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PAR
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DÉVELOPPEMENT D'UN SYSTÈME D'ENLÈVEMENT DE DÉFAUTS DANS LA SAUCE DE POMMES

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IL A FAIT L'OBJET D'UNE SOUTENANCE DEVANT JURY ET UN PUBLIC

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À L'ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

DÉVELOPPEMENT D'UN SYSTÈME D'ENLÈVEMENT DE DÉFAUTS DANS LA SAUCE DE POMMES

Thieu Quang Tho

Sommaire

La couleur est le facteur clé pour la détermination de la qualité des sauces de pommes et d'autres aliments. Plus claire est la couleur des sauces de pommes, plus haute sera la qualité du produit. Alors, les impuretés des sauces telles que les particules de couleur foncée, dites "défauts", doivent nécessairement être éliminées du produit final. L'enlèvement des défauts est réalisé par une machine conçue dans le cadre de ce projet. Elle est équipée d'un système de vision utilisant des capteurs CCD et des contrôleurs FPGA à grande vitesse. Le principe de détection des défauts est basé sur le traitement des images monochromes (niveaux de gris).

Le travail de ce mémoire repose sur une approche expérimentale. Il s'agit de la synthèse technique, la conception et la réalisation d'un prototype. Plusieurs expériences sont réalisées pour identifier les paramètres physiques importants tels que le profil de vitesse de l'écoulement, le comportement de la valve, etc.

Le principe de la machine est basé sur deux modules du système de vision. Le premier est pour détecter les défauts et envoyer les informations au contrôleur. Tandis que le second joue le rôle de vérification du fonctionnement de la machine et permet d'optimiser le contrôle. La conception des composantes de la machine est en modules interchangeables. Cette flexibilité permet de réaliser les mesures de profil de vitesse sur place en réutilisant tout le système de la machine. Le comportement du module d'enlèvement des défauts est déterminé expérimentalement en vue de minimiser la quantité de sauce rejetée lors de l'élimination des défauts.

Cette approche technique peut être appliquée aussi avec succès pour d'autres types de produits tels que la sauce de tomate, le jus d'orange concentré, etc. De plus, elle est fortement prometteuse pour des suspensions ou des liquides dont les composants se dégradent lors de la filtration.

DEVELOPMENT OF VISION MACHINE TO ELIMINATE DARK PARTICLE FROM APPLE SAUCE

Thieu Quang Tho

Abstract

Color is one of the key parameters in classifying applesauce and most other foodstuffs. The purer the color of the applesauce compound, the higher quality classification it merits. Therefore, elements which differentiate themselves in color (in this case the darker particles, called defects) from the applesauce compound must be removed. The defect detection was carried out through the application of machine vision technology using CCD sensor in conjunction with high speed FPGA based controller. The defects are diagnosed and then removed based on gray level in the image scene.

The work in this thesis involves an experimental approach which includes the synthesis and design of a prototype and realizing and identifying the various subtasks of the system such as the defect detection parameters, the applesauce flow profile under specific conditions and the mechanical behavior of the defect removal device.

The algorithm used to set up the system is based on two vision modules. The first module detects defect and generates its information that is used in the removal process. The second module is designed to verify the operation of the machine and to optimize the control if necessary. The machine is mechanically designed in modules that are easily interchangeable and perform the flow profile self-test ability in response to changes of the subject material. The removal device behavior is experimentally identified to minimize the waste of quality applesauce removed along with the defects.

This technical approach can also be successfully applied to remove defects in other foodstuffs like tomato sauce, orange concentrate, etc. Suspension or liquid compounds that have properties, which degrade when using a filtration approach, could all potentially benefit from this technology.

DÉVELOPPEMENT D'UN SYSTÈME D'ENLÈVEMENT DE DÉFAUTS DANS LA SAUCE DE POMMES

Thieu Quang Tho

Résumé

Pour améliorer la qualité du produit final, il est très important d'enlever les taches de couleurs foncées qui restent encore dans les sauces de pommes. Il s'agit de petits morceaux de pépins de pommes ou d'autres impuretés que l'étape de filtration n'a pas complètement enlevé. Donc, l'objectif de ce travail est de concevoir un appareil qui permet de résoudre le problème présenté plus haut, dans le cadre d'un programme d'études de maîtrise en mécanique à l'École de technologie supérieure en collaboration avec l'entreprise Les Contrôles Intempco de ville St. Laurent, Québec, Canada.

Ce mémoire est présenté en cinq chapitres. Le chapitre 1 décrit les généralités de la production des sauces de pommes et la problématique du sujet. Le projet se fait évidemment en commençant par une étude du comportement mécanique des sauces de pommes. Il s'agit de la nature des sauces de pommes et de l'état physique des impuretés suspendues dans la sauce. La sauce de pommes, composée d'une phase liquide et d'une phase solide, est considérée comme une suspension non newtonienne. Les mesures expérimentales révèlent que la viscosité des sauces de pommes est une fonction de puissance, donc non linéaire, par rapport au taux de déformation du fluide. Ce résultat est un facteur indispensable dans l'étude de l'écoulement des sauces de pommes dans les conduites. C'est une partie très importante du design de l'appareil en question que l'on verra dans les chapitres suivants. Le coeur du problème est de reconnaître les impuretés dont on a besoin d'enlever de la sauce. Dans ce chapitre d'introduction, plusieurs

méthodes de reconnaissance des impuretés sont analysées. Elles peuvent être classifiées par différents critères tels que la forme, la dimension, le poids, la couleur ou les propriétés hydrodynamiques des impuretés. Pour le matériau étudié, on trouve que la densité, la taille et la forme des impuretés sont très différentes que celles du matériau de base. En conséquence, la couleur des impuretés est visuellement beaucoup plus foncée par rapport au matériau de base qui est, par contre, très clair à la lumière.

Dans l'industrie alimentaire, les systèmes de vision sont beaucoup appliqués pour le contrôle de qualité des produits alimentaires dus à leur haut rendement et efficacité. L'application d'un tel système pour enlever les impuretés des sauces de pommes est la partie principale de ce projet. Dans le Chapitre 2, la conception fondamentale de machines de vision en général est présentée. Le principe des systèmes de vision est d'exploiter les propriétés optiques des matériaux. En fait, on peut dire qu'un système de vision est purement celui de traitement d'image. Comme les caractéristiques optiques du matériau de base sont différentes de ceux des impuretés, un système de vision est capable de les reconnaître et distinguer. De plus, il peut facilement localiser des impuretés et les enlever à l'aide d'un système mécanique. Un système de vision généralement comprend trois composantes principales : une source de lumière, une scène d'exposition du matériau traversé par la lumière et l'ensemble de caméras et de système électronique de traitement d'image. Sous la lumière proprement ajustée, la scène d'exposition va donner des images desquelles sont retirées les informations représentatives servant au système d'exécution. L'intensité de la lumière est conçue de sorte que le capteur optique puisse obtenir une image optimale pour le processus de traitement. Un bon choix de source de lumière peut simplifier les étapes intermédiaires du processus global. L'image obtenue est généralement bidimensionelle et numérisée pour que les signaux soient facilement traités par ordinateur. L'image digitale possède les deux propriétés photométrique et morphométrique. Dans le cadre de ce projet, la seule propriété photométrique est intéressante, c'est-à-dire le degré de clarté des couleurs. Ici, les signaux optiques captés par la caméra sont transformés en image grâce aux capteurs visuels qui sont souvent des CCD (charged coupled device) dont les signaux de sortie et d'entrée dépendent de l'intensité de la source de lumière. L'image digitale sera traitée et simplifiée pour obtenir justement les informations nécessaires. Le processus de traitement d'image se réalise à l'aide d'un 'hardware' et/ou d'un logiciel.

Basé sur l'analyse de principe présentée dans le chapitre 2, la conception d'une machine est décrite en détail dans le Chapitre 3. Il s'agit d'un appareil équipé d'un système de vision étant capable de détecter et d'enlever des taches de couleur foncée des sauces de pommes. Cet appareil doit répondre les critères suivants :

- Être suffisamment robuste pour fonctionner dans les environnements sévères.
- Être automatisé, 'friendly user' et sécuritaire pour l'utilisateur.
- Être équipé de systèmes de contrôle intelligent pour travailler en temps réel.
- Être capable de détecter les défauts d'enlèvement du système.
- Économiser le matériau perdu causé par l'enlèvement des impuretés.
- Satisfaire les conditions sanitaires des normes alimentaires.

L'appareil est conçu en modules. Il comprend deux modules de vision de détection des impuretés, un module pneumo-mécanique d'enlèvement, un panneau de contrôle et des autres modules mécaniques. D'abord, grâce à une pompe, la sauce de pommes est transporté, à un débit donné, du réservoir à une filière plate sur laquelle sont montés le module pneumo-mécanique et les deux modules de vision. La lumière du premier système de détection éclaire la sauce s'écoulant à travers la filière. Le balayage se réalise en plusieurs canaux pour raffiner la détection. Quand le système de détection reconnaît une impureté dans la sauce, il va localiser sa position. Puis, un signal est envoyé au système de contrôle pour ordonner au mécanisme pneumatique d'enlèvement d'ouvrir l'orifice pour aspirer cette impureté avec un délai déterminé par le débit du liquide et le profil de vitesse de l'écoulement. Finalement, le second système de vision va vérifier si l'exécution est bien faite. Le fonctionnement de l'appareil se fait de façon continue et parallèlement à plusieurs canaux. Les délais de temps pour ouvrir et fermer les valves d'aspiration, par rapport au moment de détection du système de vision, dépendent de la vitesse de déplacement du liquide dans la filière plate. Cette vitesse, à son tour, dépend de plusieurs facteurs tels que le débit, la viscosité du fluide et la construction de la filière. En fait, une étude expérimentale a permis de déterminer la vitesse et le profil de vitesse de l'écoulement de la sauce dans la filière en fonction du débit du liquide. Cette étude se fait directement avec la filière plate de la machine que l'on verra plus tard dans le Chapitre 4. Ces données, la vitesse et le profil en fonction du débit, sont mémorisées préalablement dans le système électronique de contrôle de l'appareil.

Un point très important dans le design est l'harmonie des composantes du système au niveau du temps de cycle. Quand le système de vision détecte une impureté, le signal est envoyé au système de contrôle qui à son tour, après avoir calculé, donne un autre signal pour le mécanisme d'enlèvement. La réponse de la partie électronique est très ponctuelle. La partie la plus difficile est la réponse rapide du mécanisme d'enlèvement, car il existe tout le temps l'inertie du système. Une étude expérimentale du comportement du module d'enlèvement a été réalisée pour déterminer le temps de réponse du système et le débit du fluide s'écoulant à travers l'orifice de la valve d'aspiration. Grâce aux résultats expérimentaux, on peut réaliser un design optimal au niveau de l'harmonie de cycle de temps du système.

Il est évident que le système de contrôle est la partie centrale de l'appareil. Les Figures A-1 et A-2 démontrent le schéma de principe du système de contrôle de l'appareil. Il comprend:

- Un panneau de contrôle pour la communication entre l'opérateur et l'appareil.
- Une carte vidéo pour lire et traiter les informations captées par les caméras et envoyer l'information nécessaire au contrôleur.
- Un contrôleur pour faire la communication entre le panneau de contrôle, l'unité centrale de calcul (CPU) et les cartes de pilotage (drive cards); et pour lire les entrées de données venues des cartes de vidéo et du débitmètre.

- Les cartes de pilotage pour recevoir les ordres du contrôleur via des canaux à 8 octets et puis activer les valves.
- Un débitmètre pour mesurer le débit du fluide.

Les figures et le fonctionnement du système de contrôle sont présentés en détail dans l'annexe A.

Ensuite, le Chapitre 4 de ce mémoire décrit en détails les tests expérimentaux pour mesurer le profil de l'écoulement du fluide dans la filière plate. Le principe de mesure est très pratique. On utilise tout simplement les deux systèmes de vision de l'appareil, qui sont disponibles, pour mesurer la vitesse du fluide en plusieurs canaux et trace le profil de l'écoulement dans la largeur de la filière. La vitesse est déterminée en mesurant le temps de délai de détection et la distance des deux systèmes de vision. À cause de la présence de la viscosité, la vitesse du fluide aux parois est différente qu'au centre. Plus large est la taille, plus grande est la différence. On a choisi une filière suffisamment mince pour négliger cet effet dans l'épaisseur de la filière. Alors, cela se dit une filière plate. Seulement la différence de vitesse doit être tenue compte dans la conception de cette machine. Mesuré par un débitmètre, le débit du fluide dans ces tests varie de 1 à 10 GPM (gallons par minute). Notons que le débit de 8 GPM correspond à un rendement de 15 m^3 par quart de travail. La pression des sauces est mesurée également à l'entrée de la filière plate. Cela est un paramètre important à contrôler car la sauce de pommes se décompose lorsque la pression dépasse 30 psi. Les expériences montrent que le profil de vitesse du fluide est très uniforme dans la largeur de la filière, sauf deux couches très minces aux parois. La vitesse du fluide aux parois est théoriquement nulle. Mais, pratiquement les impuretés sont de dimensions finies, alors elles peuvent quand même s'écouler à une vitesse non-nulle. Donc, le système de vision est capable de les détecter et enlever des sauces. De plus, pour minimiser l'effet de la gravité, qui peut causer le collage des impuretés à la base de la filière, on pose la filière plate verticalement. Cela améliore beaucoup le fonctionnement de l'appareil.

Le moment de détection par la caméra, le délai du circuit électronique, le délai et le temps pour l'ouverture et la fermeture des valves d'aspiration sont des facteurs très importants pour le fonctionnement efficace de l'appareil. Une étude expérimentale est indispensable pour les déterminer. Une analyse profonde sur les cycles de temps du système est bien présentée dans le Chapitre 5 de ce mémoire. Particulièrement, un dispositif est monté pour mesurer le temps d'exécution et le débit de l'aspiration des valves en fonction de différence de pression et l'ouverture de l'orifice.

En conclusion, le système d'enlèvement des impuretés des sauces de pommes est développé en se basant sur les paramètres expérimentaux en vue de satisfaire les contraintes imposées pour la production des sauces. Malgré que le nombre de tests et de matériaux n'est pas très large, les résultats montrent que le système conçu peut fonctionner efficacement. Un prototype de la machine est fabriqué à l'entreprise Les Contrôles Intempco Ltée. pour vérifier le principe choisi et évaluer le fonctionnement du système complet. Finalement, on trouve dans la dernière partie la discussion sur les avantages et les inconvénients du design:

- Un des avantages le plus important est que la machine conçue peut fonctionner non seulement avec des sauces de pommes, mais aussi avec beaucoup d'autres matériaux similaires. D'une part, le principe de reconnaissance des impuretés est si robuste pour détecter d'autres produits dans l'industrie alimentaire. D'autre part, la vitesse et le profil d'écoulement d'un nouveau matériau dans la filière plate peuvent être déterminés facilement avec ce design.
- Avec le système de vision à haute performance comme celui de l'appareil, la détection des impuretés de type non-contact est appropriée pour la production à haute vitesse. Cela répond étroitement aux besoins de l'industrie alimentaire. Le rendement d'une telle machine peut atteindre jusqu'à 15 m^3 par quart de travail.

- Équipée par deux systèmes de vision, la machine est également capable de détecter facilement des défauts par la seconde caméra, donc d'évaluer la qualité du produit au cours du processus automatiquement.

✓ Cependant, quand le matériau est opaque, le système de vision ne peut pas distinguer les impuretés et le matériau de base : la source de lumière visible et la caméra sont opposées par rapport la filière plate, la lumière est donc trop perturbée après avoir traversé le matériau. En conséquence, la caméra n'est pas capable d'obtenir une image claire et nette.

✓ De plus, la largeur de la filière est limitée par la capacité de focalisation des caméras. La focale des caméras au centre et aux côtés de la filière est différente. La caméra ne peut plus obtenir de bonnes images partout quand l'angle d'observation des caméras est plus grand qu'une limite donnée. Le premier problème du système de vision peut être résolu en utilisant des autres types d'objectifs optiques, tandis que l'utilisation d'un autre type de source de lumière à plus haute performance peut éliminer le second.

✓ Quoique la vitesse du système électronique soit rapide, la machine ne peut pas dépasser une limite de taux de production à cause de l'inertie du système mécanique d'enlèvement. L'utilisation des actuateurs solénoïdes au lieu des valves pneumatiques peut améliorer la situation.

✓ En addition, pour résister la pression interne du fluide, la fenêtre en verre doit être suffisamment épaisse. Mais, plus épais est le verre, pire est la condition optique pour le fonctionnent correct du système de vision. La diffraction angulaire de lumière est la cause principale de ce problème.

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LIST OF ABBREVIATIONS AND SIGNS

μ	Viscosity [cP]
β	Diameter fraction, constant
η	Coefficient of duty cycle, constant
φ	Volume fraction of inclusions, constant
ζ	Duty cycle, constant
τ	Shear stress, N/m^2
$\theta(\varphi^2)$	Order-2 correction term
ρ	Density, kg/m^3
A	Area, m^2
C_d	Orifice discharge coefficient, constant
f	Focus length, m
g	Gravity acceleration, constant $9{,}81 m/s^2$
h	Height, m
m	Magnification ratio, constant
P,p	Pressure (N/m^2, bar) or Probability (constant)
Q	Flow rate, m^3/s
R,r	Radius, m
S	Surface or Section (m^2)
t	Time, s
V,v	Speed, m/s
X,x	Dimension on direction X, m
Y,y	Dimension on direction Y, m
Z,z	Dimension on direction Z, m

A/D	Analogue / Digital
CCD	Charged coupled device
CPU	Central processing unit
DAQ	Data acquisition
DPI	Dot per inch (image resolution)
DSP	Digital signal processor
FPGA	Field programmable gates array
GPM	Gallon per minute (flow rate unit)
ID	Inside diameter
LED	Light emitting diode
MCU	Micro controller unit
MOSFET	Metal oxide semiconductor field effect transistor
OD	Outside diameter
PC	Personal computer
PSI	Pound per square inch (pressure unit)

CHAPTER I

INTRODUCTION TO TREATMENT OF APPLE SAUCE

1.1 Production of Apple Sauce

Apple sauce is used frequently and broadly in every family: as a topping on ice cream, adding excitement to hot or cold cereal, on cinnamon toast or muffins, filling in pies and cones, serving as an oil substitute in baking, and so on. The main ingredient in apple sauce is apple. There are many kinds of apples that are used in combination, including edible apples and varieties.

Apples are supplied to food processing plants by cultivators in large wooden crates mostly in the fall season. After being unloaded into a washing tank for cleaning, the apples travel in a water flume, or canal, to the peeling section where the apples that do not meet the required quality specifications are removed. The apples then are peeled and cored automatically by machines. Next the cored and peeled apples are cooked in steam pressure digester and then pressed through a screen to primarily grind and filter out any apple seeds or other materials, as well as to ensure purity and appearance. The screened applesauce maybe further processed chemically for color and flavor. They are then ready for packaging and consuming. The whole process is schematically presented in Figure 1-1.

