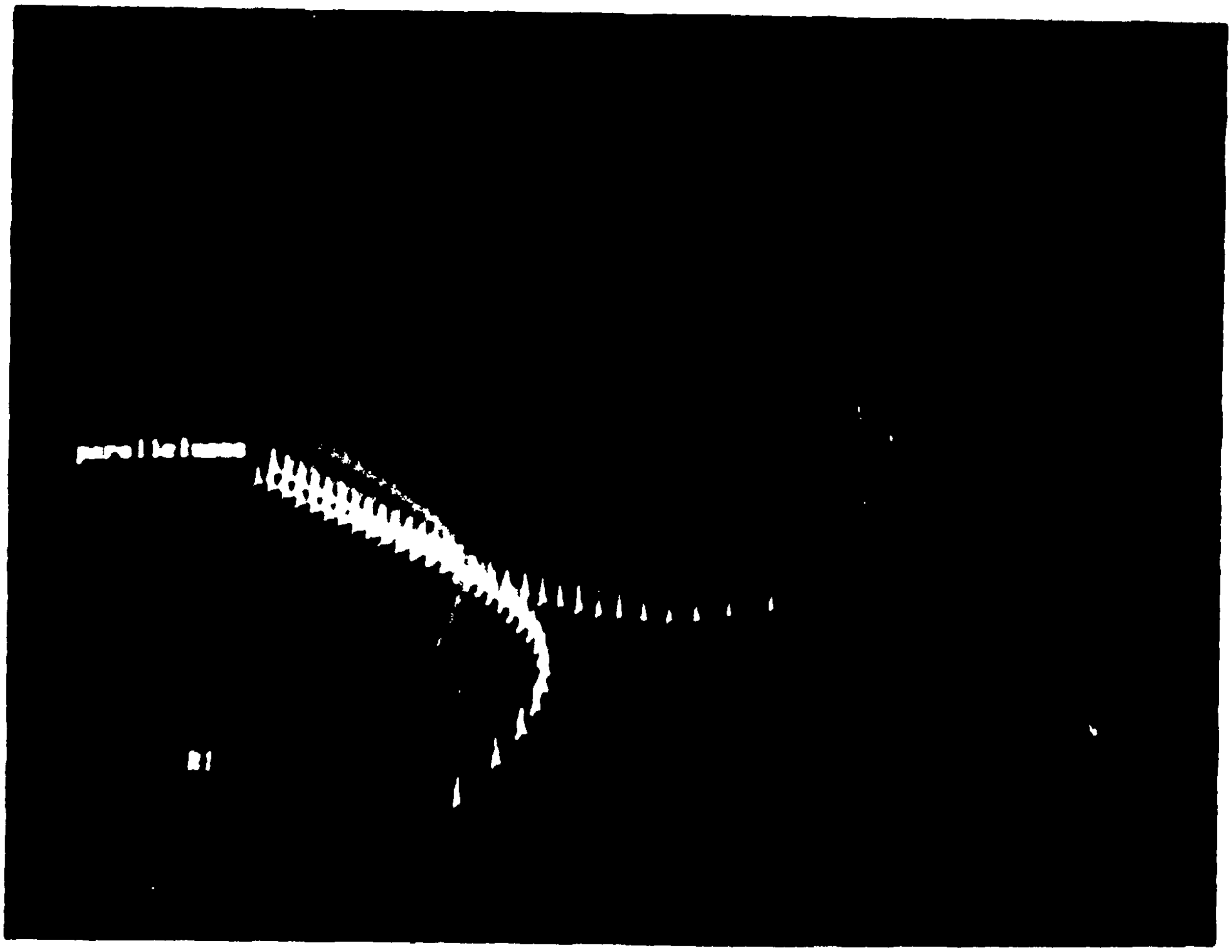


Figure 10 : A graphic representation of the mathematical solution for the thickness by the program THICK.BAS. The solutions occur where the dotted lines or ridges intersect.

the reflection of the beam. Therfore, the two spots were investigated - first on a simulated parison and later on a real parison - to determine how accurately it is possible to measure the separation.

The surface of the molten parison causes the light to scatter and thus increases the area of the spots imaged by the imaging systems. The parison was found to have two types of surface roughness. The first is a modulation observed when moving around the perimeter of the parison. This modulation is most likely caused by small scratches present in the die which effectively put streaks on the parison as it is extruded. The streaks are large enough to be seen with the naked eye. The second type of modulation occurs along the length of the parison. It is so fine that it can be seen only under high magnification. To the naked eye it simply makes the parison look white. This modulation may be caused by a form of melt fracture that occurs at the die lips where high stresses exist. This modulation is so small that it scatters the laser light in a relatively uniform manner. It does not change the location of the spot maximum intensity as much as it broadens the peak of the intensity profile. Figure 11 is a photo of the spots produced by a helium neon laser striking a parison at an angle. Figure 12 is a typical intensity profile of the two spots as imaged with the EG&G S-series line array camera.

Figure 11 : An enlarged photo of a helium neon laser beam striking the parison as seen filtered for the detector. Notice how one spot (the first reflection) is sharp, and the second is diffuse.

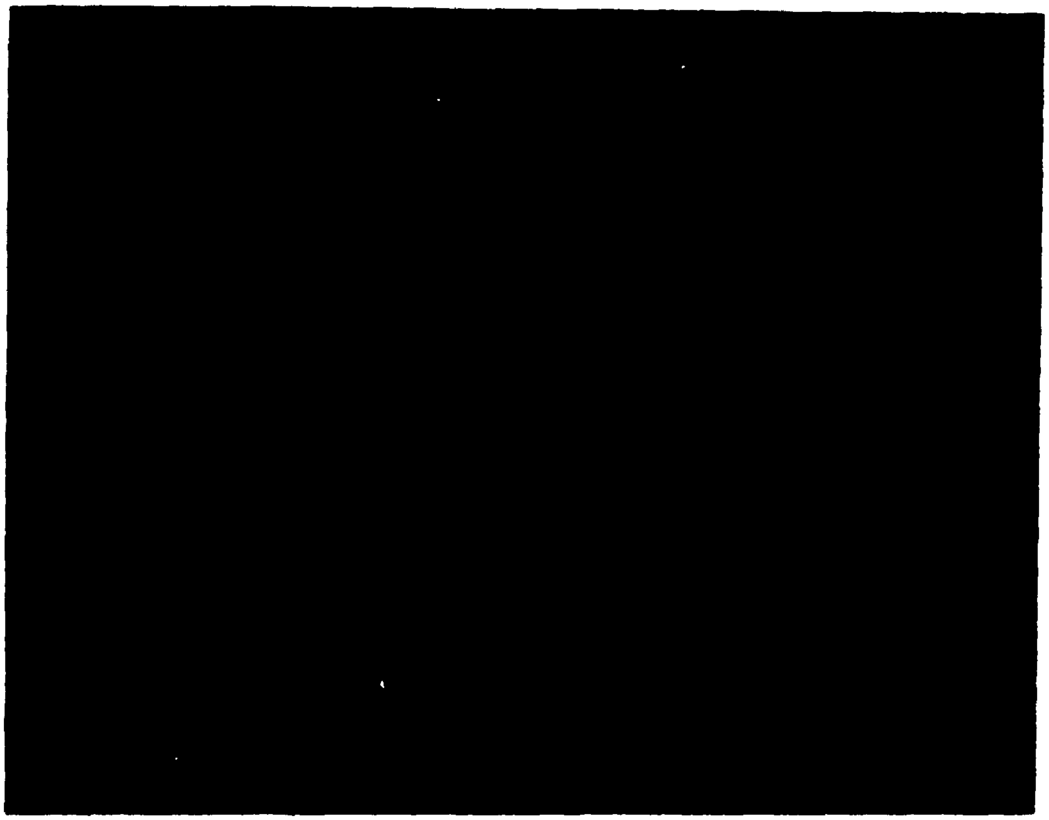


Figure 12 : A photo of the output from an S-series array used to image the two spots on a parison.

Ashizawa et al. (30) have also investigated the parison's surface characteristics. They also observed that the majority of light scattering from the parison was from the surface, and not from the interior. They discussed the possibility that the surface scattering may be due to changes in the crystalline morphology, as well as surface roughness.

After our study of the parison, the following conclusions were reached. First, it would be possible to determine the position of the centre of the first peak with an accuracy of about ±25 μm, and the second peak with an accuracy of about ±250 μm. Secondly, achieving this would require high resolution lenses, low electrical noise, and an excellent peak location algorithm. Thirdly, with raw data of this accuracy from three lasers at different angles, it would be possible to calculate the thickness, refractive index, and wall angle of a point on the parison with an accuracy of no better than about 20%.

There were ideas for ways to improve upon the accuracy of the measurements. Assuming that the refractive index would be relatively stable, one could average a large number of calculated refractive index values to obtain a "more accurate" value. This average value could then be used in the calculation to improve the thickness estimates.

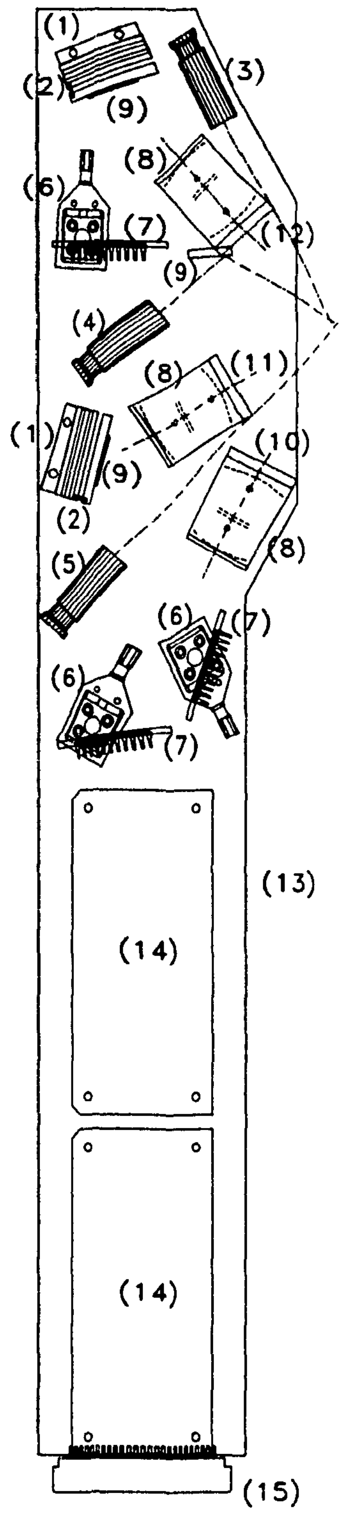
Another alternative was to obtain the refractive index some other way; with the correct refractive index given, calculations showed that the thickness could be determined with an accuracy of 1.5%. Refractive index could be determined in a number of ways. For some resins, such as amorphous polymers, one can obtain the refractive index value from published tables in the literature (31, 32). Resin manufacturers can often provide this information. There are affordable instruments that can measure refractive index such as an Abbe Refractometer.

A prototype device based on the three beam technique was designed in order that the idea of averaging the refractive index might be tested. In building the prototype, many of the practical aspects of measuring parisons by the beam reflection technique were worked out. The next section discusses these practical aspects in detail and makes recommendations specific to each component discussed.

3.3 Details of Sensor Design

3.3.1 Optical Arrangement

The arrangement of the optical components mounted in the head is shown in Figure 13. The optimum arrangement of these components was determined with the aid of a computer program.



(1) Positioner bracket
(2) Flexture mirror mount
(3) 830 nm laser light pen
(4) 780 nm laser light pen
(5) 680 nm laser light pen
(6) Translation stage
(7) Linear CCD array
(8) High resolution lens
(9) Mirror
(10) 830 nm narrow band filter
(11) 780 nm narrow band filter
(12) 680 nm narrow band filter
(13) Main mounting plate
(14) Evaluation daughter boards
(15) 50 pin connector

Figure 13 : The optical arrangement of components in the sensor head.