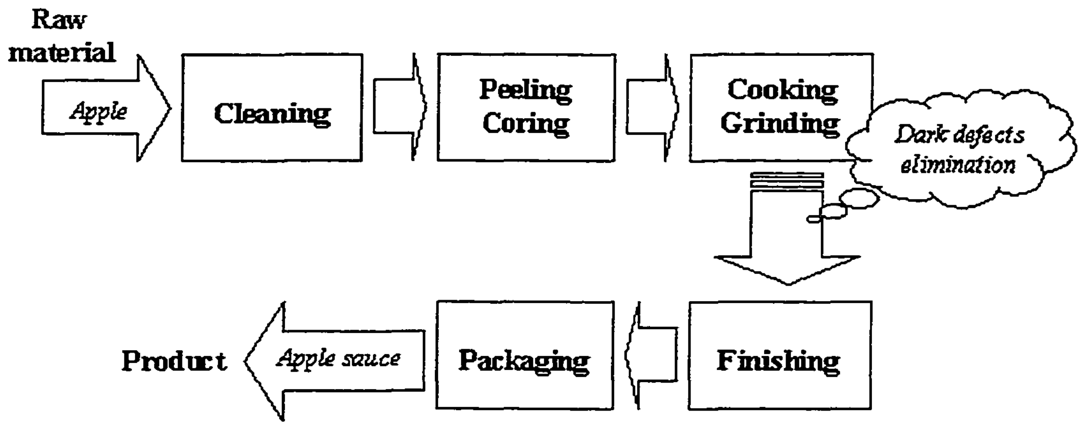

Figure 1- 1: Simplification of apple sauce production

The quality of the finished apple sauce can be enhanced in all steps of the processing procedure. However, this thesis is concerned exclusively with the process of removing left over apple seeds, peels or whatever elements degrade visually the apple sauce quality. These elements are called defective particles or defects in this thesis.

Some manufacturers grind the apples before cooking to improve the cooking efficiency. In that case, the defects must be removed after grinding and before cooking.

1.2 Properties of Apple Sauce

Apple sauce is a compound containing constituents in both solid and fluid form. The added or condensed water and the apple juice are the only liquid constituents of this substance. The other is the ground apple particles in suspension which may behave as Hookean solid. Although apple sauce is easily pumped as well as packaged in any form of container, it can sustain a given level of shear stress before observing a shear rate. This is a typical behavior of granular material (sand, snow, etc…). Figure 1- 2 illustrates the ability of apple sauce to keep its form under gravity on a flat surface.

Since it does not meet the definition of a fluid which must take up the shape of any container, it can not be simply considered as a Newtonian fluid or a solid.

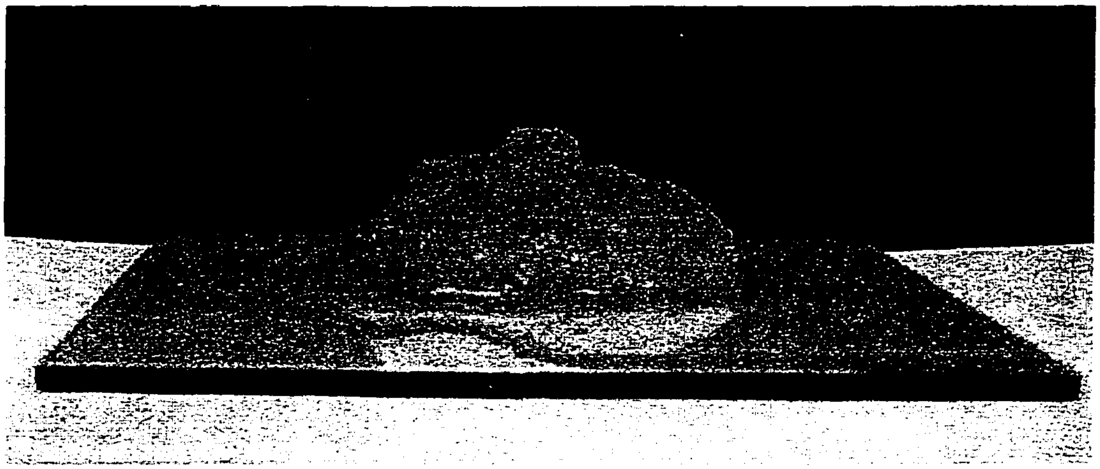

Figure 1- 2: Apple sauce shape holding ability

Thus, apple sauce, as with most foodstuffs, is a non-Newtonian suspension. In reference [1], the authors Kelvin and Maxwell introduce the simple binary models (Figure 1-3) that study the flow based on the relationship force – deformation under the point of view of shared stress or shared strain between two elements.

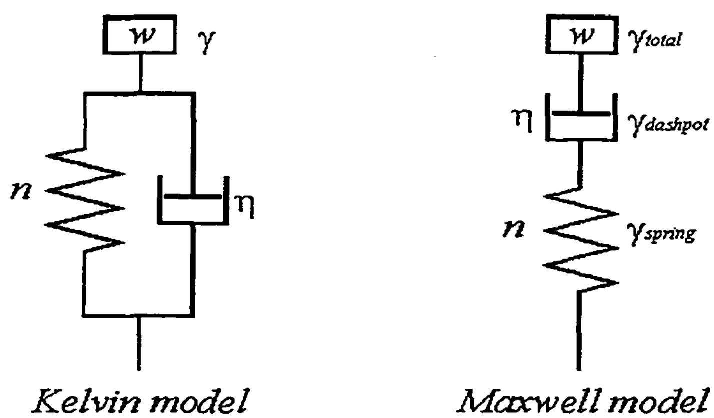

Figure 1- 3: Binary models of Kelvin and Maxwell

1.2.1 Viscosity

The viscosity of apple sauce is not a constant, or in other words, the shear stress is not linearly related to the rate of shear strain. For a shear thinning fluid, the apparent viscosity decreases with increasing shear rate. The harder the fluid is sheared, the less viscous it becomes. Oppositely, the fluid whose apparent viscosity increases with increasing the shear rate is called shear thickening fluid. Figure 1- 4 illustrates the behavior of several types of fluids (Munson, Young and Okiishi - figure 1.5 p18 - [3]).

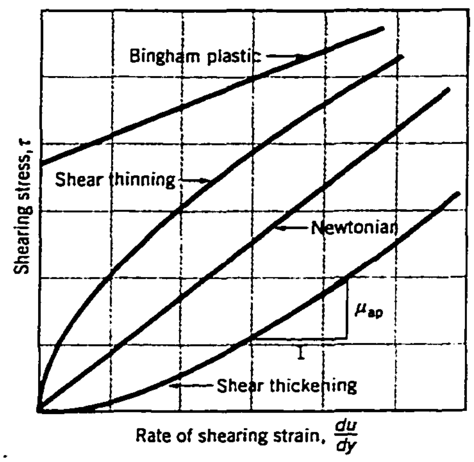

Figure 1- 4: Variation of shearing stress with rate of shearing strain of fluids

The fluid viscosity is sensitive to temperature. The viscosity of liquids decreases with an increase in temperature, whereas for gases an increase in temperature causes an increase in viscosity. This difference can be traced back to the difference in molecular structure. As the temperature increases, the cohesive forces between molecules of liquid are reduced with a corresponding reduction in resistance to motion. Since the viscosity is an index of this resistance, it follows that the viscosity of liquids is reduced by an increasing in temperature. In gases, the intermolecular force is negligible. But an increase in temperature augments the resistance to relative motion, corresponding with an increase in viscosity.

Beside the temperature, the viscosity of apple sauce strongly depends on the percentage of its constituents and the shape of the inclusions. Einstein and Brinkman in reference [1] show the variation of apparent viscosity by the equation:

$$\mu' = \mu_0\left[1 + 2.5\varphi + \theta\left(\varphi^2\right)\right] \qquad (1\text{- }1)$$

where μ' : apparent viscosity of current suspension

μ_0 : viscosity of the fluid constituent

φ : equivalent volume fraction of inclusions

$\theta(\varphi^2)$: second order correction term.

It is difficult to identify theoretically the apparent viscosity of a natural foodstuff. By experiments, we can estimate the viscosity of a particular sample of apple sauce, and we can use that property qualitatively. Figure 1- 5 illustrates the measured viscosity of an apple sauce sample with a density of 1080 kg/m³ using digital viscometer Brookfield model DV-III, spindle RV7 at 20°C.

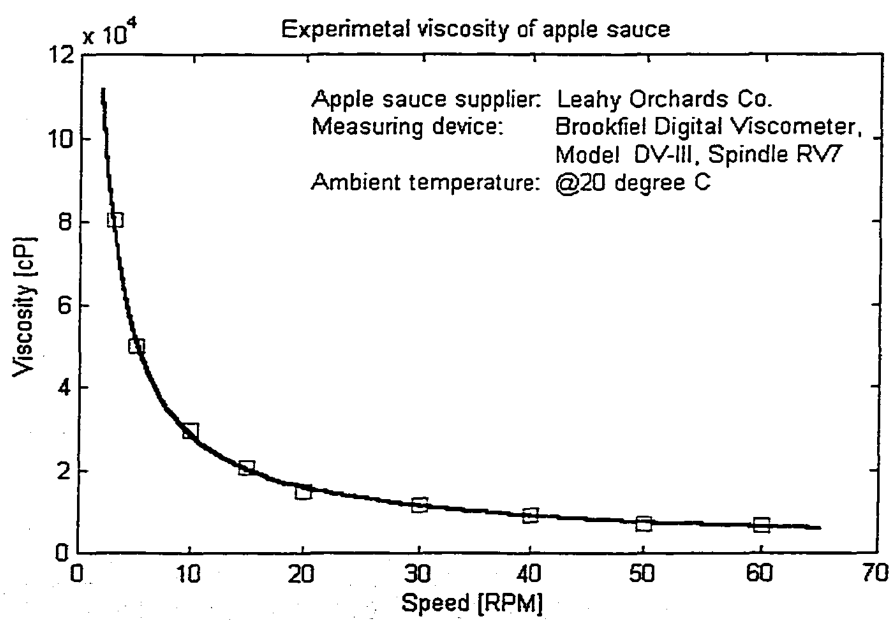

Figure 1- 5: Viscosity of the apple sauce sample

The measured viscosity curve clearly shows that apple sauce is a shear thinning suspension, a type of non-Newtonian suspension.

Furthermore, the measured viscosity is nearly linear on a logarithm scale as shown in Figure 1- 6. That means that a Power Law model can be applied in the analysis.

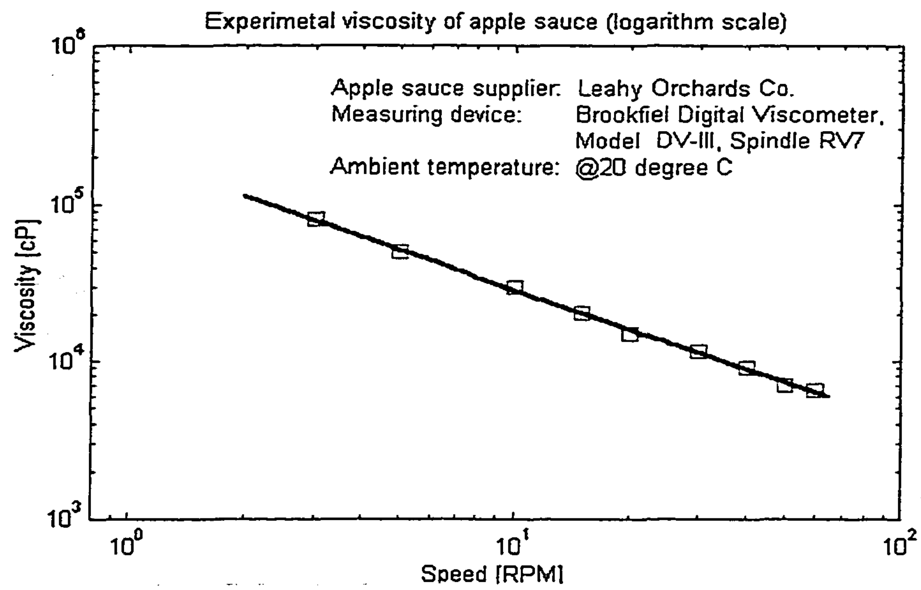

Figure 1- 6: Viscosity of the apple sauce on logarithm scale

1.2.2 Yield Value

Some fluids behave much like a solid at zero shear rate. They will not flow until a certain amount of force, called yield value or yield stress, is applied at which time they will revert to fluid behavior. The pour-ability of a material is directly related to its yield value. The yield value can help determine whether the pump has sufficient power to start in a flooded system, etc.

In the viscosity measurement using the Brookfield device, the yield value can be extrapolated from the curve of viscosity-speed by the equation given in reference [10]:

$$\tau_0 = X_1 . f_a \tag{1-2}$$

where τ_0: yield value (dynes/cm²)

X_l : viscometer reading (poise) extrapolated at 0 RPM

f_a : constant, according to measured equipment. f_a=83.8 for spindle RV7

The extrapolation of the curve gives X_l= 3 500 [poise], so the yield value of the apple sauce sample is estimated:

$$\tau_0 = 3\,500 \times 83.8 = 293\,300 \text{ [dynes/cm}^2\text{]} = 2.93 \text{ [N/cm}^2\text{]}$$

1.2.3 Flow Performance

The velocity profile of apple sauce flowing through a rectangular conduit depends on a number of parameters including the geometry of the conduit, the friction and resistance of the walls, the hydrodynamic properties such as apparent viscosity, etc. Apple sauce, as other shear thinning suspensions, will behave as a solid (a small deformation, but not a continuous deformation) if the applied shearing stress is small. But if the applied stress exceeds a critical value (yield stress), the substance will flow (continuously deform).

We will consider the flow of a shear thinning suspension (yield stress τ_0 , apparent viscosity μ) through a tube (radius R, length l) under pressure P. At the cylindrical surface S of radius r, the shearing stress τ is constant on S and identified by:

$$\pi r^2 P = \int_S \tau dS = \int_0^l 2\pi r \tau dl = 2\pi r l \tau \quad \Rightarrow \quad \tau = \frac{P.r}{2l} \tag{1-3}$$

When the stress in the neighborhood of the wall, i.e. the maximum shearing stress

$$\tau_{\max} = \frac{P.R}{2l} \tag{1-4}$$

exceeds the yield stress τ_0, some flow will take place. The material near the wall will flows as a fluid with its current apparent viscosity.

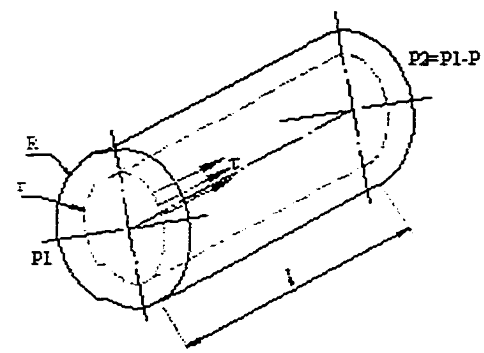

Figure 1- 7: Model for tube flow

The stress is reduced when r is decreased, and the shearing stress is balanced with the yield stress τ_0 of suspension at the critical radius r_c:

$$\tau_0 = \frac{P.r_c}{2l} \Rightarrow r_c = \frac{2l\tau_0}{P} \quad (1\text{-}5)$$

The central core, the part of the suspension sample whose radius is less than r_c, will not exhibit shear flow, but will move solidly as a plug, with a velocity equal to that of material at critical radius r_c. That means the velocity profile of the suspension is uniform at the central core.

In addition, in the interval (r_c , R), the bigger the radius r is (i.e. closer to the wall of tube), the harder the suspension is sheared, and the less viscous the suspension is. This implies that the velocity of suspension in the interval converges to its uniform value quickly.

The authors Herschel, Bulkeley and Casson in reference [1] showed that the velocity profile of the steady-state flow of a shear thinning fluid can be represented by the Figure 1- 8.

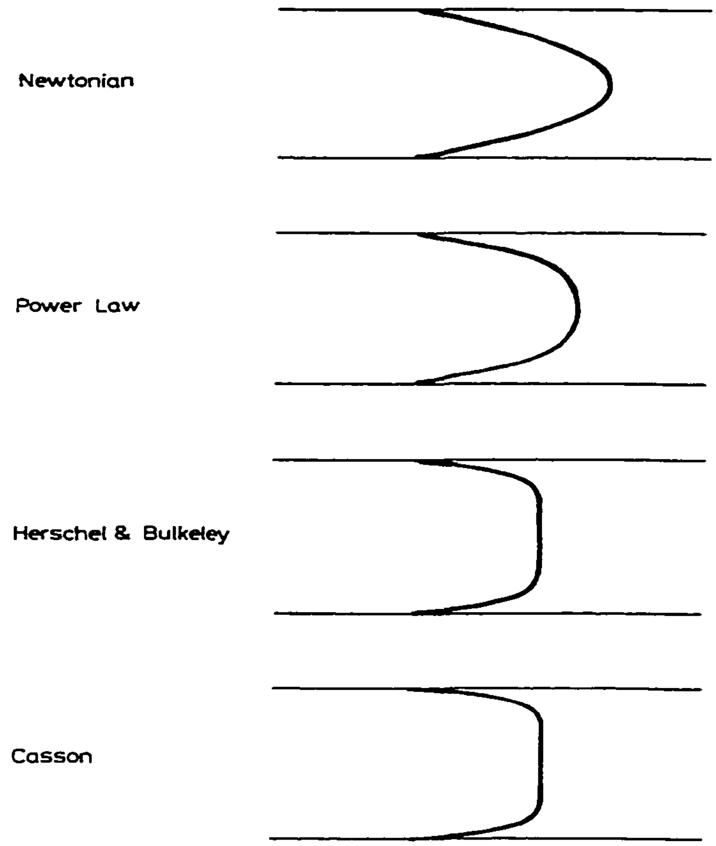

FIG. 14. Velocity profiles in steady flow through tubes.

Figure 1- 8: Velocity profiles of steady flow according to the different approaches.

This is particularly relevant to flow through a flat rectangular die, where the width is much larger than the height. This idea was also verified experimentally by observing the apple sauce flow form. The characteristic of mostly uniform velocity is very useful in dealing with the natural variability of apple sauce.

The rheological study of apple sauce is complicated and beyond the domain of this report, so we only performed the necessary experiments to determine the control parameters of the system under study. Further research can be performed to verify the experimental results presented in this thesis.

Other characteristics of the apple sauce samples have been collected, such as:

- Density: 1080 kg/m^3 @ 20°C
- Color: light orange, light yellow-green
- Consistency: ground, mostly uniform
- Defects: small dark particles, 0.18 to 0.5 mm (0.007 to 0.02 inches)

The primary goal of this project is to develop a system to remove defects from the apple sauce while meeting the output requirement of 15 m^3/shift (1 shift = 8 hours, equivalent to 31.25 l/min).

1.3 Canadian Standard of Grading Apple Sauce

According to the standards of the Canada Food Inspection Agency, the grade of applesauce is classified as Canada A, B or C by the color, the flavor, the type and consistency, and the quantity of discolored (dark) particles (section 20, Part I, Schedule I of Processed Product Regulations – Canada Agriculture Products Act, reference [13]).

The lower the quantity of defects found in the apple sauce, the higher the grade and the greater market and consumer value. Therefore, defect eliminating from the sauce to improve its quality has financial ramifications.

1.4 Source of Defects

The dark particles may be caused by insects, contamination, oxidation, but primarily from seed and peel fragments retained or left over from previous processing steps.

1.5 Properties concern in sorting / separating

In general, the process of separating different material is based on the following properties:

- shape and its uniformity
- size and weight (density)
- color
- hydrodynamic properties

There are many separating methods, which are based on the property differences between the defects and main material. In this study, the defects are mostly apple peel or seed particles, whose dimension (size), density, shape, etc. are comparable with the base material after the grinding process. Therefore separating the defects from the base material has to be based on color properties.

Apple sauce typically has a bright color, whereas the color of defects is dark. Consequently the defects will be removed based on a process which uses their dark color level as a rejection criteria.

CHAPTER II

INTRODUCTION TO A VISION MACHINE

The food processing industry relies heavily on technologies for inspection and sorting of materials. Inspection of foodstuffs using fully automated production systems is a challenge where high production rates and variability exist. In many cases, the subject quality varies naturally and may be difficult to measure. Methods are typically developed in-house and satisfy specific needs of particular applications.

In the food industry, extremely large quantities of raw materials are handled at a rapid speed. Due to their speed, vision systems dominate the defect inspection market. Detecting the defects in foodstuffs (e.g. apple sauce) and removing them using a machine vision system is the principle point of this project.

2.1 Overview of the Vision Machine:

Machine vision is the use of digital imaging for measurement, inspection, and control. Machine vision applications manipulate the optical properties of a material to provide information that can be used to define material characteristics (e.g., size, shape, projected area, etc.). In this project, the goal is to have the vision device detect the existing dark defects (position, time) and give the information to the controller to remove these defects accordingly.

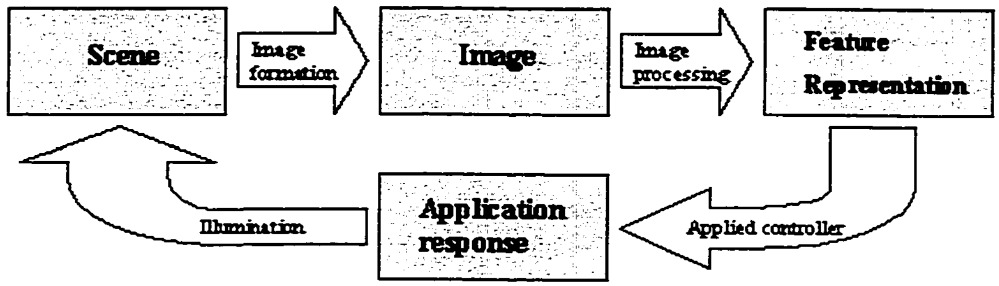

Figure 2- 1: Model of applied vision machine

The elements of the machine vision sensing system are presented in Figure 2- 1. The primary elements are the scene, the illumination, the image captured, the image processing and the response to the description of scene. Image formation is a process that converts the scene into a digital image for computer processing. In this application, the defects are small, and their presence is considered logically (yes/no) instead of measurement based . These elements form a model by which a machine vision application can be subdivided into smaller tasks.

2.2 Illumination

Machine vision is a unique sensing method because excitation energy can be regulated and even structured in a pattern to get a response from the defects in scene. The illumination is designed to consider the spectral quality of the illumination and the spatial distribution of illumination across the scene. Configuring the elements of a machine vision application requires an understanding of the photometric response of the material, spectral characteristics of the illumination sources, and spectral sensitivities of vision sensors.

The most common illumination sources are visible light from incandescent or fluorescent lights. Certain applications may select special illumination sources to generate a specific type of response from the material. These illumination sources may even be outside the visible spectrum. Some examples include ultraviolet light, infrared light, or X-rays.

The spatial distribution requirements for illumination are an important characteristic of an application. The position of light sources relative to the viewed object and the image sensor forms two general categories of illumination: frontlighting and backlighting. In backlighting, the scene is located between the light source and the image sensor. The images formed by backlighting are silhouettes of the scene or indicate the transmitted light through objects. In frontlighting, the light source is positioned on the same side of the scene as the image sensor. Images formed in frontlighting are a result of the bi-directional reflectance properties of the scene, which depends on the properties of the surface, light source, and light receiver. Grading fruit or vegetables for surface defects is an example where frontlighting might be used.

Structured lighting results from generating light in the form of dots, lines, or patterns which can be interpreted to represent changes in the features of the scene. Proper construction of the illumination system can simplify the image processing techniques needed in an application, increase the reliability of the image and save computer time.

2.3 Scene

The scene is defined by the field-of-view of the image sensor. Scene complexity can be classified as either a controlled environment or an uncontrolled environment. In a controlled environment, there are controls over many of the environmental variables like illumination, image contrast, position and orientation of objects. Good knowledge of specific properties of the objects being imaged can simplify image processing. The application is controlled in the sense that information about the types of objects in the scene can be used to simplify the extraction of useful data from the images. An uncontrolled environment is a scene where there is less precise knowledge of the characteristics of the scene (e.g. illumination is not controlled, there is uncertainty about the number or location of objects in the scene, scene boundaries cannot be specified, etc). Most applications in this latter category are really tough challenges for machine vision applications.

Figure 2- 2 illustrates an image of the dark defects to be detected and removed from the apple sauce. The machine vision sensor is the most important part of the system. Its primary purpose is to determine the precise location of defects in the image. This application represents an uncontrolled environment since the time and the location of objects that could show up in the image cannot be controlled very well. It is common for applications to have a mixture of controlled and uncontrolled variables. A practical to the engineering design of a machine vision is to structure the environment to be controlled as much, as tight, and as effectively as possible.

Optical characteristics of the material are important in the selection of both the illumination source and the image sensor. An enhanced understanding of these scene properties makes the image processing requirements of the application feasible to obtain.

Figure 2- 2: An image of apple sauce with dark defects in flat glasses die

1: Defect near the top surface of the sauce 2: Defect near the bottom surface of sauce

2.4 Image, Image Formation and Image Sensors

A conventional image sensor measures a response from the scene in the form of a two dimensional digital image. A signal transmission technique sends the analog image to a digitizer to convert the signal to a form that can be processed by a computer. The array of image pixels forms a signal that can be used to measure photometric and morphometric characteristics of objects within the image. Photometric characteristics are properties of image pixels that are related to the response to the illumination. Morphometric characteristics are size and shape characteristics of objects represented by collections of pixels in the image. In this application, the defects are nearly uniform and small, so a one-dimensional sensor is employed to generate a one-dimensional "line scan" image, which detects the positions of defects, if any, at a specific instant in time.

Two common sensors used in machine vision applications are monochromatic cameras and color cameras. Monochromatic cameras are used to measure an image intensity response most often related to the reflectance or transmitted light from a scene. Camera technology for forming the image may be based on vacuum-tube sensors or solid-state sensing elements. The former are best for applications requiring high signal resolution, while the latter are known for their ruggedness and durability. Solid-state cameras typically are sensitive to light beyond the visible spectrum into the near infrared. In today's market, most machine vision systems are based on CCD (Charged Coupled Device) sensors, whose output depends on the exposed light energy. Optical filters may be used with cameras to isolate portions of the spectrum where a scene has a response that simplifies the machine vision application.

Color camera systems are also available in tube and solid state forms. A typical goal of color sensing is to mimic the perceived color response of human vision. There are numerous industrial color sorters based on this principle. Color can also be detected by utilizing a monochromatic sensor with band-pass filters for specific portions of the visible spectrum. A vector color signal is generally formed from the response of red, green, and blue sensors in the camera.

Lenses and filters are important elements of the machine vision system. Lenses control the portion of the scene, or field-of-view, that is projected onto the sensing elements of the camera. Filters control the spectral characteristics of the illumination sensed by the camera.

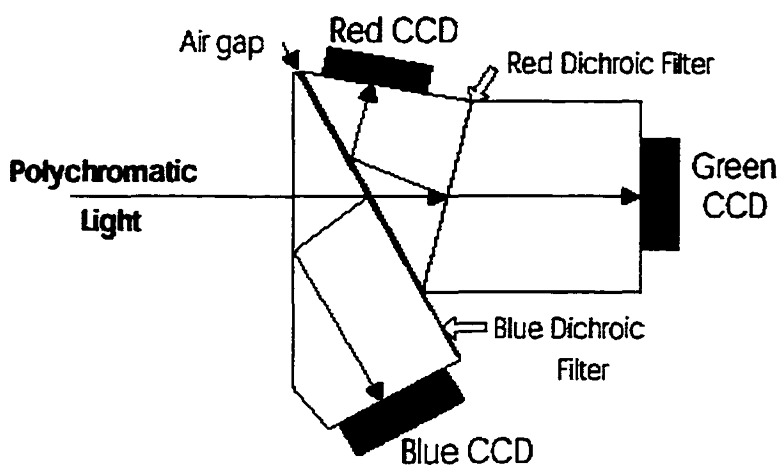

Figure 2- 3: Color camera performance with three sensors CCD

Most applications require some knowledge of the geometrical relationship between the image sensor and the scene. Spatial calibration facilitates the precise measurement of features of the scene. Intensity or color calibration is used to characterize the response of individual pixels.

After the signal is sensed at the camera, it is transmitted to an image digitizer to form an array of numbers representing the picture. An A/D converter processes the transmitted signal from the camera and converts it into an array of picture elements (pixels) representing the 2-D projection of the scene. The varying signal between the synchronizing pulses describes the analog intensities for one line of the image. A digitizer breaks this line up into pixels, which contain a digital representation of intensity. The primary considerations in the selection of the image digitization system are the spatial resolution and the signal resolution (Figure 2- 4). The image is arranged as a number of rows and columns of cells, typically representing a rectangular portion of the projected scene. Each cell of the image holds a value proportional to the response of the camera at that particular location on the image sensor. In monochromatic imaging systems, each pixel holds a single value called a gray level. In color systems, pixel values are vector values representing the response of three sensing elements representing the red, green, and blue portions of the visible spectrum. Another way to think of a color image is a set of three gray level images of the red, green, and blue sensor responses. Colors other than red, green, and blue as represented by mixing the proper proportions of these primary color signals

Normally monochromatic vision systems have only one value of 256 gray levels (8 bits) for each pixel. A color vision system would have 3 values per pixel. Increased spatial and intensity resolution (monochrome vs. color) generally increase the image storage requirements and the image processing time.

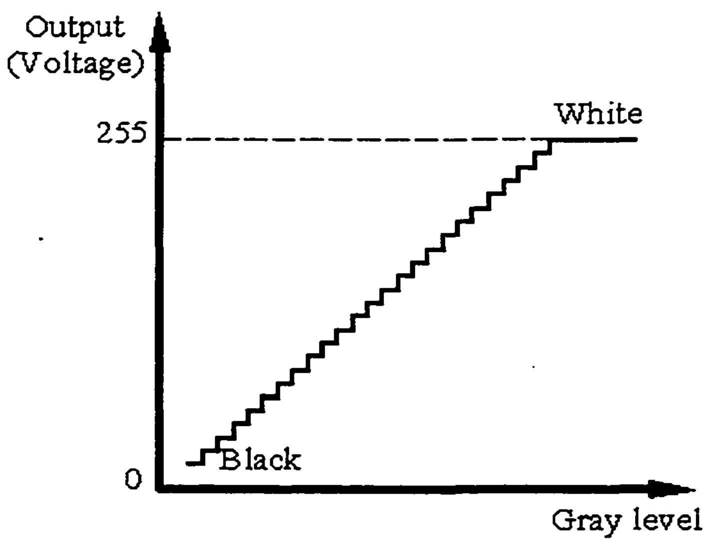

Figure 2- 4: Sensor excitation level versus the gray level.

2.5 Image Processing and Representation

The goal of image processing in a machine vision application is to extract information from the image that can be used to generate a response or understanding of the scene. The operations of image analysis can be performed in hardware or software. Hardware operations have the advantage of speed, but many applications are developed with general hardware operations and software to define the processing operations. Computer programming skills are needed to perform image processing. Newer products are using innovative technology to help minimize the programming requirements by using a windowing environment and object-oriented operations.

Image processing enhances the raw image captured by the vision sensor. Image processing simplifies the image, so that the features of interest are enhanced. Typically, the data goes through a reduction process where the enhanced image is represented in a simpler form. Represented features are used to make decisions from the image. Features that represent useful properties of the scene have to be classified based on the arrangement of pixels and pixel values in the image. A representation process in image processing transforms the image from a connected set of pixels into higher level descriptions of size and shape (location, area, length, shape factors, etc.).

Image processing operations for image enhancement can be categorized as point, frame, region, and geometric operations based on the computations that take place in the image. Point operations change the output pixel of an image based on the intensity value of the pixel. Frame operations take the values of pixels from the same location in multiple images and perform an operation to create a value for the same pixel in an output image. Region processing operations create a new value for a pixel based on the values of pixels in some defined neighborhood around a pixel.

2.6 Application Response

The application response utilizes the information from images for sorting/grading products, evaluating material properties, detecting the defects or process control. In measurement systems, information is collected on the photometric or morphometric characteristics of the image. This information is often an essential element to learn the characteristics that are useful for an automated system. In inspection or control, the image information is used to actuate a device or another appropriate action in response to the information detected in the image. Engineering this area requires an understanding of controls, actuators, computer interfacing and the interaction of materials with mechanical systems.

2.7 Application Examples

Two following examples from Elexso Sortiertechnik AG. Co. (Germany) introduce the monochromatic (gray level) and polychromatic (color) vision principles applied in sorting machines of granular products.

2.7.1 Example of Monochromatic Optic Principle:

Monochromatic sorting, the basic photoelectric sorting technology, was developed many years ago to separate granular products according to their light/dark value. Monochromatic sorting can be sufficient if only black defects are to be rejected. A background illumination reference is required in this method. This principle is introduced by an example in Figure 2- 5.

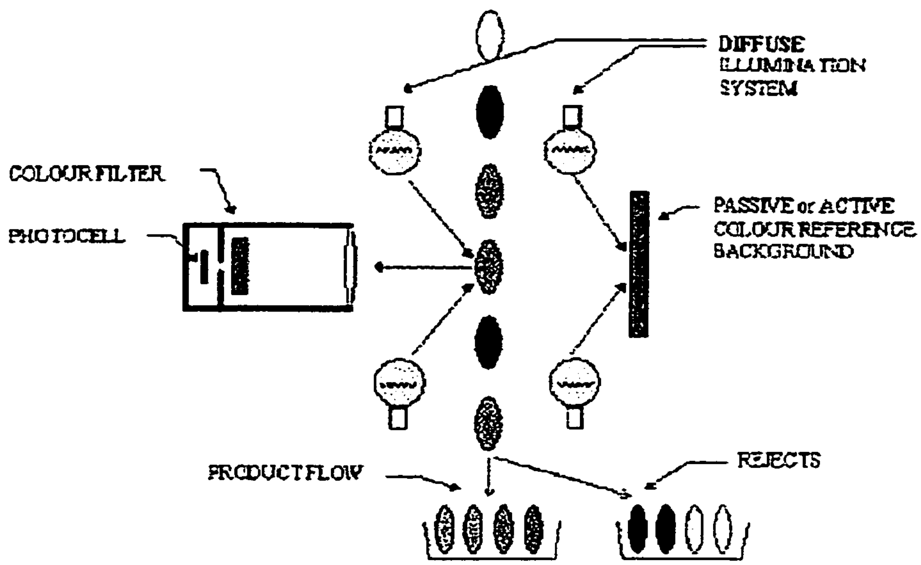

Figure 2- 5: Principle of monochromatic vision machine

2.7.2 Example of Polychromatic Optic Principle:

The advantage of polychromatic sorting is that it covers the full spectrum from ultraviolet to the near infrared. The thousands of possible color combinations are evaluated in a three-dimensional color mode.

The light source is based on a single halogen lamp, which is used to create 6 or 8 light beams. The light reflected from each side of product is collected by optical lenses mounted in front of further glass fiber bundles. These are split up to carry the light to 3 filters ranging from ultra-violet to infrared. On the other side of the filter opposite each strand of glass fiber are photocells which measure the reflected light. The analogue signal is converted to digital for processing. No background or color references are used. The example of this principle is illustrated in Figure 2- 6.

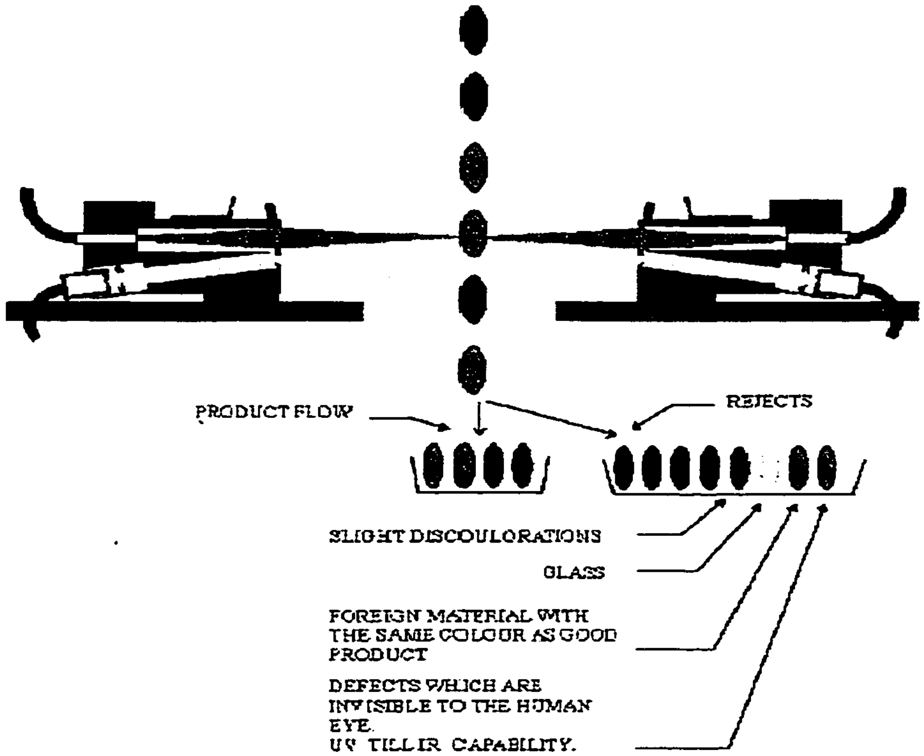

Figure 2- 6: Principle of polychromatic vision machine

CHAPTER III

DESCRIPTION OF THE PROPOSED VISION SYSTEM

3.1 Objective

Based on the color properties of the primary material (apple sauce) and the defects, the machine vision system under study is required to detect and remove the dark defects from apple sauce.

The design requirements of the proposed system include:

- Robust devices to work in harsh environments.
- Vision system capable of inspecting all sides of the material/defects without mechanical manipulation. The vision systems must be user friendly and safe for operators.
- Integration of intelligent controller to adapt to the natural variability of the subject material and to function as a real time system.
- Defect detection technologies that find a large percentage of defects (>95%).
- Defect removal techniques that remove a minimal amount of good material.

All metal components are made of a suitable stainless steel in accordance with the requirements of the food processing industry. The machine can be easily cleaned not only on the outside but also on the inside.

3.2 Model of Proposed Machine

Based on the principles of machine vision, the machine must be designed to view the apple sauce flow and act accordingly. The camera includes an onboard image processor. Defects are removed through a series of valves. The detection is processed by a digital controller, which is based on a Field-Programmable Gate Array (FPGA).

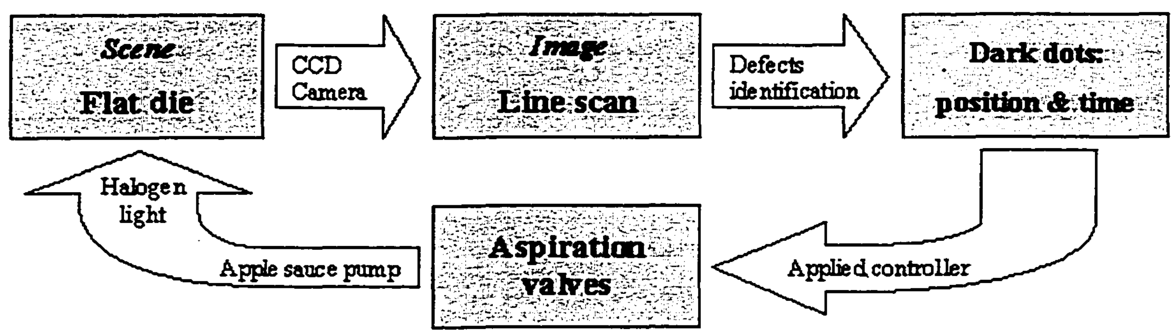

Figure 3- 1: Model of proposed system

3.3 Design of the System

The apple sauce is pumped from a holding tank through a rectangular die via a flowmeter. The flow of applesauce is given a flat distribution by the funnel. As the apple sauce flows through the rectangular die, the defects in the sauce are detected by the first machine vision system (referred to as the detection module). They are subsequently removed when they enter the manifold module. The sauce then passes the second vision system (i.e. the inspection module) to verify whether or not any defect remain. This second verification is not only used to evaluate the accuracy of the detection and removal process, but also to modify the control strategy to improve the processing quality. The two machine vision systems are exactly the same in construction, but perform different functions in the control strategy of machine. All three modules (detection, manifold, inspection) are integrated into the same flat die through which the apple sauce flows. Figure 3- 2 illustrates schematically the construction of the machine.