All of the lasers, lenses, mirrors, and detectors fit compactly into the available space in the casing without interfering with each other.

The sensor includes three main optical imaging systems for measuring the thickness. Each imaging system has a laser light pen, a lens, a filter, and a line array detector chip. As well there are mirrors which fold the beam and image paths to make best use of the available space. The detector edge, lens nodal plane, and laser beam are all aligned to satisfy the Scheimpflüg (33) condition. That is, without mirrors, they would all line up on the same point on the optical plane and this causes the images to be in focus.

3.3.2 Casing

A production model of the sensor would have to be designed to interact safely with the moving parts of the blow moulding machine. A vertical positioning system would move the sensor between the mould halves during the bottle making cycle to scan the parison. Special safety switches should be installed to insure that the sensor is clear before the mould closes. The sensor casing should be solid enough to resist damage if it is accidentally trapped inside the mould.

3.3.3 Lasers

In the visible and near infra-red portion of the spectrum, the refractive index gradually decreases with increasing wavelength of the light. For this reason, the three diode lasers in the system have wavelengths that are as close as possible to each other. In the prototype system, the wavelengths are 830 (10 mW), 780 (3 Mw), and 680 nanometres. They do not all have the same wavelength because narrow band filters are used to selectively pass each of the three wavelengths of light into a specific imaging system.

Long wavelength infra red diode lasers are known to pass through some coloured plastics. However, the CCD detectors selected for the prototype do not detect wavelengths much greater than 1000nm. Visible lasers are easier to align and focus.

The diode laser light pens used in the prototype were obtained from Hoetron Inc. in Sunnyvale, California. These light pens were focused in the factory to a point located at a specific distance from the end of the pen. Due to an error by Hoetron one of the pens had to be refocused. This was achieved by cutting open the casing. A light pen with a focusing mechanism is recommended for the second prototype.

The depth of field of the focused beam from the diode laser light pens was too short when the spot was only 80-110 mm from the end of the pen. The depth of field can be increased by increasing the distance between the laser and the focal point, but this has a side effect which is to increase the size of the focused spot. The light pens should be focused at a distance of at least 200mm in the next sensor. The path of the beam could be folded with mirrors to keep the optics in the available space.

One light pen (the 780 nm) had a power output of only 3mW. This laser provided insufficient light intensity when the arrays were run at full speed. All lasers should output at least 10mW in the future.

Mounting brackets and adjusting positioners must be very steady to insure that lasers do not shift after calibration.

The light pen lasing source is not a point but a slit. Therefore, the focused beam is not a rod, but a tiny flat shaft of light. The light pens should be rotated so that the plane of the light is 90 degrees from perpendicular (i.e. *not* perpendicular) to the scanned surface. This will produce a sharper peak on the detector output.

Stray light from the light pen should be blacked out with a mask. An anti-reflection window perpendicular to each beam is recommended as part of a shield to keep dust out of the sensor.

To allow beams to exit the detector at the correct angle, the lenses may have to be cut or small mirrors (and/or beam splitters) should be used to divert the beams around the lenses. Both techniques were used to some extent in the first prototype.

Adjustment and focusing of the lasers can be facilitated by placing a two dimensional CCD array in the measurement area of the detector to observe the beams directly. With the CCD array one can see whether the lasers are twisted to the correct angle and whether they are aimed at the same general location in space.

3.3.4 Lenses

It was determined that especially high resolution lenses would be needed to image the spots. The high resolution lenses for the prototype were obtained from JML Optical Industries in Rochester, New York. They had an F/# of about 2, were designed for .98 magnification, had an effective focal length of 41.509, and a maximum distortion of 0.02mm.

For parisons with optically smooth surfaces, a lens with a large F# is required to catch the reflected beams when the scanned surface is not directly facing the sensor. The prototype can pick up beams reflecting from optically smooth surfaces in a range of angles of about 3 degrees. If, for example, one is measuring the thickness of a glass tube and the detector goes off centre, the reflected beams will go off to one side and miss the lens. For optically diffuse surfaces, scattered light will be picked up by the lenses at a wide range of angles. However, if the specularly reflected beams are not picked up, it may be more difficult to achieve the same accuracy. The peaks may be distorted, or may not be in exactly the same place.

There is a design trade-off between the range of refractive indices, the maximum thickness, the depth of field of the sensor, and the range of allowable angles at which the surface can be with respect to the sensor. This trade-off was optimized with the use of the program called "THICK.BAS". In designing the prototype, it was assumed that fairly diffuse surfaces would be measured and this favoured a large depth of field over a large allowable angular variation. The design optimization with the 41mm EFL lens resulted in the best compromise for the sensor when measuring optically smooth surfaces. The limits of utility of the prototype are as follows:

Minimum refractive index	1.3
Maximum refractive index	1.7
Maximum thickness	4mm
Positioning depth of field	8mm (with 4mm sample)
Angular positioning variation	+/-1.5 degrees

High resolution and no aberration is essential for the lenses. The specularly reflected beam must be able to enter the lens anywhere and still be imaged onto the same point on the detector. The lenses used in the prototype may not be perfect as a slight error is observed in the measurement data that increases as the angle of the scanned surface deviates from that at which it directly faces the detector. Examine the lower right hand portion of Figure 20.

Lenses with lower F/# values could be specially designed for this sensor. Lower F/# would reduce the limitations listed above and lead to a more robust sensor. The cost of designing such lenses could be as much as $10,000.

A dust guard should be fitted around the lenses to seal the interior of the detector from dirt. Windows could be put over the lenses to avoid expensive scratches.

3.3.5 Detectors

When measuring the thickness of certain materials, there is a large disparity between the intensities of the two spots; so much, in fact, that it is not always possible to detect the weaker spot without the larger one saturating the detector. Several ideas were tested to improve the situation. The best improvement resulted from the use of a special wide aperture (1024 pixels each with 100 x 1 aperture) linear CCD array manufactured by EG&G Reticon (34). The 1024 element array provided the optimum resolution. If a 500 element "T Series" array had been used, measurements would have been probably almost as accurate, but calibration would have been more difficult.

A non-linear response type of array should be investigated to determine whether it could detect both peaks without saturating the detector. Another idea involves closed loop control of the laser power output.

Additionally, the intensities of the spots may vary by as much as an order of magnitude during a scan of one parison. This is due simply to the unpredictable way that the parison will reflect the light. Thus, often the small peaks become too weak or the large peaks saturate the detector. By regulating the output power of the laser diode, the signal strength can be maintained at a level that will make optimum use of the intensity range of the line array camera. An electronic circuit is needed that will determine the signal level coming from the camera and adjust the laser power if it is too high or too low.

It is possible that control of laser power could be performed by the computer or a processor on the frame grabber card. This might be simpler to design, but it could slow down the data acquisition rate and thus reduce the number of measurements made per second.

Another alternative would be to obtain a frame grabber card capable of 12 bit digitization. This card would be sensitive enough to locate the smaller peaks.

Focusing the optics was difficult. To make the job easier, a two dimensional CCD camera was modified so that its 2D array could substitute for the 1D array in the sensor. The modification involved building a special extender to hold the 2D CCD chip away from the camera so that the chip could be positioned inside the sensor. On a video monitor it was possible to see clearly what adjustments to the optics brought the image into focus. The calibration procedure was also tried and found to be much easier with the 2D chip. However, calibration must be done with the 1D chip if this is the chip that will be used in the sensor. One might consider making a special bracket that would allow the substitution of 2D array in place of a 1D array to enable quicker focusing.

Redesigning the device with two dimensional chips was considered. For example, the $5000.00 RA2048J from EG&G Reticon has a resolution of 2048 x 64 and a high data acquisition rate. Commercial 60 frame per second cameras ($1000.00) were also considered. 2D arrays permit easier adjustment of the optics and easier calibration. They might also make it possible to extract information useful for centring the sensor on the parison. If in the detected image the second spot is in line with the first then the lasers are striking the middle of the parison; otherwise, the sensor is off to one side. The disadvantage of using 2D cameras is that much more data must be processed to extract the locations of the peaks. This would result in a slower system, or a system that uses more expensive computers and electronics.

3.3.6 Filters

In a single imaging system, there is one laser which creates two spots which are then imaged by a lens onto a detector. With three imaging systems, it is possible that spots intended for one detector may be picked up on other detectors. This must not be permitted to happen as it would confuse the processing software. To prevent this from occurring, it was decided that each laser will have its own wavelength and each lens will be equipped with a narrow band filter to selectively pass light of only this wavelength. Thus, unwanted spots will be blocked from a detector because they would not have the correct wavelength to pass through the filter. It was possible to order reasonably priced light pens (compact lasers) and filters at wavelengths of 680, 780, and 830 nm.

In the prototype, the filters are mounted on the lenses so that they are approximately perpendicular to the light beams. This minimizes generation of multiple images caused by internal reflection. Other sources of stray light that could have been avoided by placing the filters on the arrays were a design concern; however, no such problems arose in practice.

As an alternative to using filters to separate the laser light, each laser could be pulsed to turn on only when its associated camera is being read. In pulse mode all the lasers could be of the same wavelength and the cost of filters would be avoided. Lasers could be less powerful because their light would not be attenuated by the filters. Reduced light output is a safety factor as well.

The recommended design for the second prototype suggests filters and not the pulsed laser system of separating the images. In the second prototype, simultaneous image acquisition is needed and this can only be achieved with filters. The possibility of not separating the images at all, but instead designing the peak finding algorithms to cope with two images at once may be feasible with the second prototype.

3.3.7 Electronics

The electronics are contained partially in the sensor head and partly in a second industrial strength, water resistant, steel box. The box and the head are connected by a cable. To prevent damaging electrical transients from occurring if the cable were

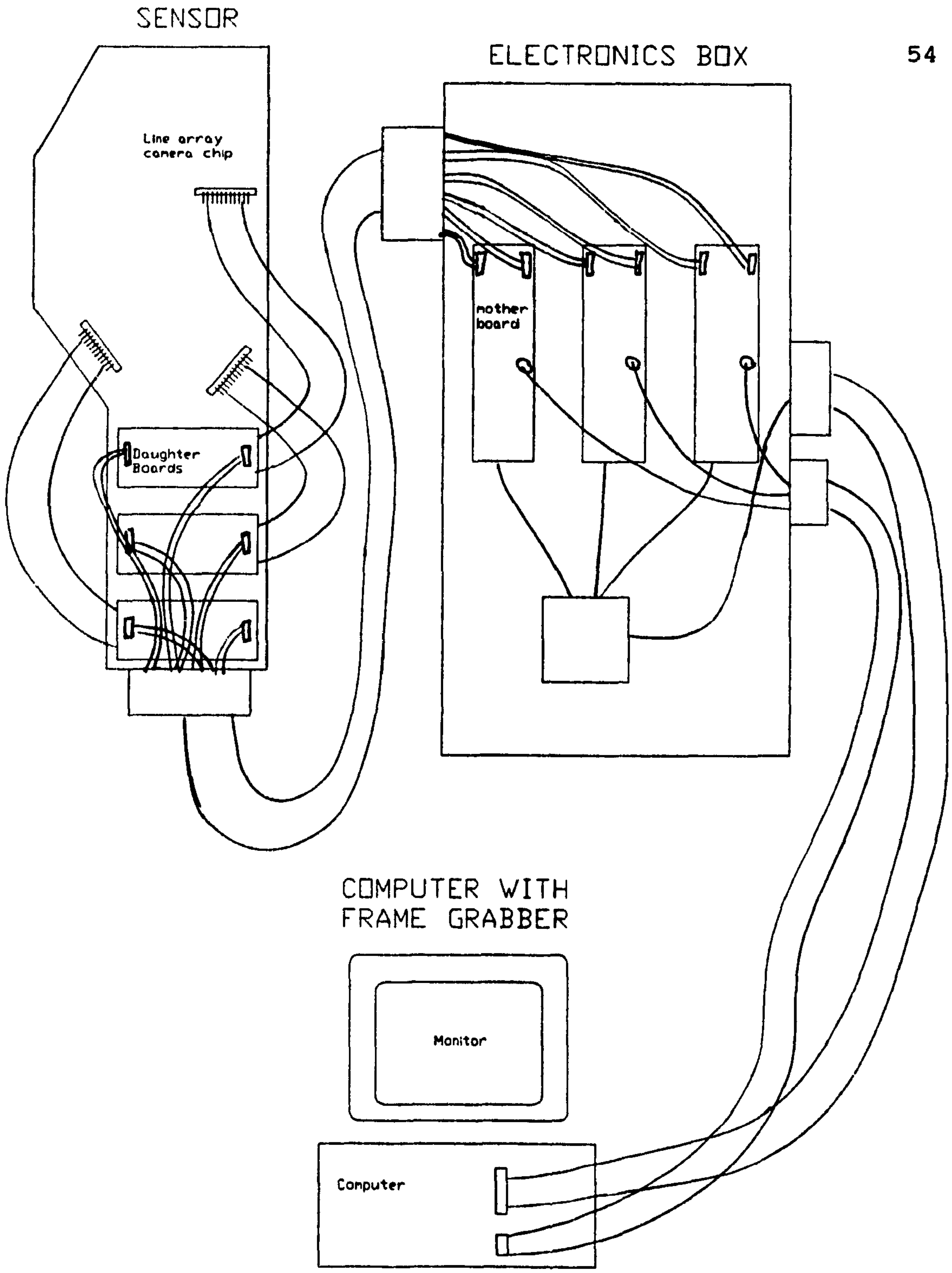


Figure 14 : The basic wiring and hookup of the sensor, electronics, and the computer. Parts are not drawn to scale.