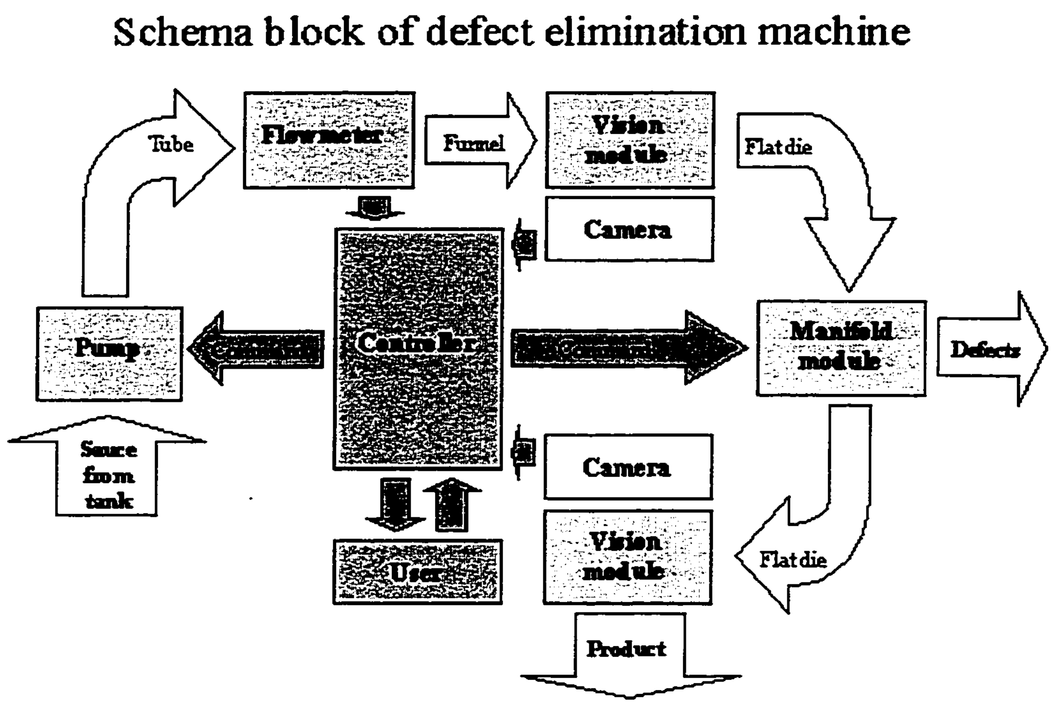

Figure 3- 2: Schematic structure of system

3.4 Flat Die:

The apple sauce is transported through the gap formed by two parallel panes of glass. The transparency and low friction coefficient of glass are useful in obtaining a good, undistorted view of the apple sauce flow. The die is designed in modules as shown in Figure 3- 3, so the device configuration can be modified as desire.

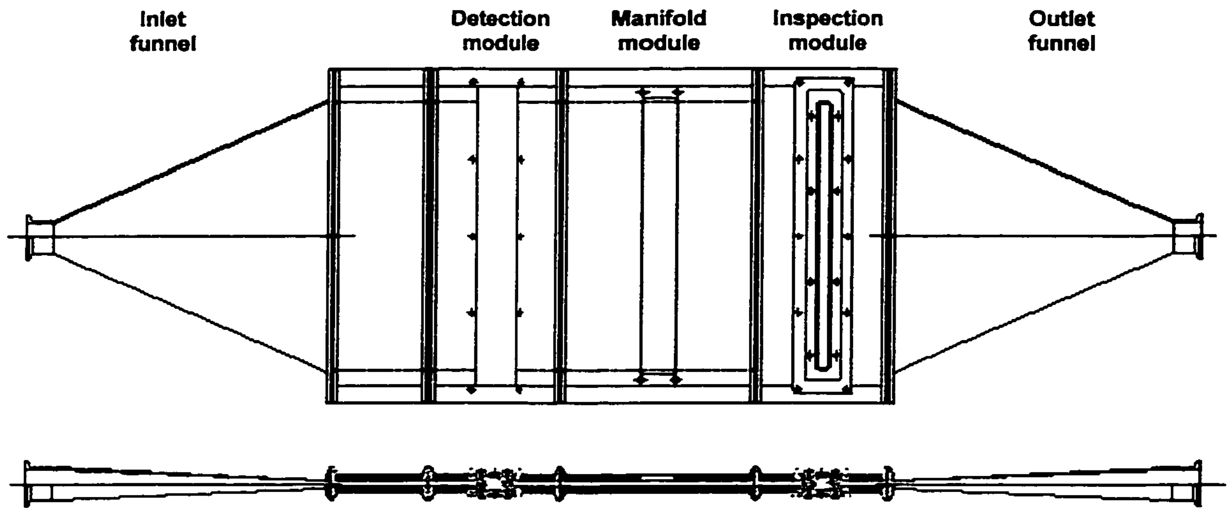

Figure 3- 3: Flat die consists of funnels, vision and manifold modules

The scene area is located on the flat die at the point where the vision operations are performed. The scene area is the first module of the flat die and may also be repeated at the end of the die to form the inspection module which is used to verify the result and modify the control strategy as if required.

The application response (defects elimination) is carried out at the manifold module where the aspiration valves are installed to remove the defects from the apple sauce flow.

Based on the light transmission properties of apple sauce as a function of the layer thickness as well as the optical properties of the light source, the limitations of flow speed and the required productivity, the proposed dimension of the flow channel within the flat die is 12"x 0.25" (304.8 x 6.35 mm).

3.5 Camera

The camera incorporates the following:

- The lens (and the filter if require)
- The sensor (CCD technology, acceptable within the visible spectrum)
- The Analogue to Digital converter (with communication protocol)

Monochromatic technology is adequate for this application (i.e. detecting dark particles within a light colored medium). During inspection, the scene is scanned one line at a time. The image consists of a line on which defects may lie. The position of each defect is recorded by a single coordinate along the line. The resolution of the line scan camera is a function of the CCD sensor (one array only), however it must also meet the requirement of providing high speed digitized video to make sure that the distance between two successive scan lines is small enough for the application.

The basic operation of the CCD sensor is to convert light into electrons. When the light is incident on the active area of the image sensor, it interacts with the atoms that make up the silicon crystal. The energy transmitted by the light (photons) enables an electron to escape from an atom and to roam freely within the device as a conduction electron, leaving behind an atom short of one electron (i.e. a hole). The more photons incident onto the sensors, the more electron hole-pairs are generated. Since the photons must have sufficient energy to accomplish the conversion operation, low energy photons (long wavelengths) are less easily detected and tend to pass further into the silicon crystal. High-energy photons (short wavelengths) on other hand are absorbed more closely to the surface of the sensor and may not reach the active part of the detector.

The selected camera DALSA CL-C7 has an array of 4096 pixels which are 7x7μm in size. The lens (NIKKOR f35mm) is integrated with the camera. The spectral response of the camera is presented in Figure 3- 4. The camera operates satisfactorily with a normal (i.e. visible spectrum) light source.

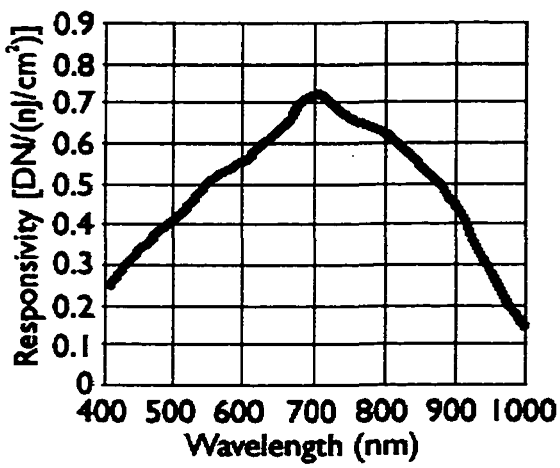

Figure 3- 4: Spectral response of CCD Line Scan Camera CL-C7

3.6 Backlighting Illumination

3.6.1 Light Source:

In the application, frontlighting has some disadvantages:

- Reflective properties of apple sauce are poor, so that frontlighting would require a high power light source.
- Glass may generate high intensity reflections of light source, which may obscure the real image.
- Defects are so small that their image may be adversely affected by the diffuse light from the neighboring apple. As a result, the image of a defect may not be clearly discernable. This is particularly problematic when the defect is not located near the upper surface of the apple sauce.

Backlighting would appear to be much more effective in this application and easily implemented in the system.

In this application, a halogen light source is employed. The light source is directed into one end of an optical cable. The other end of the cable distributes the light along a line. A cylindrical lens is used to focus the light into the apple sauce flow. The cylindrical lens can be adjusted to maximize the intensity of the light source and improve the defect capture process.

The complete illumination system consists of a DC regulated light source optical cable, parallel distributor and cylindrical lens.

3.6.2 Light Source Adjusting:

Note that the light source can be adjusted easily, but one question is how it can be adequately tuned in a production environment with a product of varying characteristics such as the natural apple sauce.

The output of the camera has been discussed in the previous sections. Each pixel has an output value varying from 0 to 255 (8-bit resolution) depending on the light exposure. This output is saturated at certain intensity, consequently the illumination system must be properly adjusted.

To avoid saturation, control system linking the camera output to the light source intensity must be implemented. An electronic board connected to the bus of the camera controller board is used to count the number of saturated pixels in a certain sample of scan line. If this number is smaller than a prescribed value, the board increases the light intensity. An opposite approach is applied if too many pixels are saturated. The goal of this system is to stabilize the image, so that the detection criteria may be applied successfully.

If a sampling ratio of 10% is used, then there are 480 samples per second to treat. That means the light source is adjusted every 2 millisecond. It is a simple task and can be solved by an open loop control board.

3.7 Reliability of Application

3.7.1 Detecting Defects:

The ability to detect an object depends upon its size and the type of instruments we use. For example, the smallest feature our eyes can resolve is in the order of 100 μm (or 0.1mm=0.0001m). Anything smaller than this scale can not be seen directly by the naked eye.

The defect size is randomly distributed in the interval of very small to a maximum dimension that is the size of the screen filter. The project goal is removing as many defects as possible, which can be observed by the naked eye. Consequently, the vision system has to be able to detect objects whose sizes are equal or greater than 0.1mm.

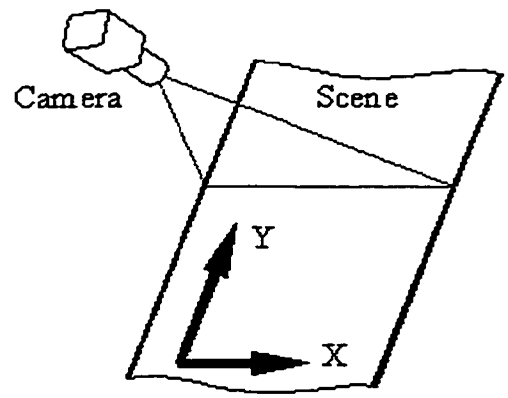

Figure 3- 5: Line scan principle of vision module

The number of pixels necessary to achieve the detection of 0.1mm objects over a 12" (304.8mm) field-of-view is calculated as follows:

$$Number\ of\ pixels \geq \frac{width\ of\ scene}{observable\ size} = \frac{304.8\ mm}{0.1\ mm} = 3048 \qquad (3\text{-}1)$$

This justifies the selected camera having an array of 4096 pixels. Over the whole width of the scene, 4096 points (i.e. dots) can be captured by the 4096 pixels of camera. So the image resolution (DPI - Dots per Inch) of the scene in the direction X is:

$$Horizontal\ resolution = \frac{number\ of\ pixels}{width\ (inch)} = \frac{4096}{12} = 341\ DPI \qquad (3\text{-}2)$$

or the minimum dimension of the defect in the X direction that can be detected is:

$$X_{\min} = \frac{304.8\ mm}{4096} = 0.074\ mm \qquad (3\text{-}3)$$

The sensor pixels are square (7x7μm), so the width of each scan line is also 0.074 mm (341 DPI). The scan rate is an important parameter in determining the minimum dimension of the defects. The higher the scan rate is, the smaller the defect captured.

In the direction Y, the minimum length of defect, which can be detected is the distance moved by the defect between two successive scan lines. The required productivity of 15 m^3/(8h shift) flows through the flat die size of 12"x 0.25" (304.8 x 6.35 mm) cross-section. This leads to the average speed of the defect given by:

$$v = \frac{Q\ (flow\ rate)}{\eta.A\ (section)} = \frac{15*10^9/_{8*3600}\ [mm^3/s]}{0.9*304.8*6.35\ [mm^2]} \approx 300\ [mm/s] \approx 12\ [inch/s] \qquad (3\text{-}4)$$

where η=90% is the coefficient of the device utilization during the shift (duty cycle).

Minimum scan rate of the camera can be deduced from:

$$Scan\ rate \geq \frac{flow\ velocity}{visual\ resolution} = \frac{300\ [mm/s]}{0.1\ [mm]} = 3000\ s^{-1} \qquad (3\text{-}5)$$

Consequently, a camera having a scan rate 4800 lines/second is selected. The captured image resolution in the Y direction at production flow rate is:

$$Vertical\ resolution = \frac{scan\ rate}{moving\ speed} = \frac{4800}{12} = 400\ DPI \qquad (3\text{-}6)$$

and the minimum size of detected defect in Y direction is:

$$Y_{\min} = \frac{300\ mm}{4800} = 0.062\ mm \qquad (3\text{-}7)$$

The scan rate of the selected camera yields an image resolution in the vertical direction Y, which is higher than in the horizontal direction. The resolution of the system in both directions is better than required. The camera is able to observe all defects that can be seen by the unaided human eye. In conclusion, the vision system can detect defects sized 0.075mm (or 340 DPI).

One important dimension has to be identified: the distance from object (scene) to camera. From defect dimension (3-3), the magnification ratio *m* of the vision system equals:

$$m = \frac{image\ size}{object\ size} = \frac{pixel\ size}{defect\ size} = \frac{7\ \mu m}{74\ \mu m} = 0.095 \qquad (3\text{-}8)$$

If *OD*, *ID* are called distances from the object and image to the lens respectively, and *f* is focal length of the lens, we have:

$$m = \frac{image\ size}{object\ size} = \frac{ID}{OD} = \frac{ID - f}{f} = \frac{f}{OD - f} \qquad (3\text{-}9)$$

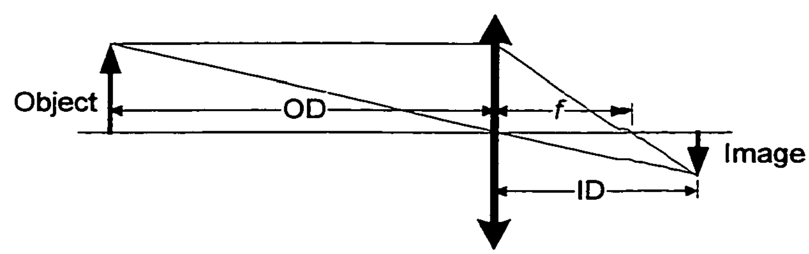

Figure 3- 6: Distance from object and sensor to lens

So that the distance from the scene to lens can be calculated:

$$h = OD = \frac{f}{m} + f = \frac{35}{0.095} + 35 = 403\ mm \qquad (3\text{-}10)$$

The focus of the scene will be properly adjusted after installation of the system.

The following figures (Figure 3- 7 to Figure 3- 10) illustrate the "line scan" images of the apple sauce as recorder by the realized machine vision system with the above configurations.

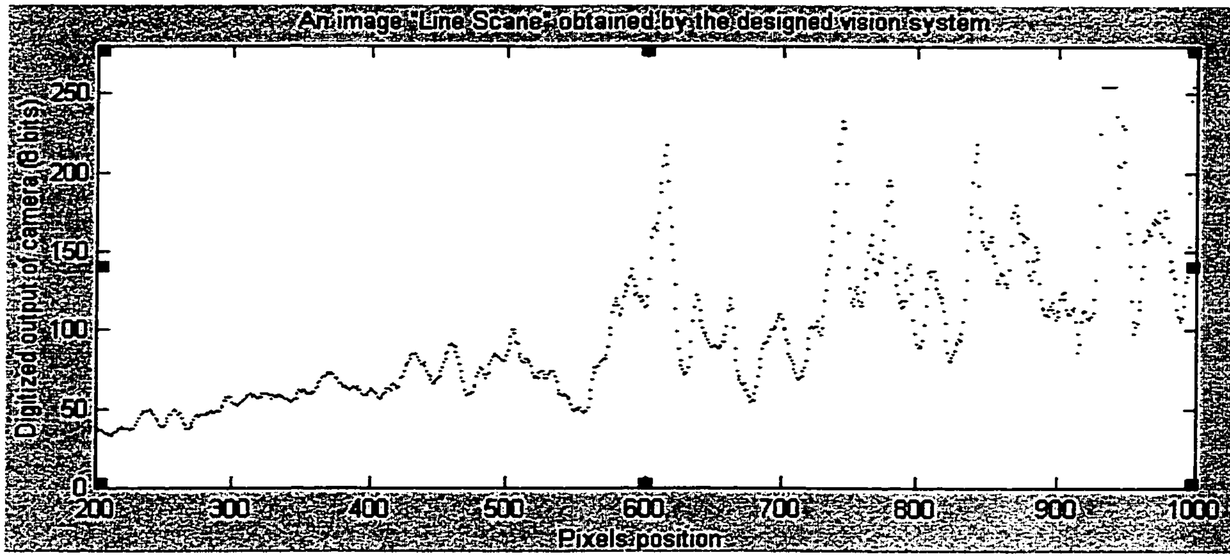

Figure 3- 7: Output of pixels from 200th to 1000th.

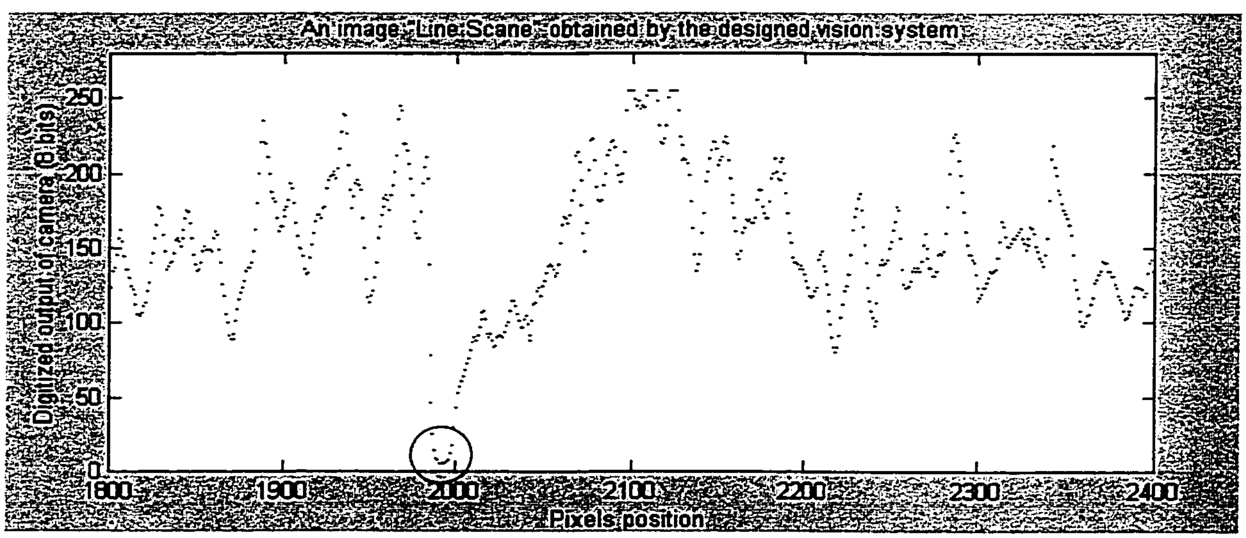

Figure 3- 8: Output of pixels from 1800th to 2400th.