accidentally disconnected, a special safety circuit was included in the design. If the cable is severed or if the fastening screws on the connectors are loosened then a circuit is opened which turns off the power to the EG&G evaluation boards.

An EG&G S-Series camera system includes a 22 pin 1.5 inch CCD chip mounted on a 4" x 1.75" daughter board which is mounted on a 4" x 8" mother board. In the prototype, the arrays and the daughter boards were in the sensor and the mother boards were in the box connected to the sensor with a cable (see Figure 14). Experiments showed that the chips could be connected to the daughter boards with up to 12" of ribbon cable without the signal becoming significantly distorted. The daughter boards could be up to 5 feet from the motherboards.

The chip to daughter board ribbon cables carried signals that were sensitive to capacitance. If they were moved, the odd even pixel adjustment on the mother board had to be readjusted. If the ribbon cables were folded so that the wires in the cable came too close to one another, the signals were distorted.

The data acquisition board used was the OC500MS supplied by Coreco in Montreal, Quebec. A data acquisition board is essential to the operation of the apparatus as it receives and stores the three detector signals in the computer's memory. With the OC500MS, it was possible to achieve data collection rates sufficient to obtain 250 one line images per second. In the prototype design, the data were analyzed using a personal computer to produce a plot of the thickness distribution.

The Coreco frame grabber card works well enough now but there were many bugs with it originally. It had to be returned to have a certain chip replaced. The driver program had to be rewritten for the present application as the card would not operate properly at slow speeds. This card is poorly documented. The best feature of the card is that it has a software switchable selector that enables it select its input from any one of four camera inputs. As the company was based in Montreal, the technical support was good.

3.3.8 Positioning System

To measure a parison on-line the sensor must scan down the length of the parison in as short a time as possible. During the downward scan, The parison must be kept centred and within the range of the sensor. The vertical position of the sensor must also be measured.

To test the prototype, a positioning system had to be designed and built. The system used a motorized, computer controlled slide to move the sensor up and down. An optical mouse was rigged to the slide to provide vertical position measurements. The parison was kept centred and at the right distance with fixed guides. These guides consisted of two vertical 1/4 inch tubes fixed about 1/4 inch apart. The parison rested against these tubes as it was extruded, and the sensor scanned between the tubes to measure the parison. The tubes were cooled by running water through them to keep the plastic from sticking.

Figures 15 and 16 show the sensor and motorized slide installed on a Fisher Battenfeld blow moulding machine. This particular machine makes one litre bottles by the continuous extrusion process. A similar setup with guide rods for centering the parison was used in the experiments to test the sensor. In an industrial system, the cooled guide tubes could not be used as they would interfere with the operation of the mould. They might also distort the parison by cooling it on one side.

Smaller guides could be cheaply fixed to the sensor to keep the parison properly positioned. These guides would be in contact with the parison for much less time an would probably not cool it significantly. There is a chance that they would snag the parison as the sensor moved rapidly up and down. A completely non-contact measurement would be desirable.

If contact with the parison is to be avoided, the centering and distance adjustment must be accomplished by moving the sensor on line. Two quick response, computer controlled,

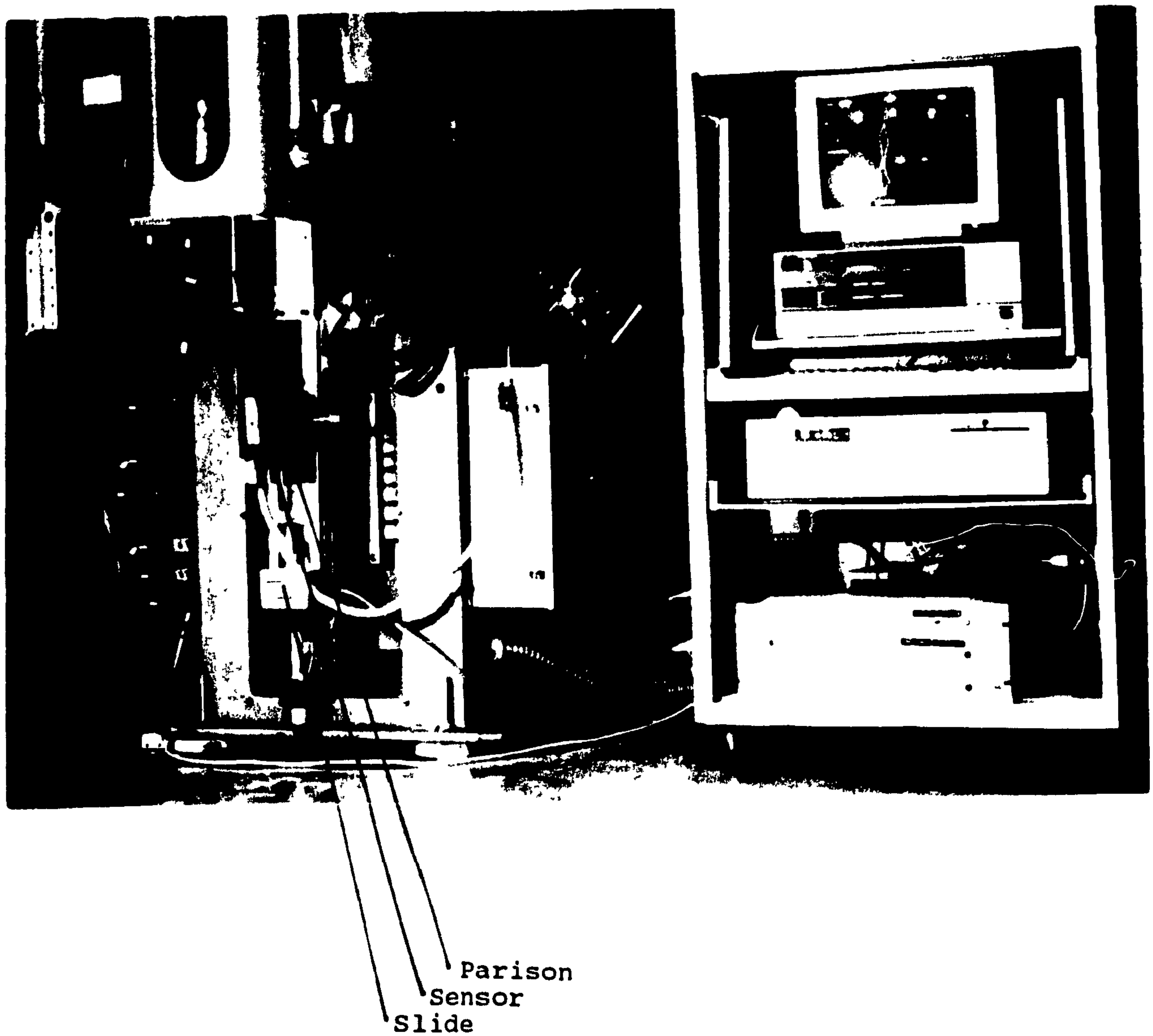


Figure 15 : The sensor and slide mounted on a blow moulding machine. The sensor is connected to the grey electronics box which is in turn hooked up to the computer in the cabinet.

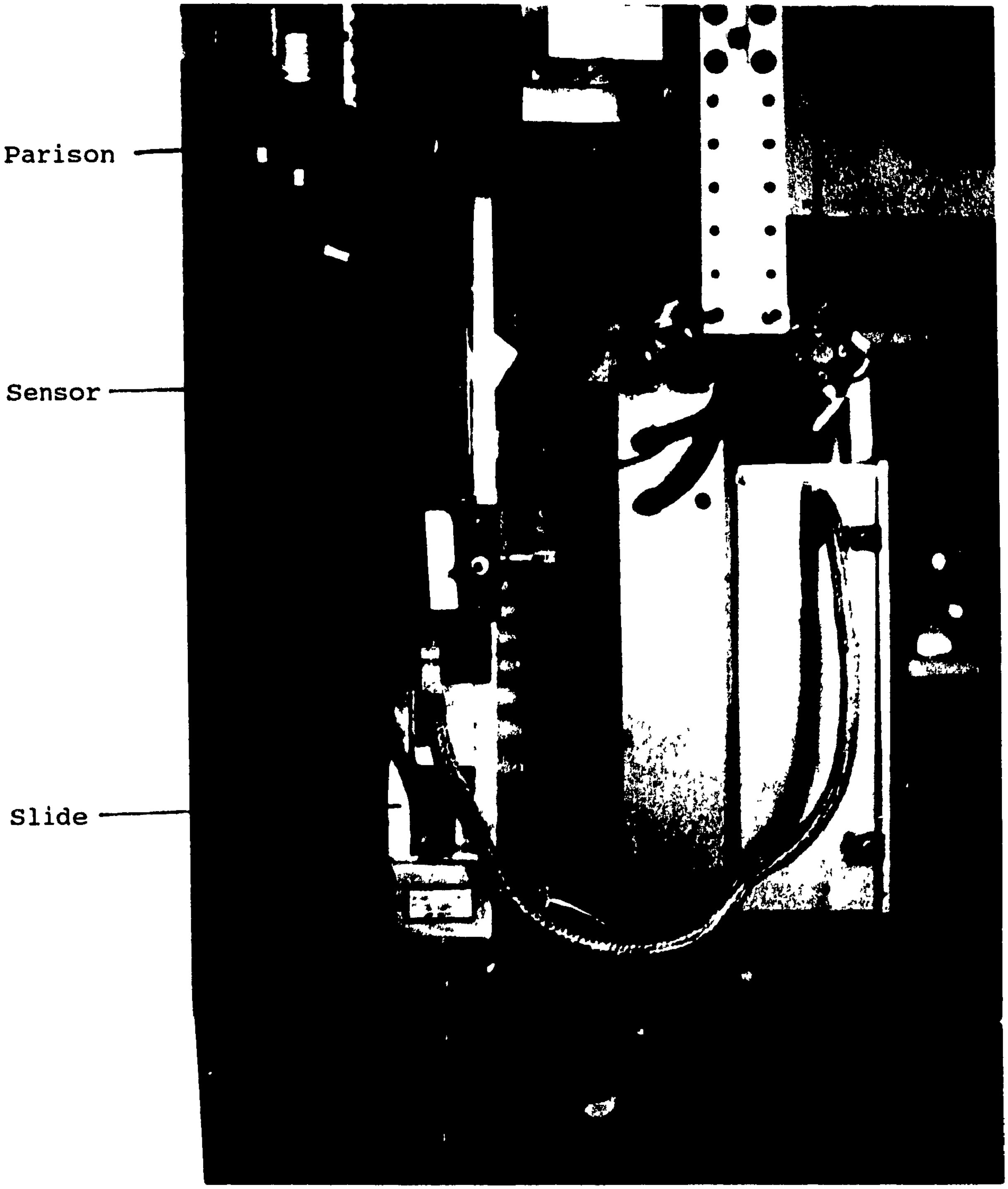


Figure 16 : A closeup of the sensor just beginning to scan the parison.

positioning systems with travel of about 2 inches would be needed to move the sensor closer to, further from, to the left of, or to the right of the parison.