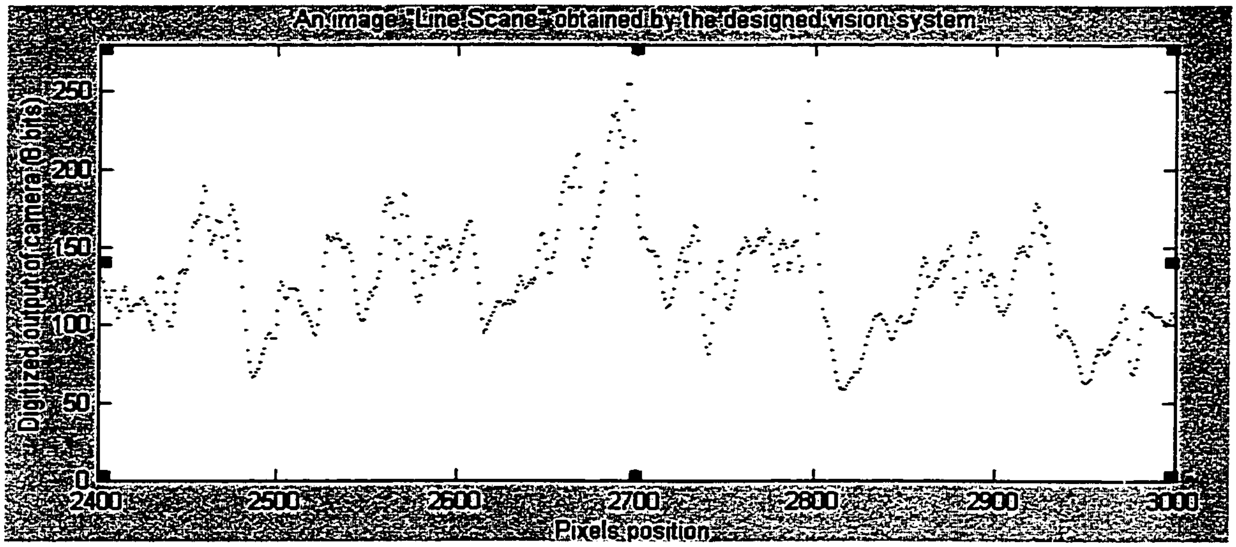

Figure 3- 9: Output of pixels from 2400th to 3000th.

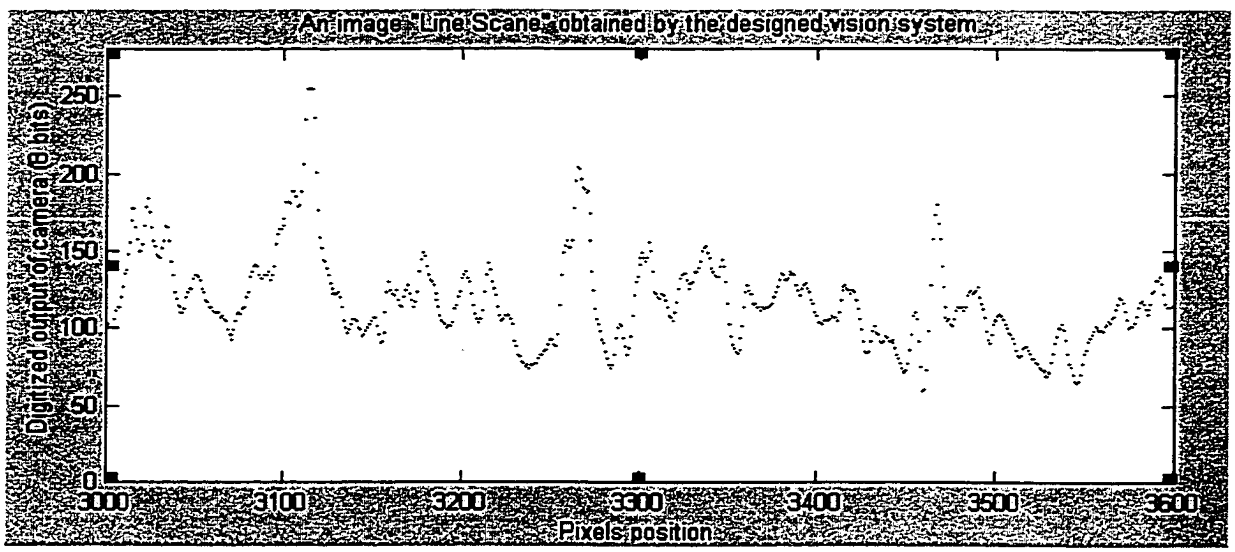

Figure 3- 10: Output of pixels from 3000th to 3600th.

With 8-bit resolution, the digitized output of each pixel varies from 0 to 255. The output level as provided by the onboard A/D converter can be adjusted by changing the light source intensity. If the light intensity is increased, the camera output will increase, but will saturate at a value of 255. In these figures, higher values imply the compound at those positions at the time of image acquisition contain more water than the others or a thin layer of apple sauce, which corresponds to a maximum exposure of those pixels. The lower (located near pos. 2000^{th} in Figure 3- 8) represent the dark defects, which prevent the light from exposing the corresponding pixels on the CCD sensor of the camera, and the output is negligible accordingly.

The preceding figures represent one line scan at a specific instant of time. The next line will be acquired at the same position, but at another instant of time. Since the apple sauce is flowing past the inspection window, normally all of the defects will be detected. The variation of the output illustrates that the vision system is very sensitive to changes in the apple sauce scene and can be applied efficiently.

One remark must be make with respect to the non-uniformity of the light source. The distribution of light rays along the length of the lamp follows a Gaussian distribution, which lacks intensity at the extremities. This leads to a light distribution pattern that resembles a typical flow profile; the ends lack light intensity.

Moreover the focus, once adjusted to the center portion of the flat die, is also poor on the ends of the visible range, i.e. at the ends of the scanned line. That leads to difficulties in obtaining a sharp image at the ends of the captured scene. A compromise in the adjustment was attempted, but test results did not prove satisfactory. The defect is very difficult to detect at the extremities ("edge lanes") since both the focus and light intensity are poor. This problem is illustrated clearly in Figure 3- 11, where the pixel output within 1 inch of the edges is very poor, especially in the first lane (about 110 pixels).

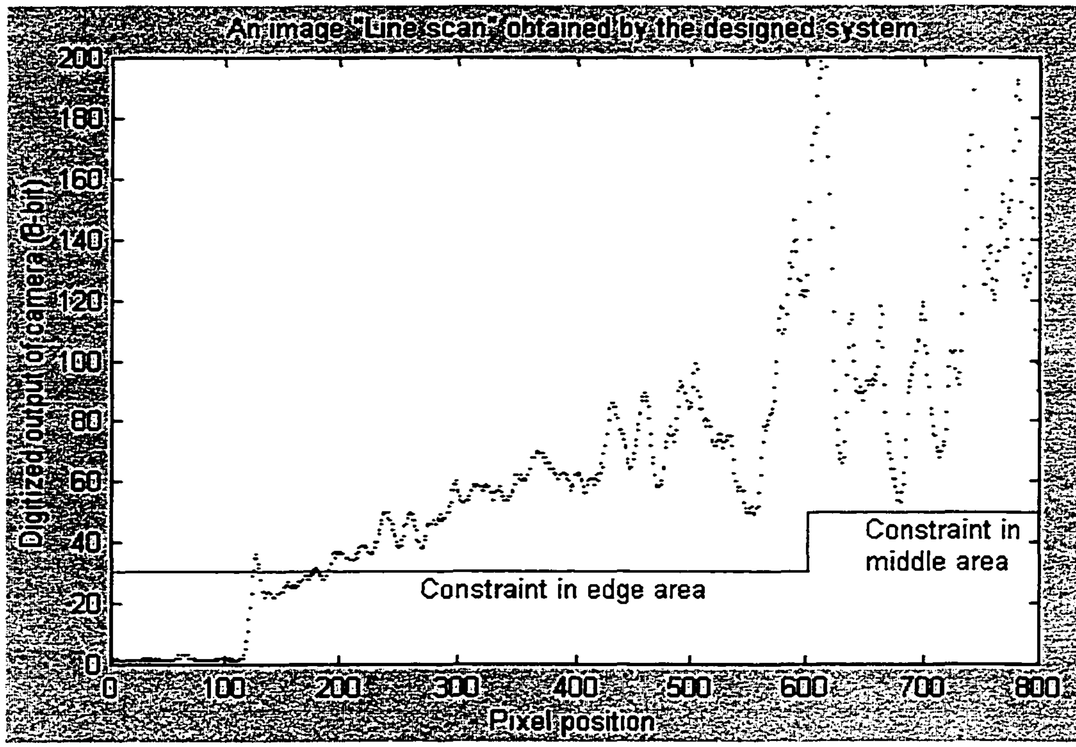

Figure 3- 11: Image in edge area and the constraint

The problem can be solved by use of 14-inch light source for a 12-inch field of detection and the use of a macro lens or similar arrangement to obtain a more uniform focus pattern over the entire filed-of-view. In that case, the first inch of the scene is the second of the light source, and the output is corrected effectively.

To identify what is a defect in the image, there are two solutions:

- Comparison with the average value of the pixels in the neighborhood around the point of interest (locally adaptive threshold): Defect is identified if the pixel output is smaller than the average value of pixels in neighborhood. This method can be applied generally, but it needs a great number of calculations and takes time. It may delay the process, which needs to be as fast as possible.

- Comparison with fixed constraints in certain areas (look up table): this method needs a stable set of parameter such as light source, material properties, etc. Defect is identified if the pixel output is less than the preset constraint. With application of an oversized light source (intensity controlled) and correction of lens focus, this method is simple and fast.

With respect to the system under study in this thesis, the look-up table method is preferably. With the percentage of saturated pixels set at between 10% and 15%, the threshold value in the first 5 lanes from the edges is set to 30, while 50 is used in the rest of the lanes (middle area). The proposed constraints are displayed in Figure 3- 11 and Figure 3- 12.

In the Figure 3- 11, the first pixels are not real defects because of the limitations in the light source presented above. There is only one defect detected near position 2000 (of 4800 pixels over the full field of view) at this particular instant of time that is presented in Figure 3- 12.

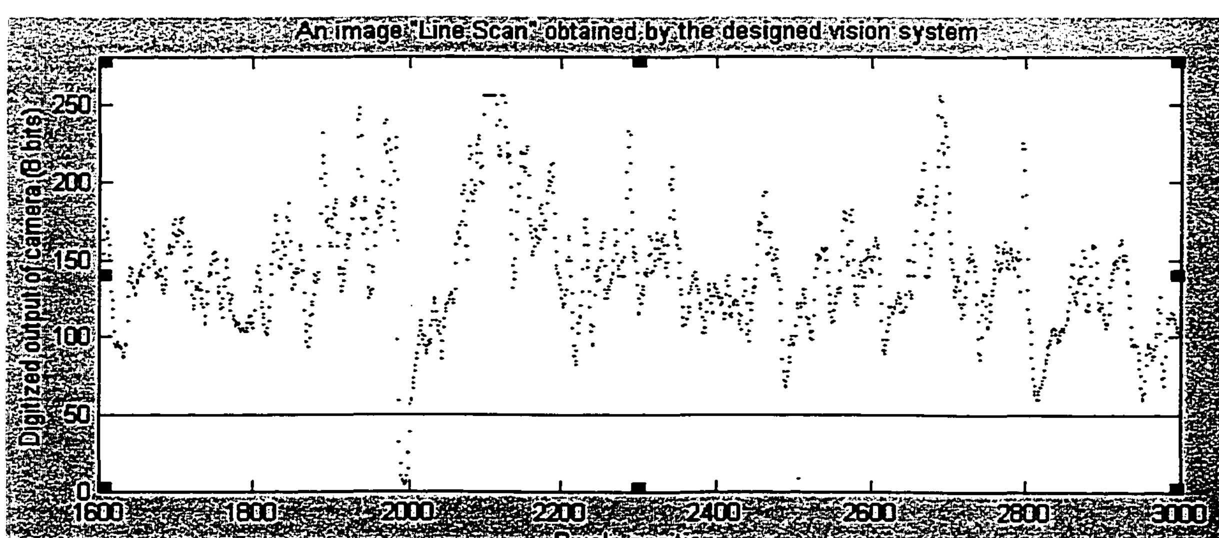

Figure 3- 12: Constraint in the middle area and defect

3.7.2 Removing Defects:

The controller treats the "line scan" image provided by the camera to recognize where there is a defect. The flat die is divided into 44 channels along the width of the flow field, each channel being 7mm in width. From hereon in this thesis, the words "channel" or "lane" represent this idea. If any defect is found within a specific channel, the controller identifies how long it will take for the defect to reach the manifold module based on the apple sauce flow rate. The controller then sends a command to the manifold module. The aspiration valve at that channel will be open in time to remove the defect (from within the apple sauce) out of the apple sauce flow. The larger the number of channels, the smaller the quantity of primary material (i.e. apple sauce) wasted. Unfortunately, the number of channels is constrained by the valve dimensions.

The aspiration valve is a logical mechanical valve which opens / closes a vacuum line connecting the applesauce flow to the waste tank. The valve may be a spool valve or disk valve. One side of the aspiration valve is apple sauce flow, the other side is connected to a vacuum waste tank.

The spool valve is easy to manufacture, but it could have leakage as well as it is difficult to self-clean, one of the most important criterion for machines used in food processing applications. We have manufactured both of types to test in practice at Intempco Controls Ltd. The disk type of valve is the right choice in this application.

There are several types of actuator, which may be used to activate the aspiration valve, mechanical spring, compressed air, magnetic force. The question is what type or combination of actuators should be applied to meet certain criteria (applicability, fast response, clean, compact). If the valves are configured as two arrays (each consisting of 22 valves), the distance between the valves is 14mm, and the space the valve can occupy is on the order of 12mm (0.5"). The spring is simple to use as a permanent force to close the valve, but it will result in a continuous load which will lengthen the time to open of the valve, or the force to open will have to increase. The space is too limited for the time being to locate a solenoid coil which can operate directly on the valve and which has the required stroke and force to open / close the valve. Solenoid activated pneumatic valves, where the solenoid opens a small valve to pilot the main pneumatic valve are a viable alternative. The aspiration valve thus basically operates as a pneumatic cylinder in operation.

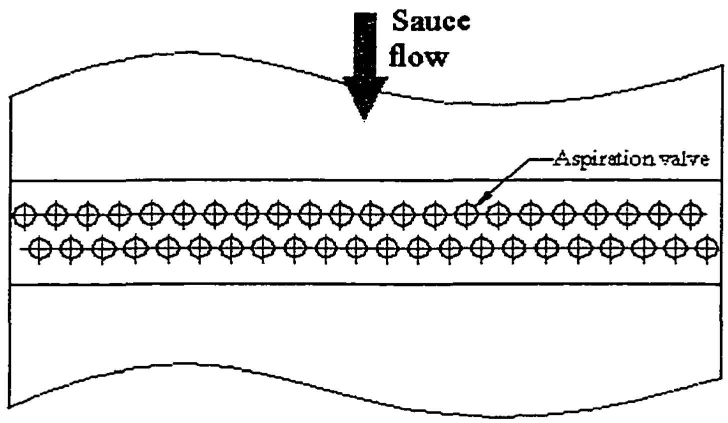

Figure 3- 13: Manifold combination of 44 aspiration valves

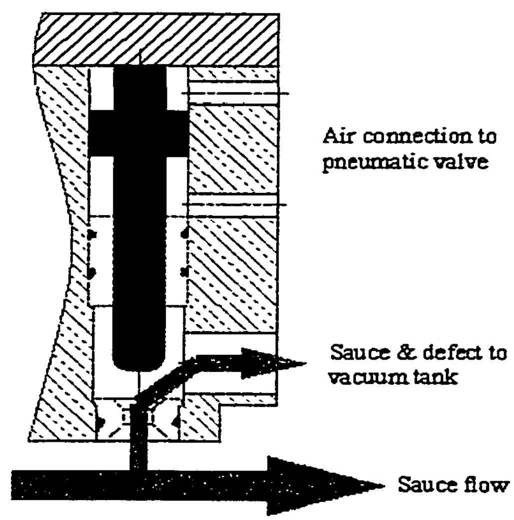

Figure 3- 14: Structure of aspiration valve

The aspiration valve can be controlled by a single pneumatic 5 way, 2 position valve (5/2) with a single solenoid, or two pneumatic 3/2 valves, of which one is normally closed and the other is normally open. The advantage of the two-valve configuration is a more rapid response of the aspiration valve, but there are two coils to control instead of one. In practice there is only approximately a one ms (millisecond) time savings associated with the two valve configuration. Consequently, in this study each aspiration valve is operated by one 5/2 solenoid actuated pneumatic valve.

3.8 Behavior of Apple Sauce Flow and Removing Valve

In the preceding section, the defect detecting and the defect removal modules were described. Both modules are integrated into the same flat die, but not at same position. This means that a defect detected at the detecting position of lane x will flow to the removal position of lane y after t seconds. At the time of detection, a signal originating from the detecting module will be sent to the controller to process. The controller will send a command to activate the removal valve to remove the defect accordingly. To obtain the required goals of design, the questions that need to be clarified are:

- Is the defect remaining in the same virtual lane ($x \equiv y$)?
- Is the time t between detection and removal constant irrespective of the channel (i.e. what is the flow behavior of the flat die)?
- What is the response time of the mechanical removal valve unit, which consists of a pneumatic valve and the aspiration valve (i.e. what is the dynamic behavior of the removal valve unit)?

Figure 3- 15 presents the model of the defect removal strategy. If the behaviors are clearly defined, the system knows exactly when the command needs to be issued, and the result is to remove the maximum number of defects with minimum waste.

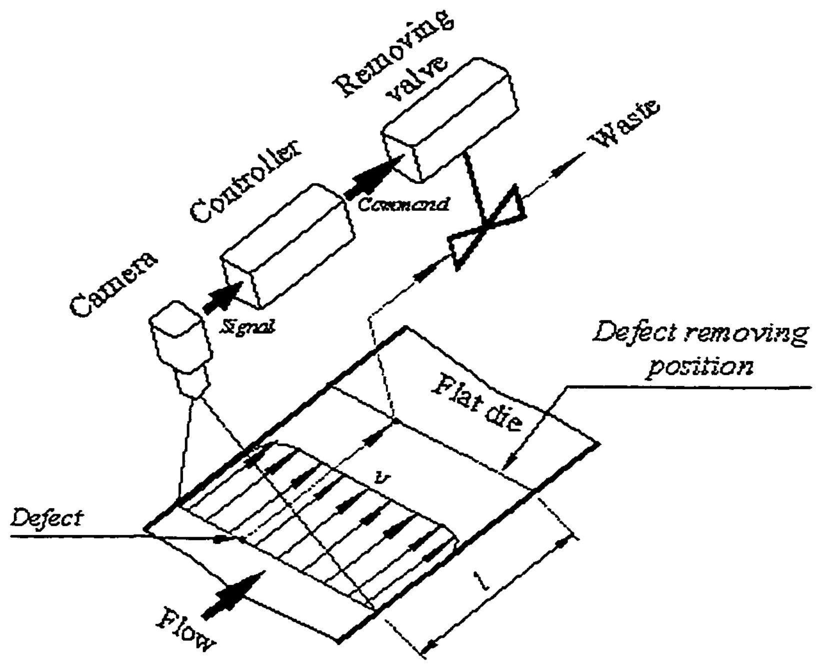

Figure 3- 15: Model of defect removing

To identify the transport delay t from detection to removal through distance l, we have to know the velocity profile of the apple sauce flowing through a closed rectangular channel. The flow through the flat die depends on many factors as presented in the first chapter. An experimental approach will be employed to identify flow form, and the moving time t will be deduced accordingly.

This method is also applied to find the response time of the removal valve unit. The response time here means the time required to fully activate the aspiration valve after receiving the appropriate command from the controller. There are two values of response time to identify, valve opening time of the aspiration valve (time required to initiate the aspiration of the apple sauce and defect) and closing time of the aspiration valve (time required to stop the aspiration).

To obtain the specified parameters of the flow and designed valve, two types of experiments are employed and described in the next two chapters.

CHAPTER IV

FLOW PROFILE OF APPLE SAUCE IN FLAT DIE

4.1 Definition:

The flow profile of apple sauce depends on many parameters such as:

- Hydrodynamic properties of apple sauce
- Shape and construction of die
- Distribution devices: distributor/collector (e.g. funnels)
- Observation position (along the length of flat die)

The flow performance of non-Newtonian liquids appears in the literature. Most studies are experimental in nature and focus on the flow through a round tube. These results are applicable to any clearly defined system, where most of the individual parameters are known.

In this application, there are many unknown parameters including the hydrodynamic properties of apple sauce, its behavior as a function of the geometry of the distributor / collector. We can suppose that the designed funnels and flat die form a combined set, where the effect and behavior of every individual device are considered mutually and coincidentally.

Based on this strategy, the problem of flow profile can be solved by identifying the velocity of discrete points within the flow at the designed detecting position on first vision module, where defects are detected. The results illustrate the behavior of the assembled set of devices where the real processing is achieved.

4.2 Applied Method

The methods to measure speed of flow can be:

- Utilization a video camera to continuously capture images of colored flow. The images illustrate the flow behavior at discrete intervals of time and the velocity of points within the flow can be identified and the flow profile determined. Digital cameras that can capture the scene at preset time intervals are available, but a resolution requirement of milliseconds is a challenge. The cost increases exponentially with the acquisition rate and is a significant barrier to application.
- Measuring the velocity of flow directly by velocity sensors. In this case, the flow behavior may be changed by the introduction of sensors due to modifications in the geometry of the conduit. More modern, non-contact sensor could be used, but expenditure needs to be considered.
- The designed system is equipped with two detecting cameras. With a proper distance between the cameras, particle carried with the flow (in other words, the flow) requires an interval of time to traverse the distance from one camera to the other. This effectively solves the problem of measuring the time to activate the aspiration valve following the detection of a defect as introduced in the preceding chapter. The results are more valuable if the distance between two cameras equals the distance between the detection module and the aspiration valves. This is easily carried out with the module design, where a module can replace another with the same interface (Figure 3-3).

The objective of this experiment is to quantitatively evaluate the time delay required to remove the defects and to verify the vision systems ability to detect defects at the required production rate. Defects can be generated by injecting particles into the flow discretely, or by mixing them into the raw material randomly.

The schematic layout of the experimental setup is presented in Figure 4- 1:

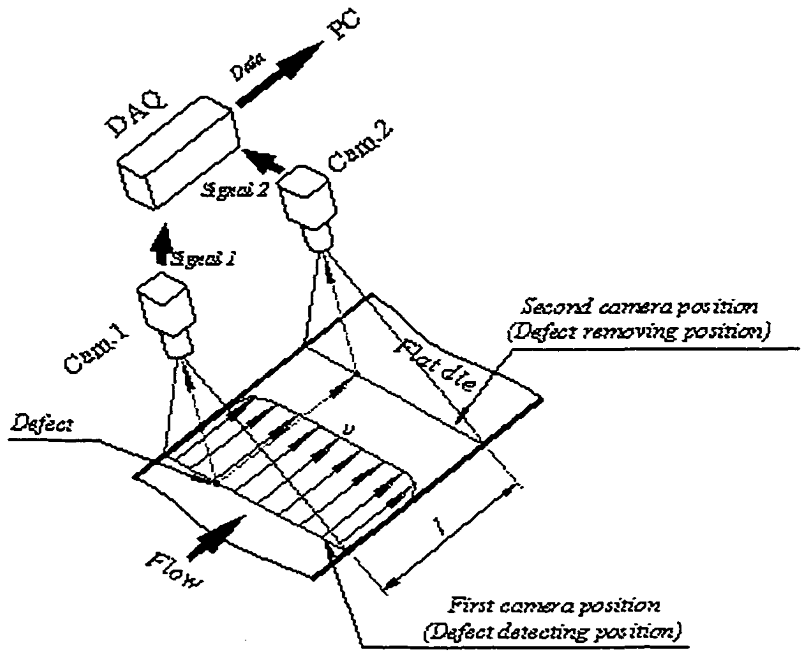

Figure 4- 1: Principle of identifying the velocity profile of apple sauce flow

4.3 Data Acquisition

For minimization the transmission delay of electronic boards, each camera has its own board to acquire and process the information related to the detection of defects. The information from the camera boards is processed by a third independent data acquisition board, which sends the data to the host computer via an RS 232 serial port.

The camera board is based on a Field Programmable Gate Array (FPGA MAX7128) which generates lane numbers (corresponding to channel numbers) specifying the location of the defect over an 8-bit bus, including a reset line. The FPGA is programmed to wait for the DAQ (data acquisition) board to acknowledge the defect detection and reset the bus afterwards. For visual validation of the functioning of the boards and the detection of defects, LED indicators are added to the boards.

The data acquisition board is based on a micro-controller (MC68HC705) which reads the 8-bit lane number corresponding to the position of the defect from both camera boards at the same time. The detection is used to create data packet, comprising:

1. MCU time stamp (8 bits, 0-255) with 1 millisecond resolution
2. Lane number defined as lane 1 to 44 for the first camera, and (128+(1 to 44)) for the second camera.
3. CPU (Central processing unit) time stamp (seconds). This is the time provided by the PC clock at the time of download. This time is incremented every 55 milliseconds (18 times per second, thanks to Intel), and it is useless to evaluate fast-paced events such as defect detection under normal operation.

The MCU time stamp is used to refine the CPU time stamp. Since the later runs over long periods of time, it becomes more practical to test the behavior of the system, while the MCU time stamp allows for a final resolution of 1 millisecond.

Each time a defect is detected, a packet is created in the MCU of DAQ board for the time stamp and the lane number. This packet is sent immediately to the PC via the RS-232 serial port, set at 9600 baud. The PC reads the event, and concatenates its own time stamp afterwards. The delay between two events is irrelevant, since it is added to all data inputs.

Note that a synchronization problem may occur when performing the transfer of data between the MCU and the PC. This problem affects the reception arrangement of the data: the normal detection process sends a time stamp followed by a lane number, each being 8-bit numbers. Due to a lack of time, one byte may not be received. From that moment of time onward the two input data are reversed in order, which leads to the lane number being the time stamp and vice versa.

In order to save the time, no handshaking protocol was used in this experimental set up, since the maximum baud rate that could be used with a 4 MHz crystal on the micro-controller MC68HC705 is 9600. The best solution would be to configure the MCU with handshaking at 115kbaud, which would eliminate the problem. The solution found to avoid the synchronization problem was to have the PC run as fast as possible during the transfer operation. This means logging data to memory, and avoiding disk access. The use of a faster computer might also solve the problem, but for the given hardware, logging data to RAM only gave good results: the synchronization problem did not appear in the collected data.

4.4 Experiment and Results:

The tests were performed with the range of flow rate from 1 to 10 GPM (gallon per minute), where a flow rate of 8 GPM allows a production run of 15 cubic meters of apple sauce to be processed in a single 8-hour shift. The flowmeter was installed before the flat die rather than after, in order to minimize restrictions and pressure in the flat die.

4.4.1 Pressure

The pressure of the apple sauce flow before the flowmeter is the highest in the production cycle so its has to be considered. Pressure gauges are installed before the flowmeter and at the defect removal position (aspiration valve location). The first is used for measuring the maximum pressure of the apple sauce, and the later illustrates the pressure of the sauce to be removed with the defect. The maximum pressure applied to the sauce is presented in Figure 4- 2. The entire range of sauce flow rate is acceptable because no pressure exceeded the limitation of 30 PSI. This constrain is derived from the decomposition properties of apple sauce.

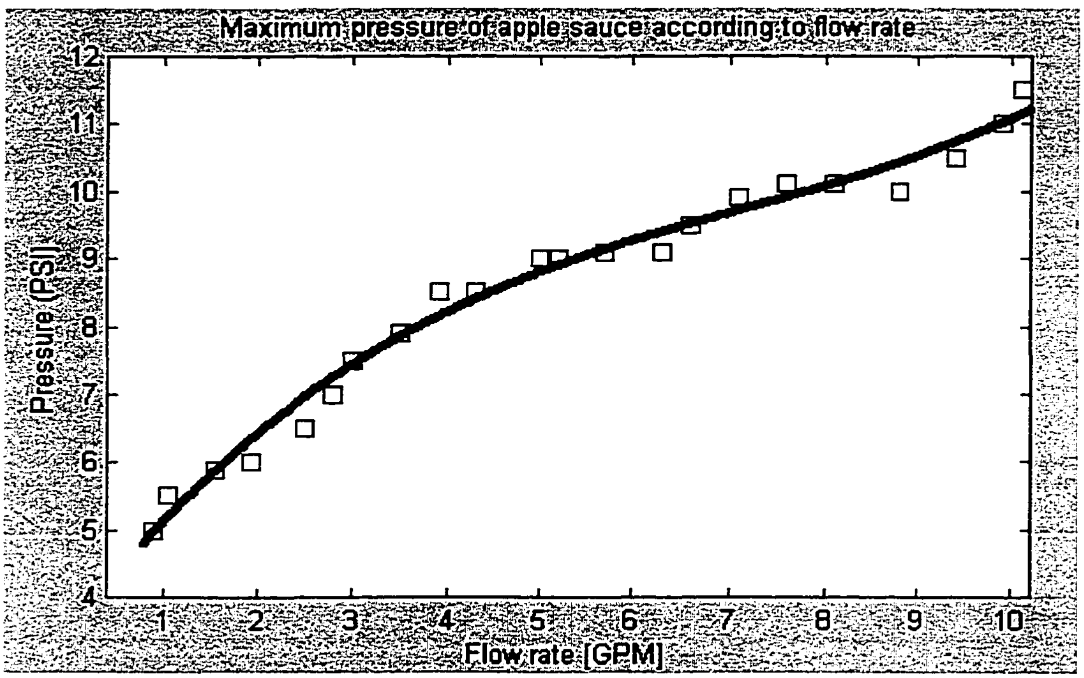

Figure 4- 2: Maximum pressure of apple sauce depends on flow rate

The pressure of the apple sauce flow at the defect removal position is used to determinate the level of vacuum of the waste tank so as to remove defects effectively. This pressure is not high because of the open exit of apple sauce following the flat die. The measured values are concentrated in the interval from 2 to 2.2 PSI for a range of flow rate from 3.5 to 10 GPM. The pressure is illustrated in Figure 4- 3. A suggested pressure of 2 PSI can be applied for this type of apple sauce in production.

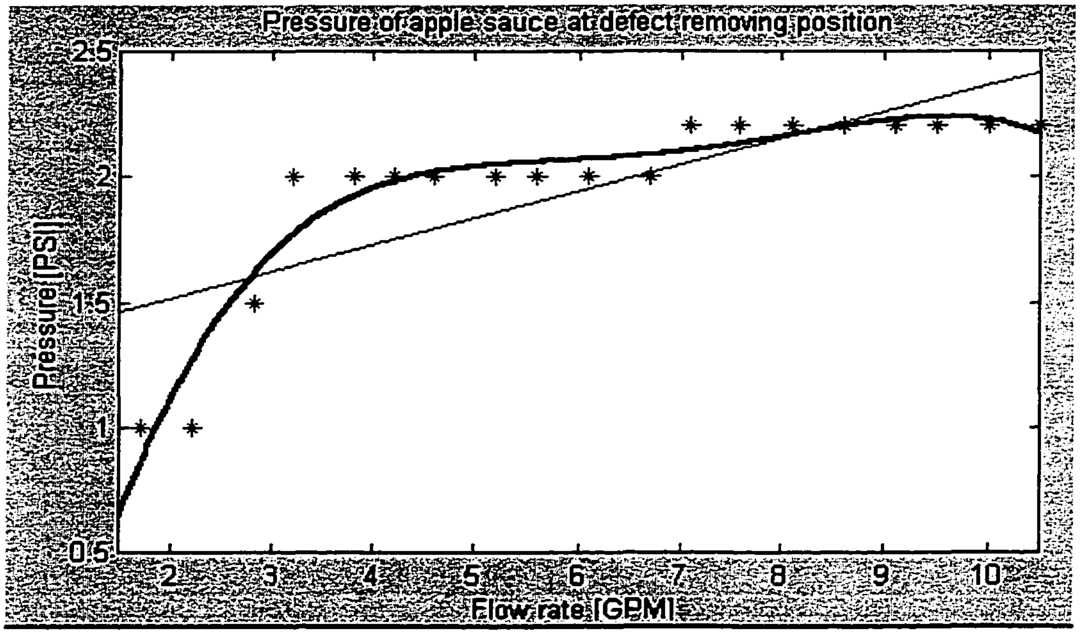

Figure 4- 3: Pressure of the apple sauce at defect removing position

4.4.2 Flow Profile

In the experiments, the resulting flow profile demonstrated exceptional qualities, such as being very flat. A zone, near the edges of the detection area, could be identified visually as having a lower speed, but could be approximated as less than 0.25 inch in width. The flow is actually laminar in the interval of flow rate (1 to 10 GPM), so that mostly there is not mass transfer in the transverse direction. In other words, the number of detected defects, which change lanes while flowing between the two stations, is negligible. This matter has been confirmed through the acquired data. There are some lane changing cases, but those defects might be on the boundary between two lanes where a distance of only 0.074mm defines the lanes. In fact, this problem is solved because an aspiration valve does not only suck in its lane, but also a part of two neighbor lanes.

The acquired data were processed and the flow profile of apple sauce at flow rate 8 GPM is illustrated in Figure 4- 4:

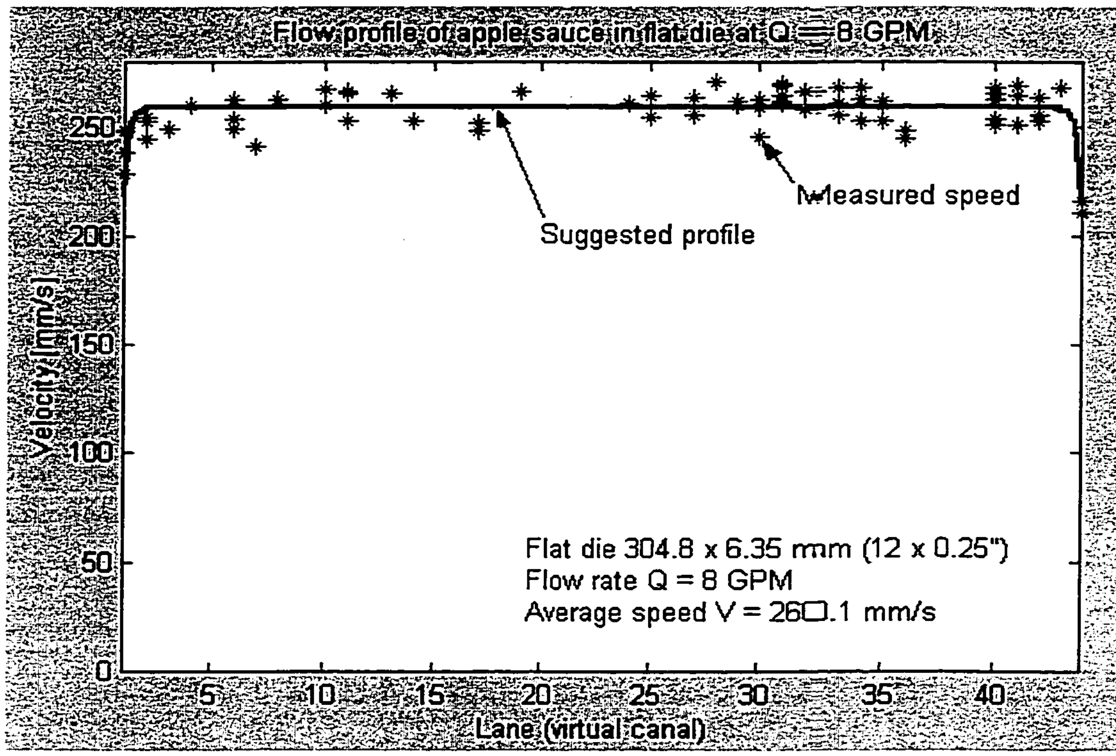

Figure 4- 4: Flow profile of apple sauce in flat die at flow rate Q=8 GPM

In supposition that the speed of flow is constant, the average speed is developed as:

$$v_{ave} = \frac{Flow\ rate\ Q}{Section\ A} \tag{4-1}$$

With Q=8 GPM indicated on the flowmeter, we obtain:

$$v_{ave} = \frac{8\,[GPM]*6309\left[\dfrac{mm^3/s}{GPM}\right]}{304.8*6.35\,[mm^2]} = 260.1\,[mm/s] \tag{4-2}$$

and the average time in this case is:

$$t_{ave} = \frac{dis\tan ce\ l}{Average\ speed\ v_{ave}} = \frac{170\ [mm]}{260.1[mm/s]} = 654\ [ms] \tag{4-3}$$

Finally in the experiment at a flow rate Q=8 GPM, we obtained:

- Maximum speed: 270.70 mm/s
- Minimum speed in steady region: 240.79 mm/s
- Average speed in steady region of flow: 259.62 mm/s, and
- Average speed of whole flow: 257.02 mm/s

These results corroborate the predicted values. The errors may be caused by inaccuracies in the measuring devices (e.g. flowmeter, etc). Defects located at different depths in the height of 6.35 mm may travel at different velocities, which explains the obtained measured speeds of defects. The average speed of defects is nearly uniform except at the two edges. The theoretical discussion of flow profile in the first chapter is confirmed.

Experimentally, the acquired velocity of the flow at the edges is not zero because the defect dimension is much greater than the characteristic height of the wall roughness. To eliminate gravity effects, which may stick defects to the wall, the flat die is mounted vertically. The maximum speed of defects for this configuration can reach 270.70 mm/s (4% higher average speed), while the minimum speed is only 240.79 mm/s (8% lower). This range may be used to control the operation of aspiration valves, but the moving time of the defect, another relative information, can be applied directly to control the defect removal process.