The computer must at the same time have feedback on the position of the parison relative to the sensor. The distance between the parison and sensor can be obtained from the same signal used to measure the thickness. Centring information must be obtained in some other way. The diameter gauging optical system could simultaneously obtain the diameter and the needed centring feedback.

3.4 Software

3.4.1 Simulation for Optical Design

A program was written to aid in the design and conceptualization of the prototype. The program is named THICK.BAS.

The THICK.BAS program can automatically calculate the positions and distances between various components based on certain design criteria. These criteria included specifications on the depth of field, maximum thickness of the sample, maximum refractive index of the sample, the sizes of the arrays, the specifications of the lenses (one could choose between a number of possible lenses), and optical principles such as the Scheimpflüg condition and the thin lens formula. These and other parameters could be adjusted while the program was running to allow different arrangements of the optics to be tried. The optimal arrangement determined with this program was transferred to AutoCAD to be refined and drafted for construction.

The THICK program was also used to simulate the collection of data and calculate the thickness to provide an indication of the potential accuracy of the device. One of the results of these calculations is shown in Figure 20, and was discussed earlier.

3.4.2 Testing the System

A number of testing programs were written during the course of the research. The useful ones will be noted here.

SNAP3.EXE (or SNAP3.C) - written in Microsoft C. It plots the intensity profiles of the three different cameras on the computer screen. It is a stand-alone program. So, to run it, just type SNAP3. Quit by hitting any key.

SCAN.C - written in Microsoft C. It continuously plots a straight horizontal line on the computer screen at a line number which can be controlled by the mouse. The brightness of the line is varied to represent the signal from the linear detector. It is bright at points where light is striking the detector, and dark where the detector is dark.

Moving the mouse and the sensor together will produce a 2D image resembling a cut away view of the object. The image is useful for evaluating the quality of the raw data for different materials and surface conditions.

SLIDE.BAS - This program can be used to activate the slide for manual control.

3.4.3 Calibrating the Optics

In order for the software that reconstructs the parison to calculate the thickness profile, information is required on how the laser beams are positioned in space. This is determined through calibration. Calibration is done using a mirror with a fine slit in its reflective coating which is mounted on an accurate positioning system. The mirror is placed in the path of a laser beam. The beam reflects off the mirror to produce a peak in the one dimensional image detected by the linear array. The mirror is then moved until the slit in its mirrored surface is in the path of the beam (see Figure 17) . The imaged peak will then have a dimple in it where the slit is not reflecting the light. The mirror is moved until the dimple is centred on the top of the peak. The (X,Y) position of the mirror is recorded along with the location of the peak on the linear array.

This procedure is repeated at several different points along the path of each beam. Then lines are fit to the data to obtain vectors for each laser beam and curves are fit to the data to obtain a relationship that maps peak positions on the array to positions in space.

The CALIBRAT.BAS program is used for this calibration procedure. After calibration is completed, it produces a graphic display of the beams in space interacting with whatever is

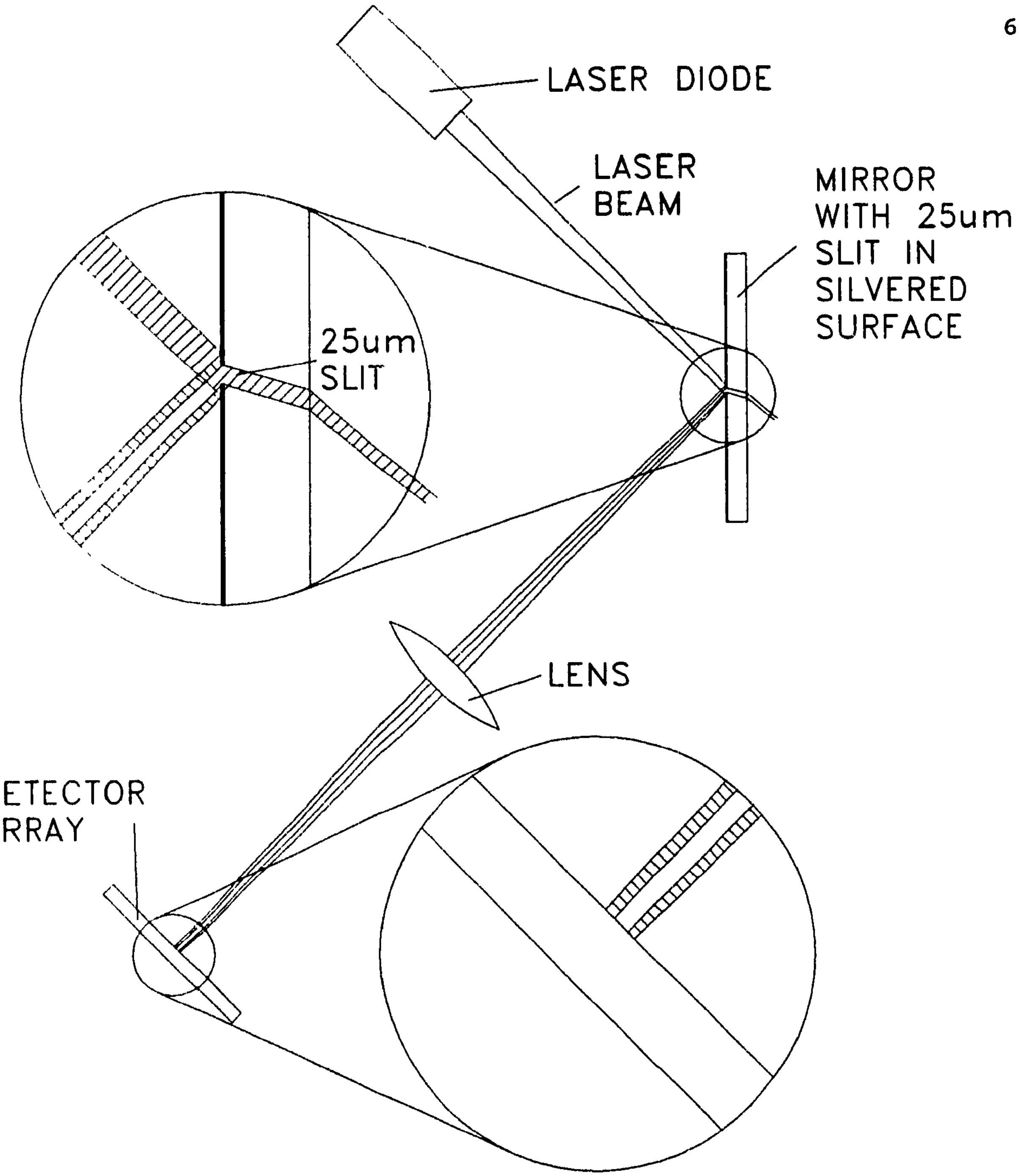


Figure 17 : During calibration, the alignment of the lasers is determined using a mirror with a slit in its silvered finish.

placed in their paths. The active display is a useful tool for verifying the calibration qualitatively.

3.4.4 Acquiring Raw Data and Locating Peaks

A special program is used to control the slide during an experiment and to store the data delivered by the prototype. This program is made as compact as possible to leave as much memory available in the computer as possible for data.

When executed, the program first determines the available memory and the slide speed, and provides instructions to prepare for a scan. Then it causes the sensor to scan the parison. Next it goes through all of the stored images and looks for the peaks in each. References 35, 36, and 37 provide some of the background mathematics used in developing the peak detection algorithms. The subroutine called "FINDPEAKS" uses an mathematically more sophisticated, more accurate, but slower, approach than those found in the references. Figure 18 is a flow chart for the "FINDPEAKS" subroutine. A graphic display is provided for the user to monitor this operation. Finally, the computer stores the peak locations and other information in a file. Another program reconstructs the thickness profile of the parison from the data in this file.

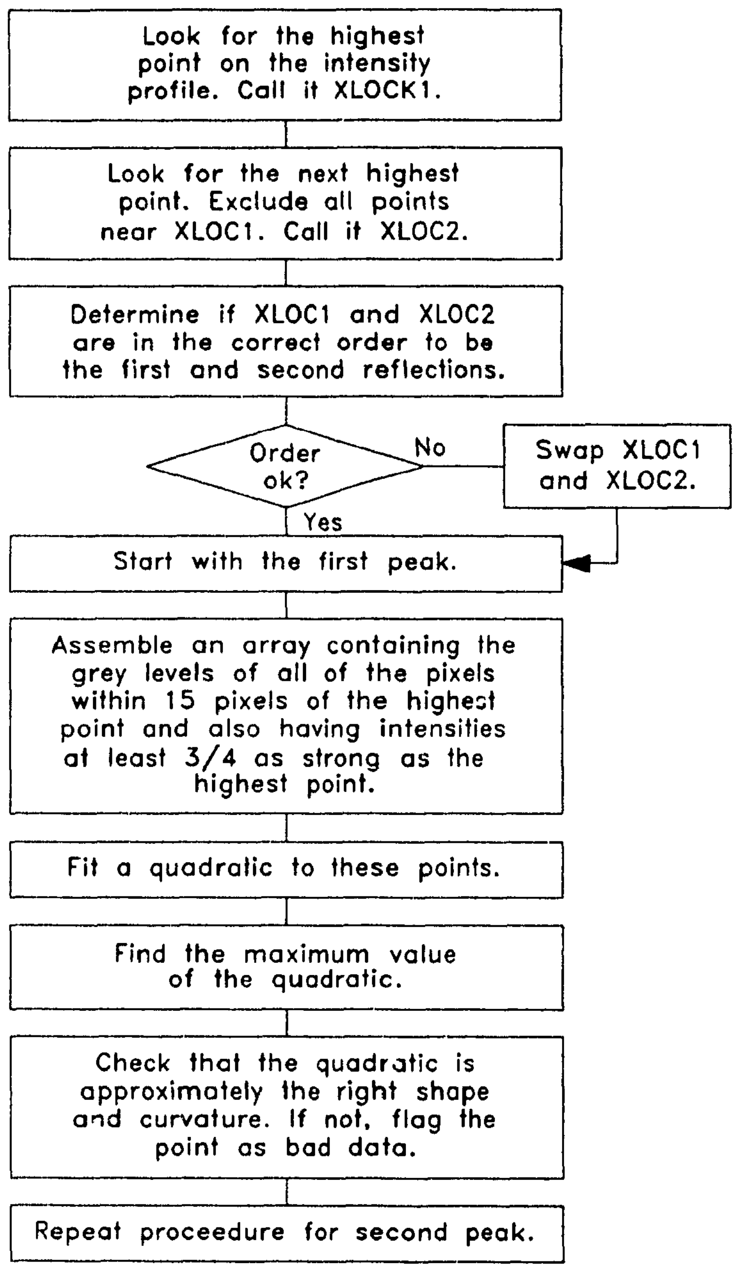


Figure 18 : A flow chart outlining the operation of the subroutine "FINDPEAKS". This routine filters out signal noise using fast curve fitting algorithms in order to determine the location of the detected peaks accurately.

3.4.5 Analyzing and Reconstructing the Parison

To determine the thickness profile, program must first obtain the front surface profile of the parison. Knowledge of the angle of the parison outer surface relative to the sensor at each measurement point is essential for reconstructing the parison thickness profile. In the prototype, it was assumed that the parison did not sway because it was supported by the guide rods. It was also assumed that the effect of sag was insignificant during the two seconds needed for the scan. The front surface angle was obtained by fitting a curve to the data which provided the sensor to parison distance variation during the scan. The recommended second prototype would find this angle directly by comparing the range data measured simultaneously by two separate beams.

After the front surface profile is known, a preliminary calculation is made to determine the thickness profile. The program uses the refractive index provided by the supplier and assumes that the back surface is parallel to the front surface. Simple ray tracing formula are used to geometrically calculate the thickness of the material at each point. Figure 19 is a flow chart of the part of the program that reconstructs the parison profile.

With the preliminary thickness profile, it is now possible to repeat the generation of the thickness profile described above, but this time it is assumed that the inner and outer surfaces are

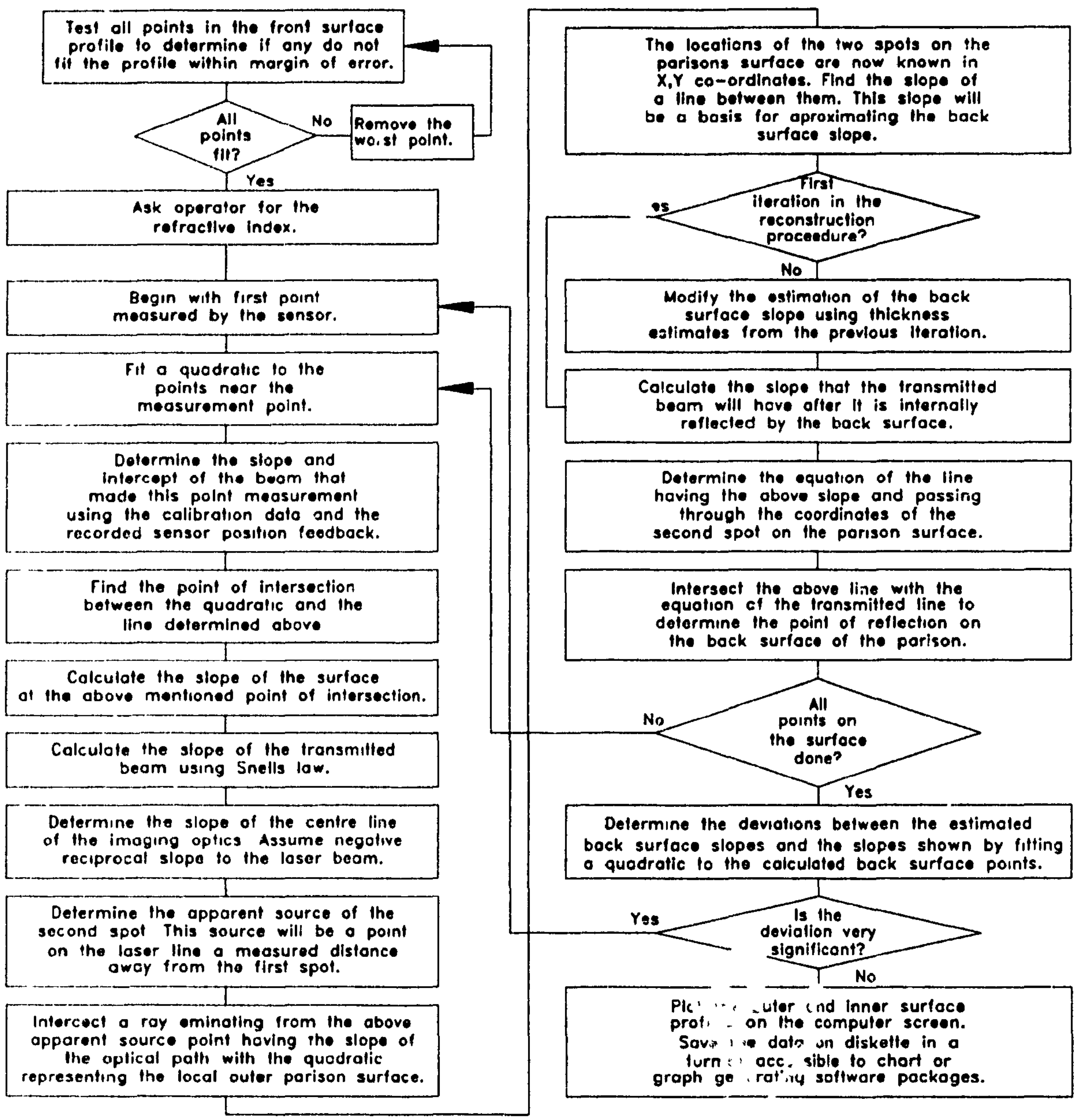


Figure 19 : A flow chart showing the steps taken to reconstruct the parison profile.

not parallel. Instead, the angle between them is calculated by fitting curves to the preliminary thickness profile.

The thickness profile can be reiterated a few times to stabilize the solution.

The program used to reconstruct the parison is called ANALYZE.BAS. It is well documented and has many graphics commands (hidden as comments) which can be activated to observe the geometry of the calculations as the beams are traced and the parison is reconstructed. The program will save data describing the final shape of the parison in a file. The file format is accessible to graphics programs such as Sigma Plot, Energraphics, Lotus 123, etc.

3.5 Evaluation of The Apparatus

3.5.1 Experimental Validation

Several experiments were carried out to test the accuracy of data obtained with the prototype. The first was a scan of a sheet of Plexiglas. This experiment was most useful because it provided a means to compare the values for thickness obtained with the sensor to values that could be measured accurately with a micrometer. Figure 20 shows the results of this test. The accuracy is within 1%.

The other tests were done measuring a real parison produced by a Battenfeld Fisher blow moulding machine. The sensor, slide, and electronics box were attached to the machine as shown in figure 15. The wiring between the various components is shown in figure 14. As well an optical mouse was attached to the sensor to provide feedback on the sensor's vertical position. A computer controlled relay link is also connected to enable software activation of the knife and the extruder.

The program entitled "ACQUIRE.BAS" is executed. It runs some diagnostics on the equipment, and activates the parison producing parts of the blow moulding machine to simulate a real blow moulding operation. When the operator is satisfied that steady state operation has been achieved, he queues the computer to measure the next parison that the machine produces. The computer scans this parison rapidly, and stores the raw data for analysis. The explanation of the software in sections 3.4.4 and 3.4.5 provides more detail on how the raw data is treated.

These on-line experiments demonstrate that the apparatus produces data with minimum scatter when measuring both polyethylene (Figure 21) and PETG (Figure 22). After each parison was measured, it was frozen in liquid nitrogen and cut open. The thick and thin points were measured on the frozen parison and compared to the thick and thin zones of the measured thickness profile. These comparisons are noted on the two figures. Due to the distortion of the parison that occurs during freezing, an accurate match in the thickness was not expected. However, the values were in reasonable agreement with each other.

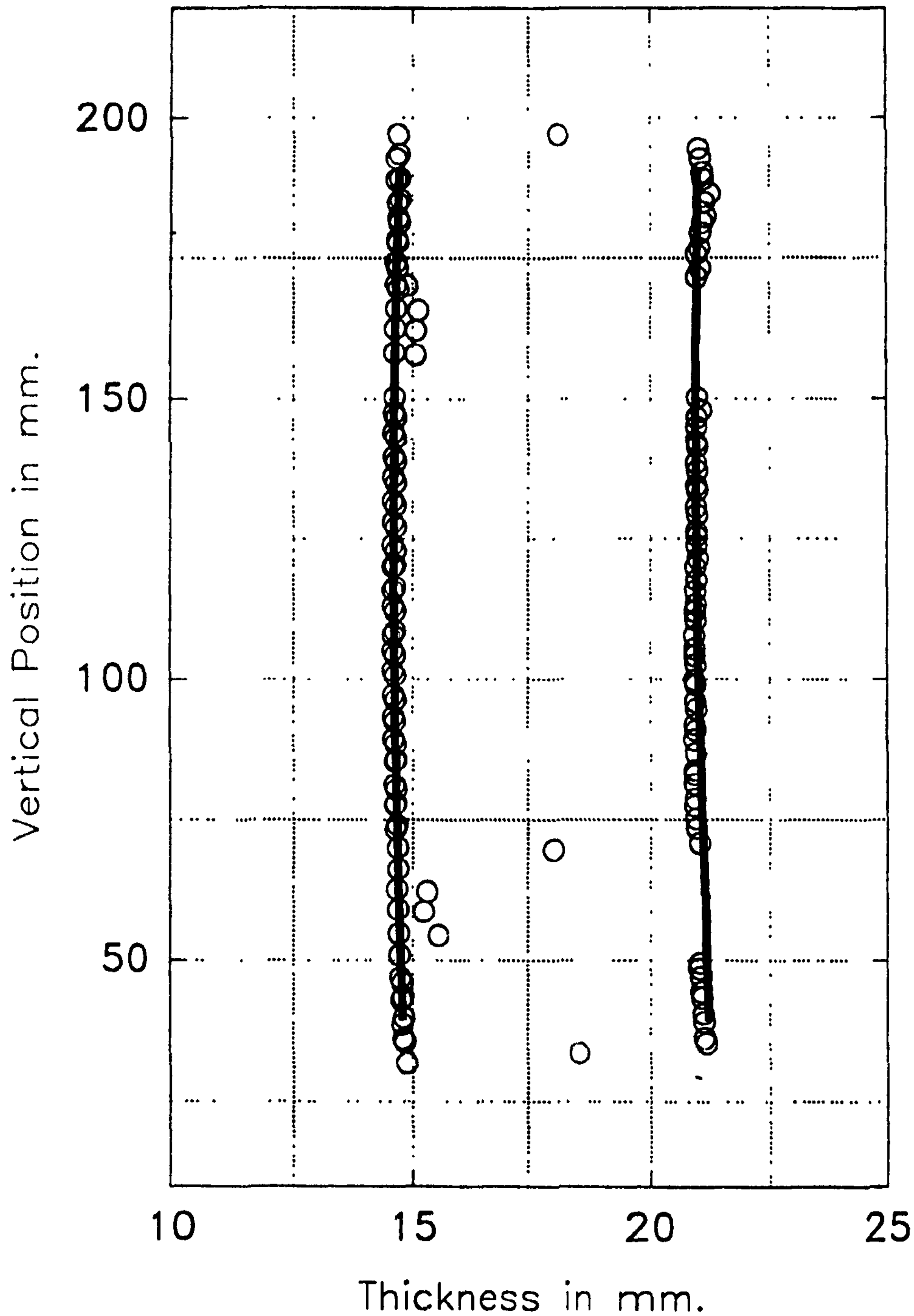


Figure 20 : Measurement of a piece of Plexiglas (n = 1.49). Solid lines show thickness measured with a micrometer. Circles are measurements made with the optical device. Gaps in data are blacked out areas needed as indicators of vertical position.