4.4.3 Moving Time

As present in above sections, the acquired data are the moving time of defects between two vision stations. The objective is also the time to operate aspiration valves to remove detected defects accurately and properly. This parameter can be deducted directly from the collected data.

Operation time of a cycle is the time from defect detection to removal (i.e. opening and closing the aspiration valve). It includes the delays inherent in various devices and the controlled waiting time.

It should be noted that the controlled waiting time is based on the knowledge of the others, included the total cycle time. This cycle time includes the moving time of particles from the detection position to the aspiration position. Consequently, the moving time of particles has to be studied as one of the key parameters of the problem. The other time periods will be discussed later on in the next section.

A packet of data consists of MCU time, lane number and PC time as presented in the previous section. A small program converts that packet into a new packet of information, in which a lane number and a real time with 1 millisecond resolution of detected defect was shown. A pair of packets in the same lane of two stations permits the determination of the moving time of the defect with a resolution of 1 millisecond. Actually, the same lane means a difference of 128 between two lane numbers as defined above.

A graphical representation of moving time was constructed from the acquired data at a flow rate Q=8 GPM as shown in Figure 4- 5:

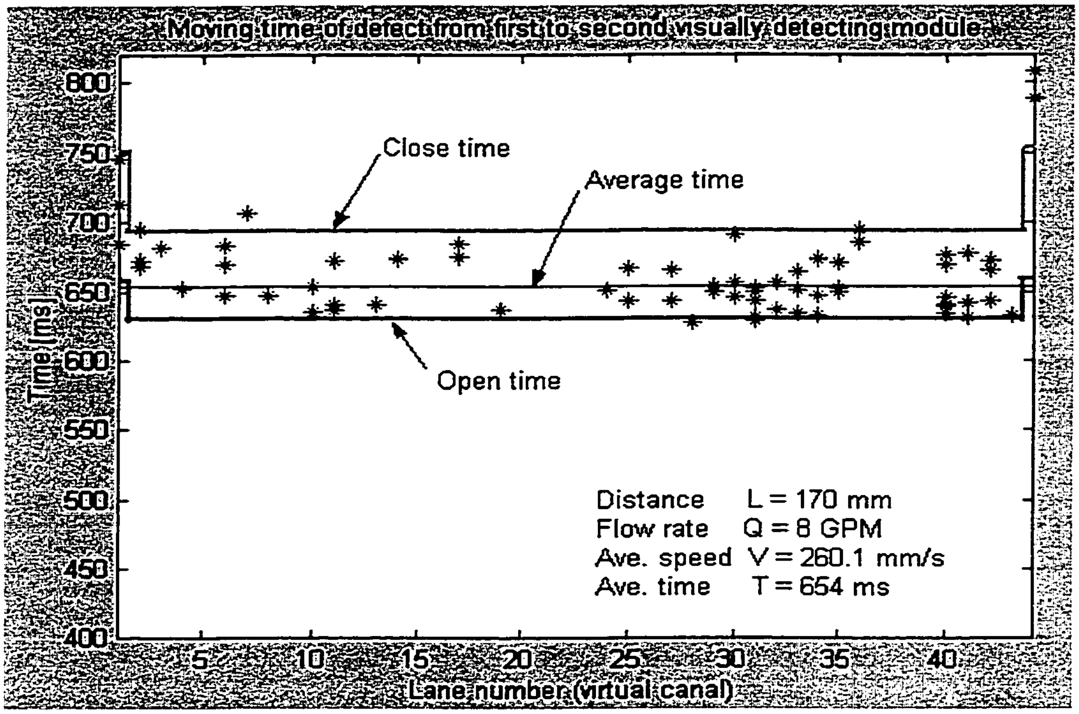

Figure 4- 5: Particle moving time of apple sauce in flat die at flow rate Q=8 GPM

The average moving time corresponding to this flow rate is 654 ms as calculated by equation (4-3). The defects in this experiment were introduced randomly, and the data obtained as following:

- Average moving time in steady-state region: 655 ms (close to the predicted value)
- Maximum moving time in steady-state region: 706 ms (+8% of average time)
- Minimum moving time in steady-state region: 628 ms (-4% of average time)

The minimum and maximum values of moving time relate directly to the time to open and close the aspiration valves respectively. The maximum value of 706 ms is an improbable event in the measured data and can be eliminated (Chauvenet criterion), so the maximum moving time in the steady-state region is closer to 694 ms (+6% on average time). During the operation of the system, each of these values can be configured as a variation (add / subtract a percentage) of the average value which is calculated from the flow rate (equations (4-1) to (4-3))

In this case, the steady region defined from the end of lane 2 to the begin of lane 43 is computed from the acquired data as discussed in the previous section, and the edges can be configured as two lanes on either side. Particles in the edge area move slower than those in the steady-state region, and the time values can be estimated by interpolating. In fact, uniform probability of a defect existing on either edge is 4.5%, and the estimation can be good enough for the problem.

In conclusion, the designed system employs a moving time of defects for a production rate of Q=8 GPM given in the table 4-1 :

Table 4-1

Suggested operation time of aspiration valve

Suggested aspirating time (defect removing time) at Q=8 GPM			
Lane number	***1 and 44 (edge)***	***2 and 43 (pseudo-edge)***	***3 to 42 (steady)***
Aspirating start time [ms]	686 (t_{ave}+5%)	628 (t_{ave}-4%)	628 (t_{ave}-4%)
Aspirating stop time [ms]	785 (t_{ave}+20%)	706 (t_{ave}+8%)	694 (t_{ave}+6%)

The larger the difference between the start time and the stop time, the more apple sauce is wasted. The range at the edges is the largest because of the highest variation of flow speed (slow areas of flow profile).

These values of operation time are important and were embedded into the control program of the MCU as a look up table. These values will be used in the next chapter.

4.4.4 Prediction of increasing speed:

One question that can be asked is that if a compromise is made on the defects' acceptable size, can the designed vision system be enhanced to accept an increase in flow speed? This would permit a reduction in the gap in the flat die to better detect the dark particles or maintaining the gap and augmenting the productivity. Before this can be done, we must ensure that the vision system does not saturate on the defect detection process, whereas at high speeds, a certain percentage of defects will not be detected. The curve of defect number versus speed should follow a Gaussian distribution where the highest value represents the optimal detection ability.

An experiment was conducted to validate the principle described above. A small batch of apple sauce was used to get the same probability of defect generation at difference speeds. The flow gap at the deduction module was reduced down to 1.58mm (1/16"). This means the real speed of sauce in this experiment was four times greater than normal condition (gap positioned 6.35mm = 0.25") at the same flow rate. The number of defects (each defect only counted one time, although it may be detected several times) at first station was determined and presented in Figure 4- 6.

In this experiment, the flow speed was increased up to 1,300 mm/s, but it has not reached its maximum yet. The curve shows that the system can be further enhanced for one particular sample of apple sauce. Maybe there are a large percentage of large defects in the batch, but the experiment gives us an idea of the acceptable speed range. One important point is the minimum size of detected defects in this case (1,300 mm/s), approximately 0.27mm which can be observed easily.

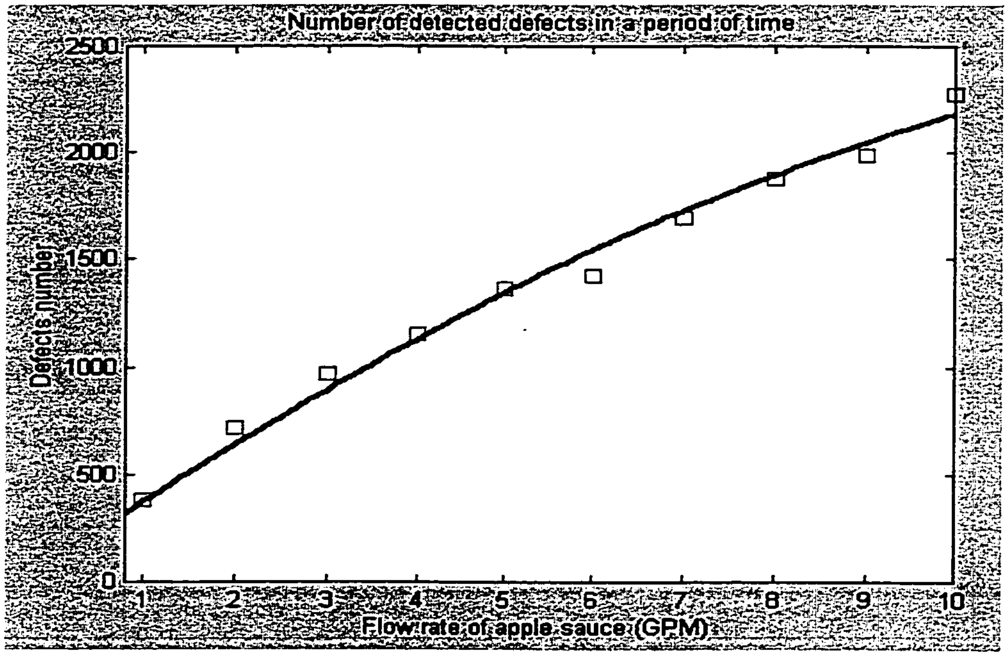

Figure 4- 6: Detecting ability of vision system

4.5 Reference Pictures:

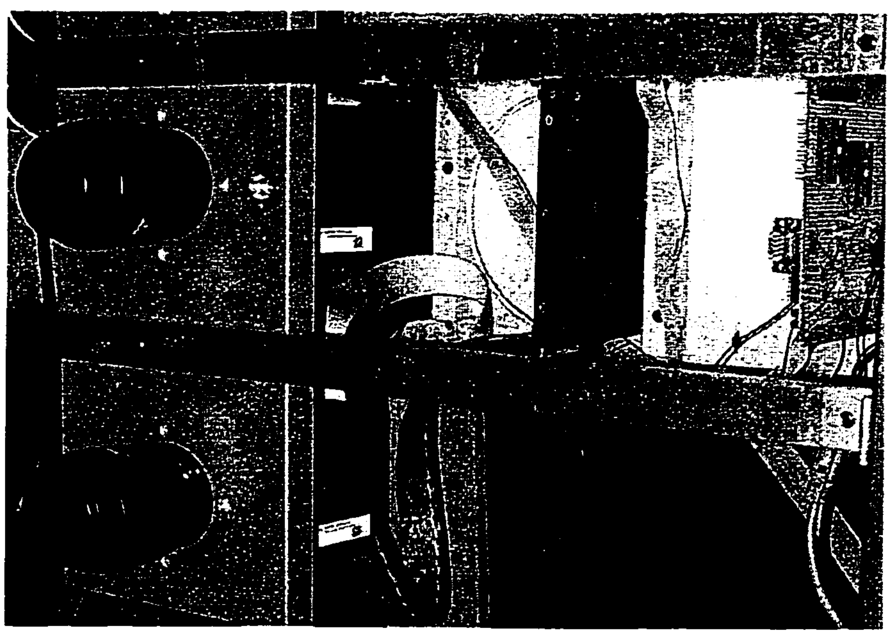

Figure 4- 7: Detecting, checking cameras with boards and data acquisition card

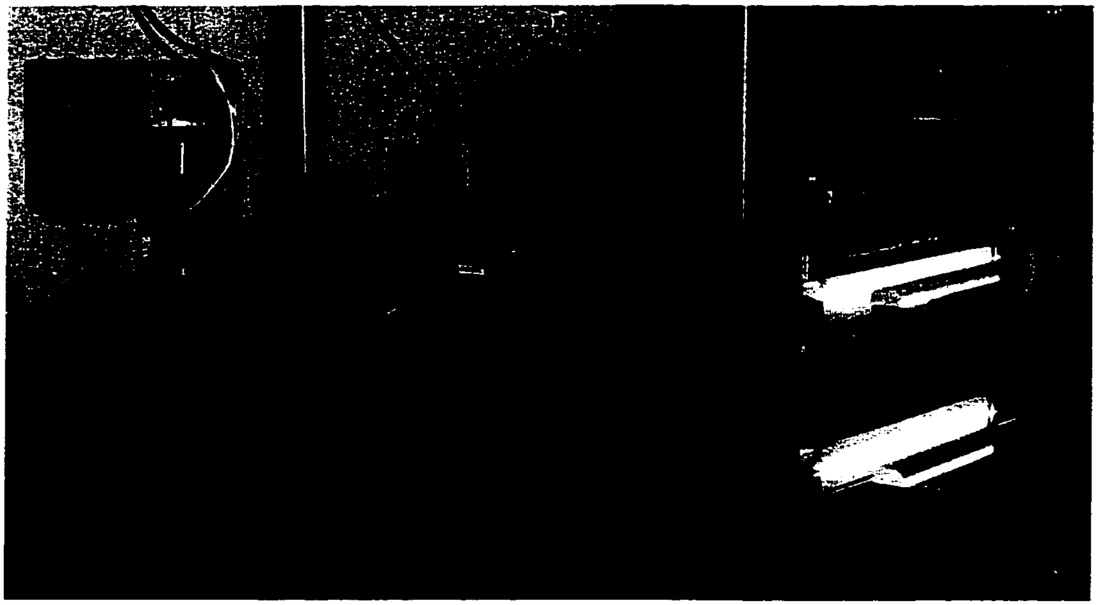

Figure 4- 8: Detecting, checking cameras with backlighting

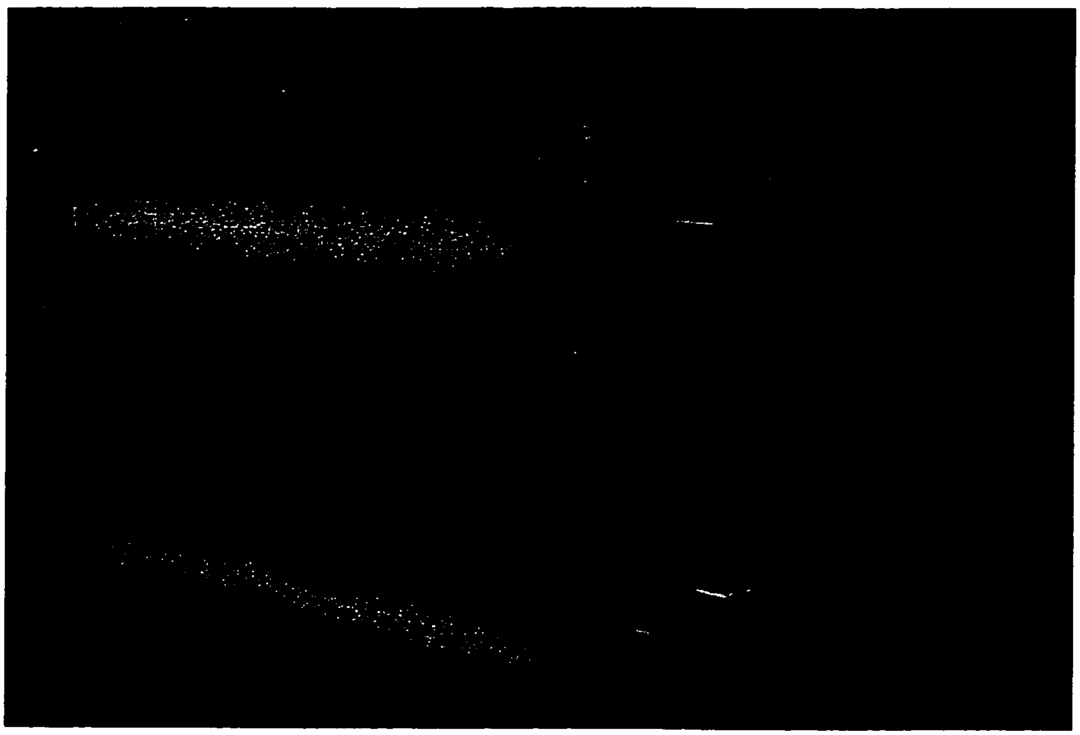

Figure 4- 9: Scene of apple sauce with back-lighting

CHAPTER V

OPERATION TIME AND FLOW RATE OF VALVE

5.1 Definition:

When a defect reaches the detection position and is detected, the camera transfers its information to the camera board where a packet of position and time data is created. This data is then sent to the controller to process and give the appropriate command to pneumatic valve drive board. From the drive board, a power signal activates the pneumatic valves to pressurize and open the aspiration valve. After a certain time, the command expires and the aspiration valve closes to complete the defect removal cycle. The operation time of the whole cycle can be divided into:

1. Delay time of camera detection
2. Delay time of information processing in the camera board/control board
3. Waiting time (objective to be controlled) to send the command to the removal manifold (current to operate pneumatic valve)
4. Switch on time of removal valve, e.g. time from sending "open" command to pneumatic valve, to aspiration valve really opening (to be identified).
5. Operation time of aspiration valve, in other words, aspirating time to removal of defect.

6. Switch off time of removal valve, e.g. time from sending "close" command to pneumatic valve, to aspiration valve really closing (to be defined)

Operation timing of system is presented schematically in Figure 5-1:

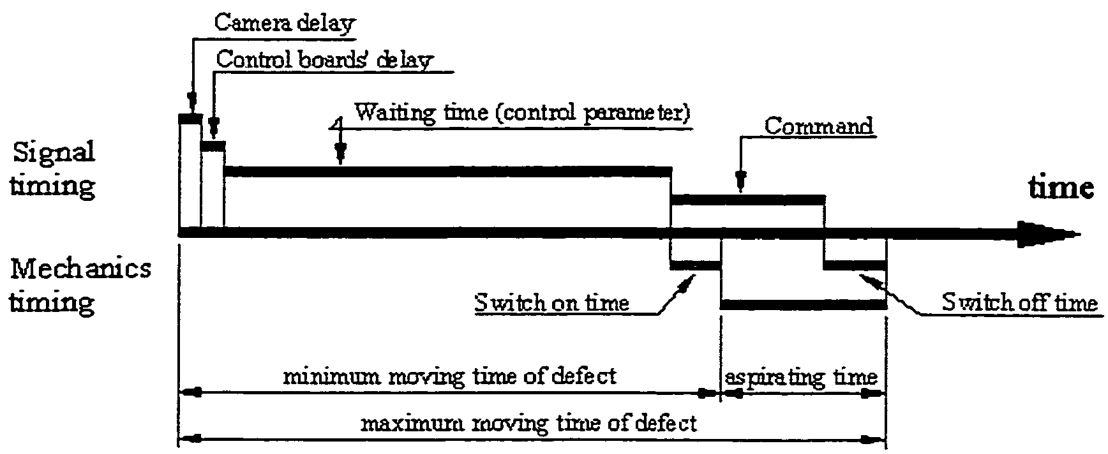

Figure 5- 1: Timing of system operations

The components of the operation time is illustrated in the following equations:

$$t_{move}^{min} = t_{cam} + t_{board} + t_{wait} + t_{on} \quad (5\text{-}1)$$

$$t_{move}^{max} = t_{cam} + t_{board} + t_{wait} + t_{command} + t_{off} \quad (5\text{-}2)$$

where:

t_{cam} , t_{board} are delay time caused by camera and electronic boards respectively

t_{wait} is the time that the controller should wait to give action command to removal manifold to remove the defect

$t_{command}$ is the time that command lasts to remove the defect effectively

t_{on} , t_{off} are the switch on and switch off time of removal valve

$t_{move}^{\min}$, $t_{move}^{\max}$ are minimum and maximum moving time of defect respectively at studied flow rate

The first two items the response time of the electronic devices. The response time of the whole control system can be evaluated by different methods, such as:

Estimation of the operation time by calculating response time of every component in chain, e.g. operation time camera data processing, operation time of MCUs achieving the specified code in combination with device operation clock, delay time of transistors, etc.