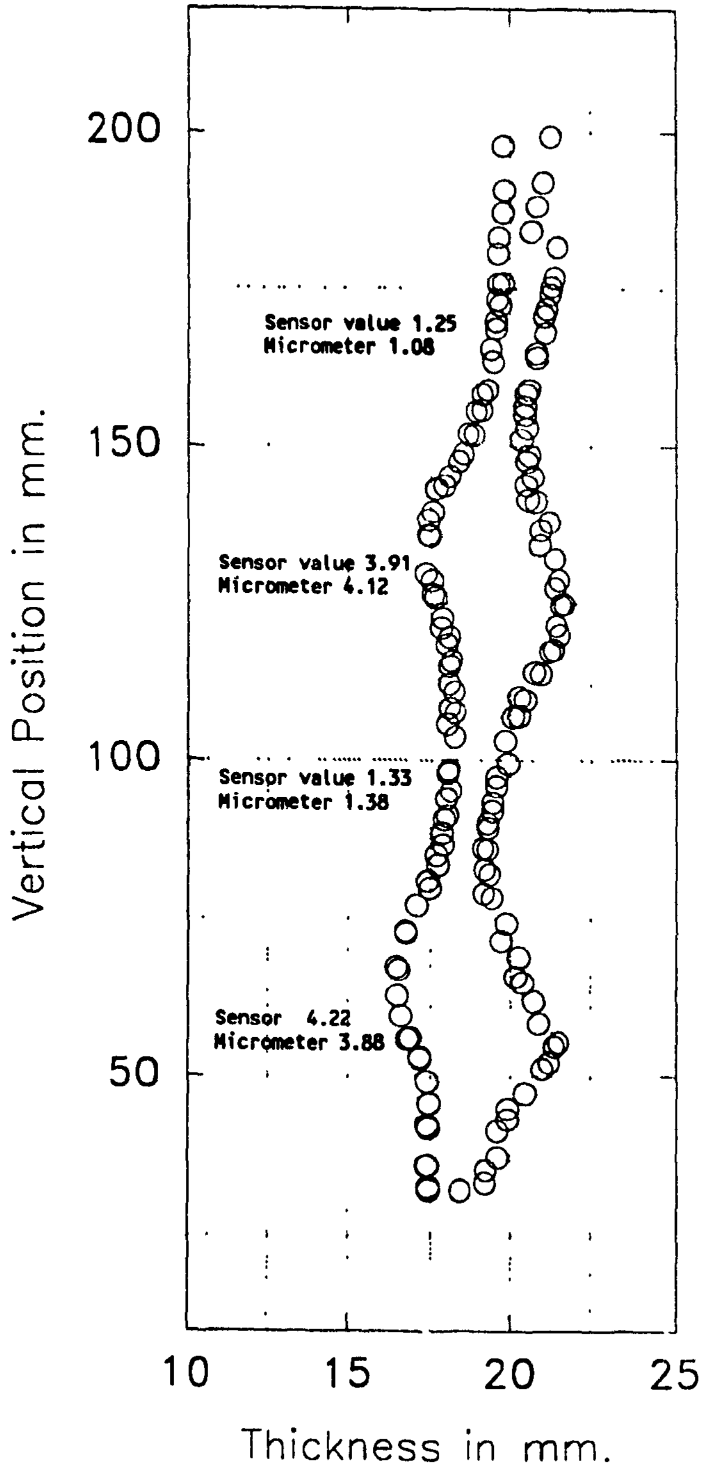


Figure 21 : On line scan of the bottom portion of a Sclair 56B polyethylene parison. A micrometer was used to make the indicated measurements on a similar parison that was frozen in liquid nitrogen.

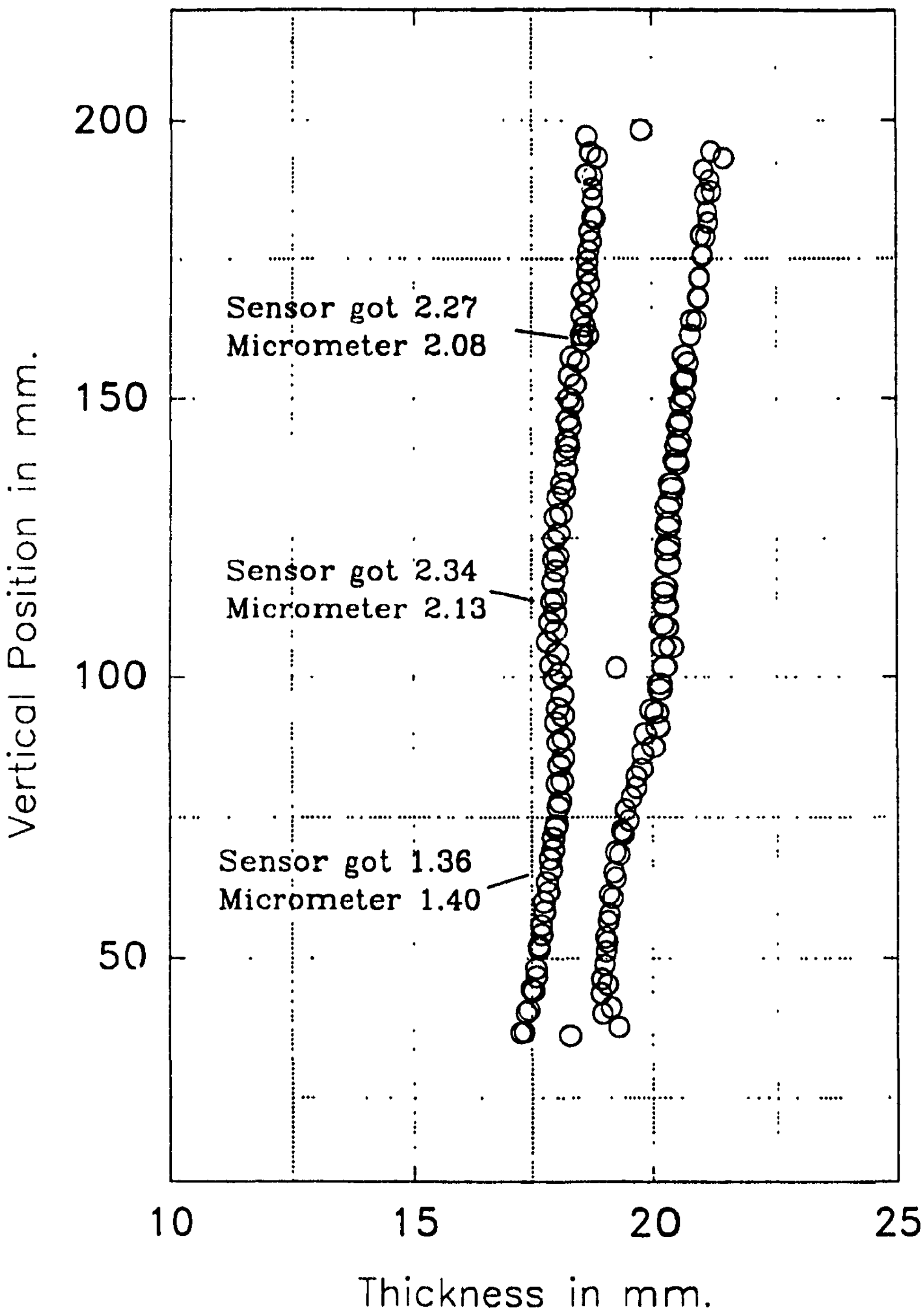


Figure 22 : On line scan of the bottom portion of a Kodak PETG polyethylene parison. A micrometer was used to make the indicated measurements on a similar parison that was frozen in liquid nitrogen.

3.5.2 Evaluation With Respect To Selection Criteria

3.5.2.1 Technical Criteria

The prototype sensor meets all but one of the criteria that were listed earlier. The missing criterion is that the sensor fails to work where none of the materials properties are known. To obtain accurate absolute thickness measurements, the refractive index of the molten resin must be supplied. For one of the materials that were used in our tests, the refractive index was obtained from the manufacturer. For another, it was obtained from the literature. For materials where no data is available, the refractive index can be easily measured with an affordable instrument (e.g. an Abbe refractometer).

The refractive index does not vary significantly due to stresses in the polymer imposed during parison extrusion. This can be shown from the Stress Optical Law (38) used in birefringence research. The Stress Optical Law is

$$\Delta n \equiv n_{\parallel} - n_{\perp} = C\sigma$$ where

$C \equiv$ stress optical coefficient
$\sigma \equiv$ stress
$n \equiv$ refractive index
- $\parallel$ parallel to stress field
- $\perp$ perpendicular to stress field

For polyethylene, C is 1800-2400 $\times 10^{-12}$ m^2/N. The residual molecular orientation after swelling extrusion will be much less than that during extrusion. To get an idea of the maximum change in the refractive index due to molecular orientation let us determine the approximate stress in the die, and substitute this value into the stress optical equation. Assume the annular die has an outside diameter of 31mm and an inside diameter of 29mm. Assume the flow rate is 10 g/sec, polymer density is 1 g/cm^3, and the viscosity of the melt is 2 x 10^4 Pa•sec during extrusion (estimated from measurements made for reference 11).

Let us estimate the shear rate, shear stress, and finally the maximum change in refractive index under the above conditions.

Area of die opening = (0.1 cm x 3.0 cm x 3.14)
= 0.942 cm^2

Ave. Polm. velocity = (10 g/sec) / (1 g/cm^3) / (0.942 cm^2)
= 10.6 cm/sec

Assume the velocity at the centre of the gap is roughly twice the average velocity. Assume velocity at the wall is zero. For conceptual simplicity, assume shear is linear between the centre of the gap and the wall.

Shear rate ≅ (2 x Ave. Vel.)/(1/2 Gap)
≅ (2 x 10.6 cm/sec) / (0.5 x 0.1cm)
≅ 424 sec^{-1}

Shear Stress, $\sigma \cong$ Viscosity / Shear Rate

$$\sigma \cong (2 \times 10^{4}\ \mathrm{Pa{\bullet}sec}) \ / \ (424\ \mathrm{sec}^{-1})$$

$$\sigma \cong 47\ \mathrm{Pa}\ \text{or}\ 47\ \mathrm{N/m^2}$$

Using the stress optical law,

$$\Delta n \cong (2400 \times 10^{-12}\ \mathrm{m^2/N}) \times (47\ \mathrm{N/m^2})$$

$$\Delta n \cong 1.1 \times 10^{-7}$$

$$\Delta n \cong 0.00000011$$

... which would cause an error in the measurement of no greater then 0.000011%. This demonstrates that the effect of stresses on the polymer refractive index can be neglected during the calculation of thickness by the beam reflection technique.

Refractive index does vary with density changes caused by cooling. What the sensor is in fact measuring is the optical thickness, which resembles the true amount of material in the parison more closely than does the physical dimension of thickness.

Even if the refractive index is not known, the sensor still produces consistent profiles showing the relative variation in the thickness quite accurately. This is sufficient for the application as a parison programming aid, part of a closed loop control system, or for comparative studies of die or resin properties.

Table 1 compares the performance of the sensor against the technical criteria established earlier.

3.5.2.2 Subjective Criteria

1) It is desirable that the apparatus occupy a small amount of space in the vicinity of the parison. It must not interfere with the operation of the machine.

The dimensions of the sensor are as follows:

Height	22cm
Width at top	10cm
Width at bottom	8cm
Breadth	4.5cm

The apparatus is connected to a second box with a four foot cable. This box is about 50 x 20 x 20 cm.

With these dimensions, the sensor just fits in between the mould halves of the Battenfeld Fisher blow moulding machine in Figure 15 that makes one litre bottles. The sensor needs only a 5cm space between the mould halves to vertically scan a parison.

Table 1 : Performance of The Sensor in Relation to Established Criteria.

Attribute	Criterion	Performance of Sensor
Measurements per sec	100	250
Parison geometry	See section 2.??	Meets all criteria if parison surface is diffuse.
Swell, Sag, and Sway	It must work despite these effects.	Works with an adequate positioning system.
Temperature of parison	400 Celsius	Above 400 C
Distortion to parison	Should cause none.	Causes none.
Marking of parison	Should not mark parison.	Does not mark parison.

2) It is desirable to obtain a large number of measurements before the mould closes in order to achieve better parison dimensional control.

The sensor can acquire raw data at a rate of 250 measurements per second.

3) The technique should be suitable for use with a variety of materials, additives, and colours.

It is essential that the object being measured is transparent at the wavelength of the beam. Many commercial polymers are transparent to visible light and even more are transparent in the near infra-red. Even some colorants will permit IR light to pass, although most cause significant attenuation. The accuracy is dependant on the amount of scattering caused by the material.

4) The technique should be both inherently reliable and easy to maintain.

The optical sensor head itself has no moving parts inside to cause wear. The optics may become dirty and have to be wiped clean occasionally. As long as it is solidly constructed, it should last a long time.

The mechanical positioning system will have moving parts. The reliability of this part of the apparatus will depend on the supplier of the mechanical positioning equipment. Reliability will likely be a function of price.

5) Ideally, the apparatus should not be expensive.

The main parts for the prototype cost about $18,000[2].

6) The measuring technique should not require placement of components inside the parison or physical contact with the parison as sticking and fouling may occur.

The technique does not require that anything be placed inside the parison.

7) The technique should not contribute to polymer waste.

The sensor does not sacrifice material in order to make measurements.

8) The technique should be sufficiently accurate.

The accuracy determined during our tests was 5% or better provided that the refractive index was known.

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[2] The proposed second prototype would cost significantly less.

9) The technique must be safe.

The only danger from the sensor is the lasers. These lasers are very low power and are not dangerous unless aimed directly into the eye at close range. For this to happen, a person would have to have his head in the machine. Blow moulding machines generally have elaborate safety systems to prevent this.

CHAPTER 4

Conclusions

4.1 Summary

The blow moulding industry needs tools to facilitate the setup of an extrusion blow moulding operation. The programming of the parison profile is one of the most difficult setup steps for an operator. On-line measurement of the parison dimensions would help an operator significantly. It would also help others develop technology to automate parison programming.

Measuring parison diameter has been done; however, until now to the best of our knowledge, no one has ever designed a device that will directly measure the thickness of a blow moulding parison on-line.

A number of techniques by which thickness measurements could be made were proposed and assessed. A technique based on beam reflection was chosen for further development because it appeared that it would be cheap, fast, safe, and accurate. A prototype device using this technique was built and tested on a blow moulding machine. These tests showed that the technique works very well, and thus, would be useful to the blow moulding industry for parison programming.

The sensor is capable of making 250 point measurements per second. It uses these point measurements to reconstruct the thickness of the sensor with an accuracy of 5% or better.

4.3 Recommendations

Based on what was learned in building the first prototype, we have considered how a better second prototype could be designed. Figure 23 is a schematic of a possible design with several advantages over the first design. These advantages are mostly related to parts cost, simplicity, smaller size, and the built in ability to measure diameter without peripheral equipment.

It was not possible to determine the refractive index with the triple imaging system approach. Therefore, the second prototype will not need three imaging systems. The second prototype will require that the refractive index be supplied, or that the device be calibrated specifically to determine the refractive index.

The angle of the parison surface is an important consideration in calculating thickness. The second prototype will measure this directly by imaging two laser beam reflections simultaneously. The locations of the first reflections of each laser beam can be used to determine the surface angle.

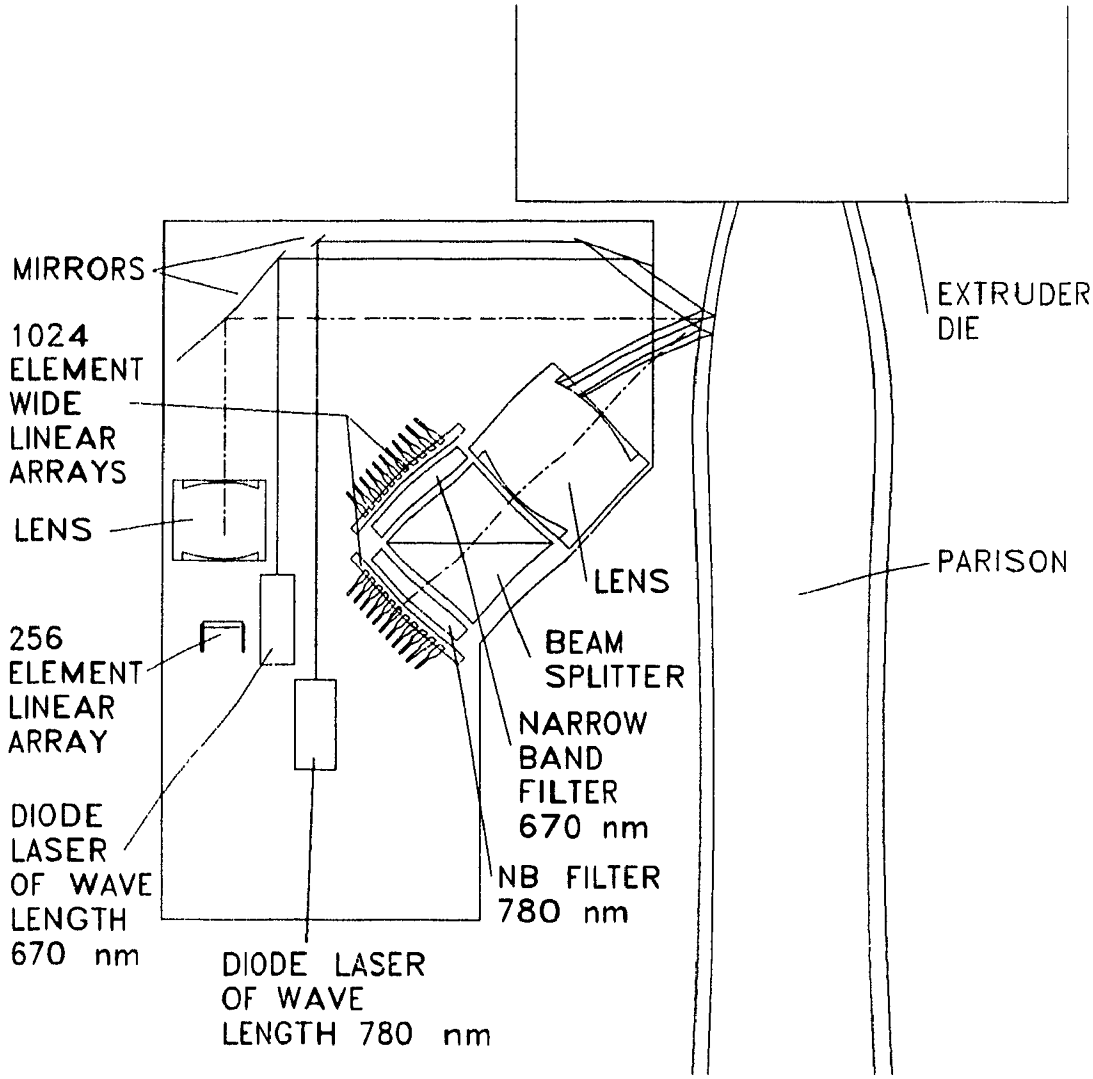

Figure 23 : A diagram of a possible design for a second prototype of the thickness sensor. This design would be smaller, cheaper, faster, and would obtain diameter measurements at the same time as it obtained thickness measurements.

In the Figure 23, the two beams are imaged by a single lens. This reduces lens cost by two thirds and leaves space for a lens with a lower F/#. The image is split into two images with a cubic beam splitter. Each image is then filtered to select light from one of the lasers (note that the lasers have slightly different wavelengths) and the image is detected on a wide line array of the type used in the first prototype.

More money could be saved by doing away with one filter and the beam splitter and simply imaging both points onto one detector (see Figure 24). If the laser beams were far enough apart, then the processing software would be able to distinguish which peaks belonged to which laser. Still more savings could be realized by replacing the two lasers with a single laser and a beam splitter to create two beams. A filter is still needed to filter out ambient light.

The lasers in Figure 17 have longer focal lengths as recommended in the discussion. All of the optics are arranged in such a way as to give the sensor access to the top portion of the parison. Diameter measuring optics are included in the design. Lighting for diameter measurement would be provided externally and the background would have to be painted dark.

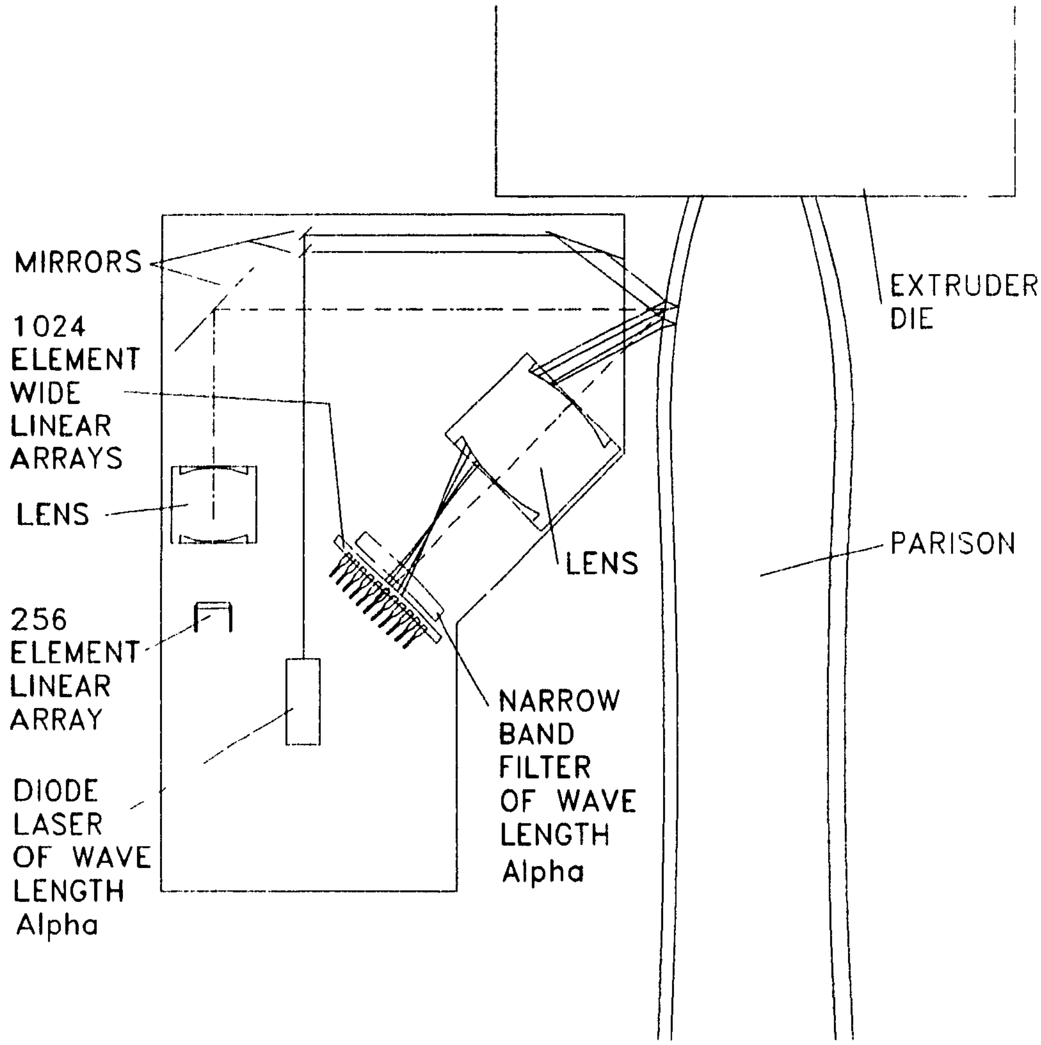

Figure 24 : Second alternative for next prototype.

In addition to constructing a second prototype, the development of software that would make use of thickness and diameter measurements to improve parison programming is recommended. For example, software could be designed to help an operator to interpret the information provided by the sensor and use it to improve the gap-time profile. Such software could be sold with a sensor system as a product useful to the blow moulding industry.

An ambitious goal, but one which has been pursued by several experts in the field, is the development of a closed loop parison programming system. Most professionals in the blow moulding industry agree that the biggest barrier to its development is the need for a practical device for obtaining the thickness profile of the parison on-line. It is hoped that the developments that have been presented here will entice others to reevaluate their ideas for closed loop control in light of this new sensor technology.

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APPENDIX

A1. Derivation of an Equation for Relating Parameters in a Beam Reflection System

When a beam strikes a parison, most of the light will be transmitted through the parison, but some light will be reflected

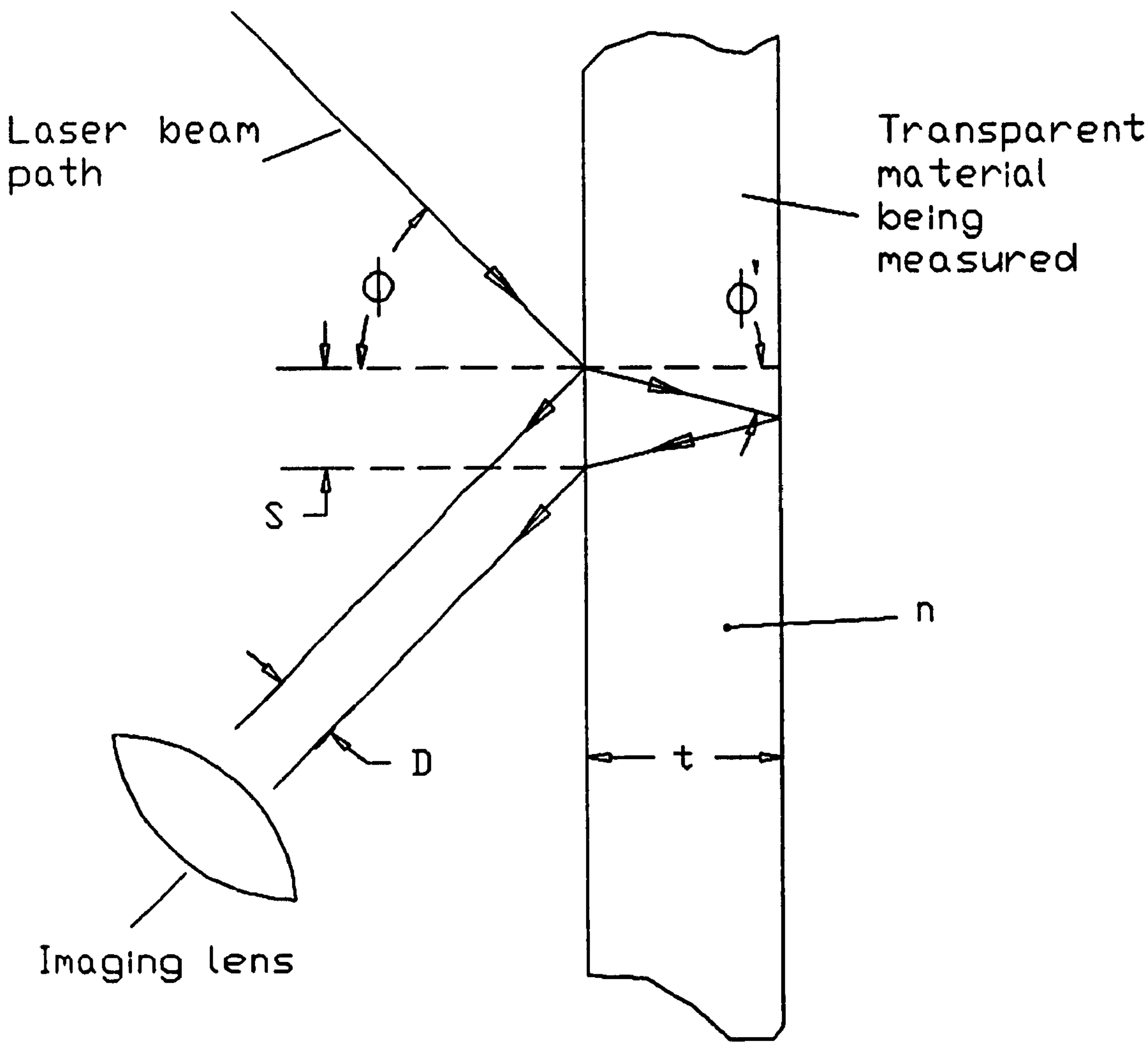

Figure 25 : Relevant dimensions in a simple beam reflection system.

at the two air/polymer interfaces. This effect is illustrated in Figure 25. There is a relationship between the separation of the two reflected beams, the angle of the entering beam (ϕ), the refractive index of the material, and the thickness of the material.

The distance between where the light enters and where it leaves - measured along the material's front surface is 'S',

$$S \cong 2 \bullet t \tan(\phi') \qquad (1)$$

From the point of view of the imaging system, this separation will be "D".

$$D \cong 2 \bullet t \bullet \tan(\phi') \bullet \sin(\phi) \qquad (2)$$

Using Snell's Law we can relate ϕ to ϕ'.

$$n_{air} \sin(\phi) = n_{parison} \sin(\phi') \qquad (3)$$

$$\sin(\phi') = (n_{air}/n_{parison}) \sin(\phi) \qquad (4)$$

Using the basic double angle formula's we find $\cos(\phi')$

$$\cos(\phi') = 1 - [2 \bullet (n_{air}/n_{parison})^2 \bullet \sin^2 (\phi)] \qquad (5)$$

Substituting (4) and (5) into (2), we obtain the following relationship.

$$D \cong 2t \frac{(n_{air}/n_{parison}) \sin(\phi)}{\{1 - [2 \bullet (n_{air}/n_{parison})^2 \bullet \sin^2 (\phi)]\}} \bullet \sin(\phi) \qquad (6)$$

As well, the angle of the imaging system relative to the material, and the parallelism of the inner and outer surfaces, play a role in establishing the above relationship. These additional factors are accounted for in the software developed during the project. The diskette included with this thesis contains a program called THICK.BAS. The simultaneous solution of three beam equations similar to (6) is orchestrated by a subroutine called COMPS. For a detailed understanding of how the COMPS subroutine works, list this program.

A2. A List of Major Components and Suppliers

The first items are numbered in order to correspond to the list of parts in figure 13.

Prices are in Canadian Dollars (around 1990) unless otherwise stated.

1. Positioner Bracket

Machined at IMI of the NRCC

2. Flexure Mirror Mount #MFM-075

Newport Instruments Canada Corporation
a/s Georges Duchesne
4439, Kingston
Pierrefonds, Quebec
H9A 2T2

Quantity : 2
Price : $127.00 each

3. Laser Pen HCP830-PC, 10mW laser power at 90mA, 5V

Hoetron Inc.
776 Polomar Avenue
Sunnyvale, CA 94086-2914
U.S.A.

(not a recommended supplier for future purchases)

Quantity : 1

Price : (U.S.A.$) $415.00

4. Laser Pen HCP680-PC, ?? Mw laser power at 72 Ma, 5V

Hoetron Inc. (see item #3)

Quantity : 1

Price : (U.S.A.$) $625.00

5. Laser Pen HCP780-PC, 3 Mw laser power at ?? Ma, 5V

Hoetron Inc. (see item #3)

Quantity : 1

Price : (U.S.A.$) $295.00

6. Translation Unit MR1, Part #338 044

(note: this particular stage is not recommended in future as it is too stiff.)

Klinger Scientific

2136 rue de la Province

Montreal, Quebec

J4G 1R7

tel: (514) 442-4666

Quantity : 3

Price : $156.00 each

7. Solid State Line Scanner part # RL1024SAQ

EG&G Reticon

35 Congress Street

Salem, MA, U.S.A,

01920-6529

tel (508) 745-7400

Quantity : 2 purchased (one we already had)

Price : (U.S. $) $995.00 each

8. High Resolution Lens, Part # 56700

-41.569 mm EFL

-Distortion .02mm max

-Mag. 0.98

-Special mounting features

JML Optical Industries Inc.

690 Portland Avenue

Rochester, NY, U.S.A.

14621-5196

Claude Fedele

Quantity : 3 total in two separate orders

Price : (U.S. $) $575.00 each

9. Mirror, 3/4" #M7D20DM.4

Newport Instruments (see item # 2)

- Note: the mirror that reflects the beam from laser #4 in Figure 13 is a 1 cm sqr metallic surface mirror available cheaply from Newport or Klinger.

Quantity : 2

Price : $102.00 each

10. 830 nm Narrow Band Filter, part # NCI-830 or?? NMLC4-830

-MicroCoatings ML4-830 8ZAJ (code on packet)

Tasso Inc.

a/s Amile Tasso

3468, Drummond

Beareau 902

Montréal, Québec

H3G 1Y4

Quantity : 1

Price : $175.00

11. 772 nm Narrow Band Filter, part #N00722

(note : it was not possible to get an exact match between the wavelength of the laser and the filter)

-.980X.980X.260

-56%, 171nm

Optical Filter Corp.

a/s Jewel Anderson

2 Mercer Road

Natick, MA 01760

U.S.A.

Quantity : 1

Price : (U.S. $) $200.00

12. 675 nm Narrow Band Filter, part #N00675

(note : see item 11)

-.980X.980X.260

-52%, 232nm

Optical Filter Corp. (see item 11)

Quantity : 1

Price : (U.S. $) $200.00

13. Main Mounting Plate

Machined at the National Research Council Canada

Quantity : 1

Price : Estimated $500.00

14. Evaluation Daughter Board, part #RC1001LNN

EG&G Reticon (see item 7)

Alternative : Mayan Automation, Montreal
They have a cheaper board that may do the same job as items 14 and 16.

Quantity : 3 in two purchases

Price : (U.S. $) $200.00 each

15. 50 pin connector

Parts for all cables were obtained from stocks at the IMI of NRCC. Assembly was done at IMI by Phil Swan.

16. Evaluation Mother Board, part #RC1000LNN-011

EG&G Reticon (see item 7)

Quantity : 3 in two purchases

Price : (U.S. $) $400.00 each

17. Power Supply, various

Hammond

Obtained from stores at IMI

Quantity : 3

Price : $115.00 each (aprox.)

18. Electronics Box

Quantity : 1

Price : $100.00 (aprox)

19. OC500 MS Multiple Scan Input Processor (Frame Grabber)

-specially modified software.

-repairs/modifications made to board to operate at low clock speeds (i.e. 50-300 kHz).

Coreco Inc.

6969, route Transcanadien

Bureau 113

Ville St-Laurent, Quebec

Canada H4T 1V8

tel (514) 333-1301

Quantity : 1

Price : $2200.00 (aprox)

20. Motorized Slide Model # B4036K4J

-8" slider

-note : the slide was later substituted for a shorter one, 24" in length.

Motomatic Series E-652 DC motor, Tachometer Generator

Velmex, Inc.

P.O. 38, E. Bloomfield, N.Y. 14443

tel (716) 657-6151 or 624-1080

Quantity : 1

Price :
- Original slide (U.S. $) $1035.00
- Shorter substituted slide (U.S. $) $822.00
- Motor, Tach, and Control (U.S. $) $1,303.00
- adaptor bracket (U.S. $) $40.00 (aprox)

- Total Estimated Price (U.S. $) $ 2,165.00

21. Optical Mouse (used as position sensor)

Supplier unknown, was obtained from Louis Charboneau at IMI

A more rugged and accurate positioning system should be purchased to provide computer with feedback on slide position. Estimated cost of such a system $1000.00.

22. Digital I/O interface card (used for computer control of the slide and the blow moulding machine).

Supplier unknown, was obtained from Louis Charboneau at IMI

Estimated cost $200.00

23. Relay box to link digital I/O interface card with controllers.

Made by Alfredo Di Carlo 1989. Estimate cost at $1000.00 including labour.

24. Personal Computer

Need - 286 with co-processor minimum (faster is preferred)
- VGA card
- 1 Meg minimum (memory is needed for images)
- Hard drive

- At least one full size expansion slot and five half size slots. (OC500MS, DIG I/O, position I/O, VGA, Mouse, Hard drive)

Quantity : 1

Price : $1700.00 minimum estimated Oct. 1991.

25. Quick Basic 4.5 Software Package from Microsoft.

26. Quick C 2.00 Software Package from Microsoft.

27. Halo 88 for Quick Basic 5.0

Media Cybernetics
8484 Georgia Avenue
Silver Spring, MD 20910
U.S.A.
tel: (301) 495-3305

Note: The newer "Halo Professional" does not work as well with Quick Basic due to a resident driver which will crash the computer each time a Basic program is stopped and restarted without unloading this driver.