Reprogram the controllers to perform all the tasks without a programmed delay control time, introduce a detecting defect, connect the output of the control system to a measuring device (e.g. oscilloscope) . In testing operation, the control system detects that defect, processes its information and sends an aspiration command, which is displayed on the oscilloscope. The cycle time of the output is the response time of the whole control system in operation a defect. This method can also be used to evaluate the response time of the control system without the camera by using a signal generator as an input signal. This algorithm considers all of actual effects on system and is used effectively in other sections in this thesis.

Normally the response time of electronic devices is very small, and can be neglected in comparison with the delay of the mechanical components in the chain. To simplify the problem, the first method is employed to evaluate these values.

In fact, the camera scan rate is 4800 lines per second. This means that each cycle of detection lasts only 0.21 millisecond, faster than the resolution (1 millisecond) of the information. The response time of the control system is evaluated in Annex A. It is small enough to be neglected.

After eliminating these electronic delay time values, the above equations are simplified as:

$$t_{move}^{\min} = t_{wait} + t_{on} \tag{5-3}$$

$$t_{move}^{\max} = t_{wait} + t_{command} + t_{off} \tag{5-4}$$

Two terms on the left side are already defined in the preceding chapter, and their values depend on the flow rate.

The switch on and switch off time are independent of flow rate. They just depend on the mechanical behavior of the pneumatic valve, aspiration valve and their operating environment (pressure, friction, ...). These values are two of the experiment goals presented in this section.

Evidently, the control parameters of time can be deduced based on all the above times. For convenience, let us define t_{start}, t_{stop} as the start and stop time of the command, we have:

$$t_{start} = t_{wait} = t_{move}^{\min} - t_{on} \tag{5-5}$$

$$t_{stop} = t_{wait} + t_{command} = t_{move}^{\max} - t_{off} \tag{5-6}$$

Basically, the system can be controlled adequately if we know the timing behavior of the removal valve and the real operating time of the aspiration valve, or aspirating time can be determinate from:

$$t_{aspiration} = t_{move}^{\max} - t_{move}^{\min} = t_{command} + t_{off} - t_{on} \tag{5-7}$$

In the aspirating time, the defect is removed out with base material (i.e. apple sauce). To make sure that the defect is removed absolutely, flow rate through the orifice of the aspiration valve has to be no smaller than the flowrate through one channel.

The aspiration flow rate depends on several parameters including geometry of the orifice, applied pressure drop, hydrodynamic properties, Reynolds number of apple sauce and so on. In this study, the flow rate will be determined experimentally.

5.2 Applied Method

An experimental system was built to measure both the operation timing and the aspiration flow rate. The principle of this experiment device is illustrated in Figure 5- 2:

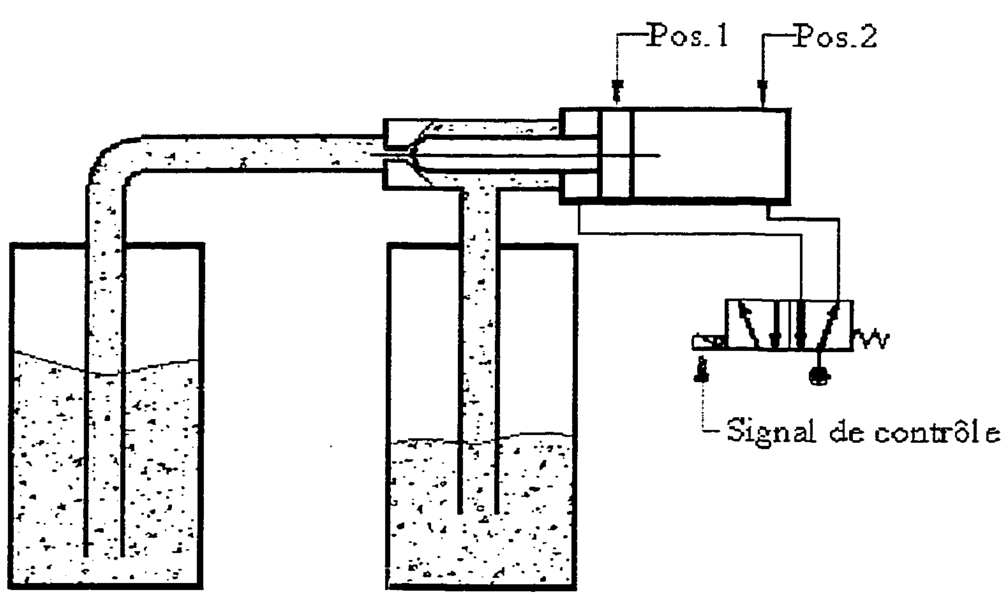

Figure 5- 2: Principle of orifice flow rate and operation time testing

The aspiration-testing valve is an exact dimensional copy of the real valve to eliminate unknown effect. The tanks, of which the left is pressurized and the right is under vacuum, are transparent to observe and measure easily. The pressure and vacuum can be adjusted easily to create a pressure drop between two sides of the orifice. The two inductive detectors used operate at a high frequency (3 kHz) and narrow field of detection (max. 0.6mm) to reduce measurement error. A FESTO pneumatic valve with low activation current (24V-1W) and high flow rate delivery (320 lit per minute) is used. The friction of the piston-cylinder is only 5N whereas its force is 50N under normal condition.

5.3 Data Acquisition:

Design of the data acquisition system for this experiment is presented in Figure 5- 3. The devices employed consist of a PC connected to a DAQ card (data acquisition card) via a serial port RS232. A drive board is inserted between the DAQ card and the actuator/sensors (valve and detectors) to modulate and isolate the signals appropriately.

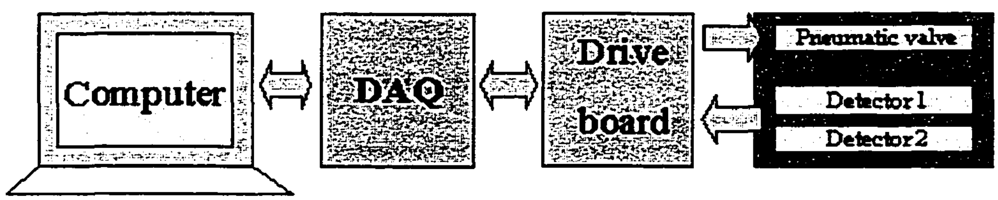

Figure 5- 3: Conception of signal communication

First, a program is executed in the PC which sends a command to the DAQ card to register the zero time (reset timer T_0 and others). Immediately, this command is transferred to the drive board to generate a power signal to activate the pneumatic valve to move the piston of the aspiration valve. When the piston just moves out of its permanent position, detector 1 changes its status and this time t_1 is registered in timer T_1

of the DAQ card via the drive board. The timer T_2 is used for timing t_2, that is the time required for the piston to reach its end position as measured by detector 2. In a similar way after a certain delay, the command is turned off and the time t_3 is registered in timer T_3. When the pneumatic valve deactivates, the piston moves back to its initial position, and sequentially the timers T_4 and T_5 register the initial and final return time (t_4 and t_5) of the piston. All timers are configured with 1 millisecond resolution, and all the delays of the electronic devices are neglected.

A packet of data consisting of 5 values in timers T_1 to T_5 of one operation cycle is temporary stored in DAQ card memory. At the end of cycle, a handshaking and transfer procedure is executed to transfer the packet to the PC and appended into a file. The process continues automatically and the measurement data is stored in a file in the PC. In addition, the quantity of aspired apple sauce is accumulated in the right tank and is used to calculate average flow rate of the aspiration valves. The data sequence is shown in Figure 5- 4.

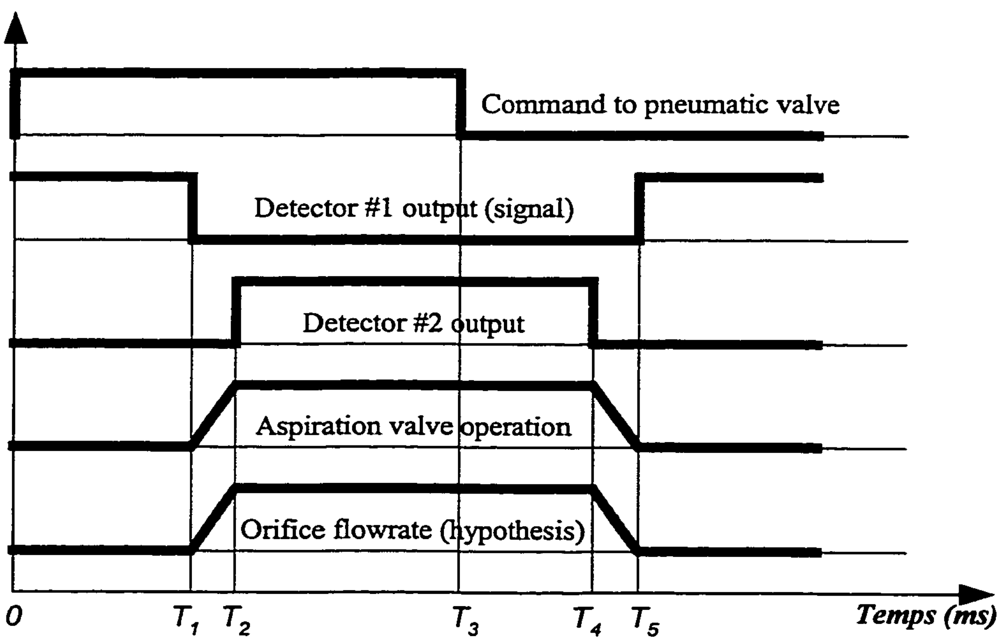

Figure 5- 4: Sequence of signals

5.4 Experiments and Results

5.4.1 Response Time

Based on the description in preceding section, the response time of the removal valve can be expressed as:

Switch on time: $t_{on} = t_1$ (5-8)

Switch off time: $t_{off} = t_4 - t_3$ (5-9)

Moving time of piston (open): $t_{open} = t_2 - t_1$ (5-10)

Moving time of piston (close): $t_{close} = t_5 - t_4$ (5-11)

The acquired data are very consistent. An experiment was done with a pneumatic tube 40 mm in length, air pressure 6 bar, and the results are (with the probability P):

$$\begin{aligned} t_{on} &= 22.93 \pm 0.68\, ms \quad (P = 0.95) \\ t_{off} &= 29.36 \pm 0.94\, ms \quad (P = 0.95) \\ t_{open} &= 1.77 \pm 0.69\, ms \quad (P = 0.90) \\ t_{close} &= 1.14 \pm 0.58\, ms \quad (P = 0.90) \end{aligned} \tag{5-12}$$

The length of tube acts as a damper, and the response time is longer with a longer tube. A fast reacting system has to be designed with the tube as short as possible. An experiment was conducted with a length of 300mm, and the results in this case are:

$$\begin{aligned} t_{on} &= 26.33 \pm 1.62\, ms \quad (P = 0.95) \\ t_{off} &= 32.71 \pm 1.59\, ms \quad (P = 0.95) \\ t_{open} &= 2.01 \pm 0.76\, ms \quad (P = 0.90) \\ t_{close} &= 1.50 \pm 1.32\, ms \quad (P = 0.90) \end{aligned} \tag{5-13}$$

The pneumatic valve will be directly mounted onto the manifold without tube, so the results of (5-12) are applied.

5.4.2 Aspiration Flow Rate:

Typically, the flow of apple sauce includes defects moving through an orifice of the aspiration valve when it opens under pressure differential. The Bernoulli equation expresses the status of the sauce between points (1) and (2) as shown in figure (5-5):

$$p_1 + \frac{1}{2}\rho V_1^2 + \rho g z_1 = p_2 + \frac{1}{2}\rho V_2^2 + \rho g z_2 \tag{5-14}$$

where p is pressure, ρ is density, and z is height of fluid.

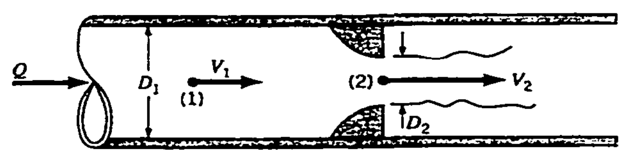

Figure 5- 5: Flow through an orifice

The continuity of incompressible fluid gives:

$$Q = A_1 V_1 = A_2 V_2 \quad \Rightarrow \quad V_1 = \left(\frac{D_2}{D_1}\right)^2 V_2 = \beta^2 V_2 \tag{5-15}$$

where β is the diameter ration between these points.

For the same elevation, an ideal flow rate through an orifice is deduced from equations (5-14) and (5-15) as:

$$Q_{ideal} = A_2 V_2 = A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}} \tag{5-16}$$

Actually, there is a certain head loss through the valve, which is difficult to quantify. The net result is that an empirical coefficient is used in the flow rate equation to account for the complex real world effect brought on by the nonzero viscosity. Thus, an orifice discharge coefficient C_d is used to take these effects into account when determining flow rate (Eq. (8.39)- reference [3]).

$$Q = C_d Q_{ideal} = C_d A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}} \qquad (5\text{-}17)$$

To verify the supposition that the flow rate is proportional with the open position of valve, or in other words, it is constant during fully opened time of the aspiration valve, the experiments were performed with the time of 100 and 500 milliseconds. In fact, there is certain difference because of material inertia, but this effect is negligible in these ranges of open time. The experiments were performed with different diameter orifices, different pressure drops, and the results are interpolated in Figure 5- 6.

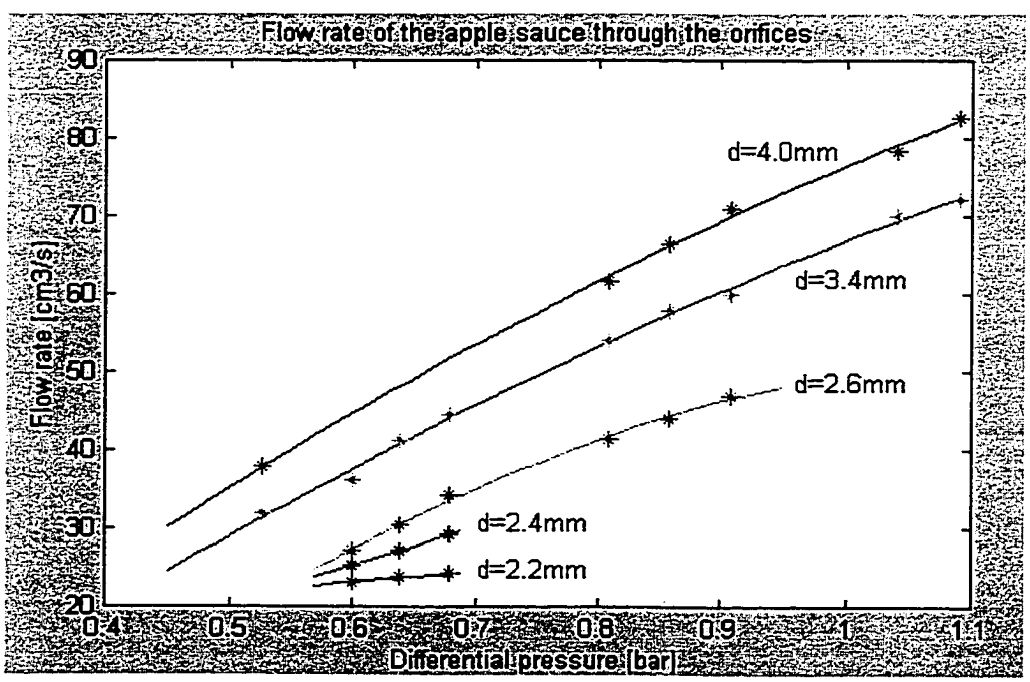

Figure 5- 6: Applesauce flow rate versus pressure drop through different orifices

From equation (5-17), the coefficient is computed from the obtained flow rate and applied differential pressure by:

$$C_d = \frac{Q}{A_2}\sqrt{\frac{\rho\left(1-\beta^4\right)}{2\left(p_1 - p_2\right)}} \tag{5-18}$$

and the obtained flow rate and coefficients are listed in table 5-1.

Table 5-1

Flow rate and discharged coefficient of apple sauce through orifice

Experimental flow rate [cm3/s] and orifice discharge coefficient					
Differential pressure [bar]	***Orifice diameter [mm]***				
	2.2	***2.4***	***2.6***	***3.4***	***4.0***
0.53				31.92 *0.3412*	37.83 *0.28*
0.60	23.16 *0.5738*	25.2 *0.523*	27.07 *0.4769*	36.23 *0.3627*	
0.64	23.7 *0.5685*	27.02 *0.5466*	30.36 *0.5178*	41.22 *0.3995*	
0.68	24.2 *0.5632*	29.31 *0.5714*	34.32 *0.5679*	44.54 *0.4188*	
0.81			41.46 *0.6294*	54.0 *0.4658*	61.56 *0.3776*
0.86			44.14 *0.6503*	57.95 *0.4851*	66.49 *0.3853*
0.91			46.91 *0.6718*	60.06 *0.4888*	71.0 *0.4*
1.04				69.9 *0.5316*	78.32 *0.4123*
1.09				72.15 *0.536*	82.59 *0.4247*

If the pressure drop increases, the flow speed (and consequently its Reynolds number) increases, and in this case, the coefficient is augmented (only the first column of orifice ∅2.2mm slowly decreases). If the diameter ratio increases, the coefficient decreases at the same flow rate (same Reynolds number). This corresponds with the property of the nozzle, whose geometry is similar to designed aspiration valve (figure 8.43 page 531- reference [3]).

The flow rate of apple sauce with the defect should be removed in one channel at the required flow rate of approximately 24 cm^3/s. Based on the flow rate of waste through an orifice and the pressure of flow (presented in previous chapter), the diameter of the orifice should be designed from 2.4 to 2.8mm, and optimal value of vacuum is in the interval from -0.3 to –0.4 bar accordingly. For simplicity in this case, we can interpolate the necessary value of flow rate, or consider 0.5 as the value of the discharge coefficient.

5.5 Reference Pictures

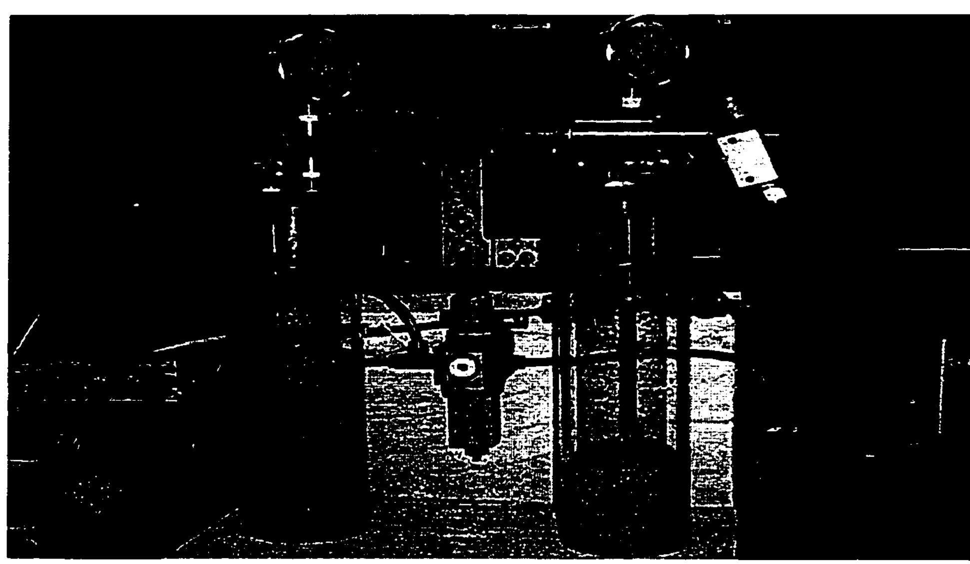

Figure 5- 7: Testing device for behavior of defect moving valve (flow rate, timing)

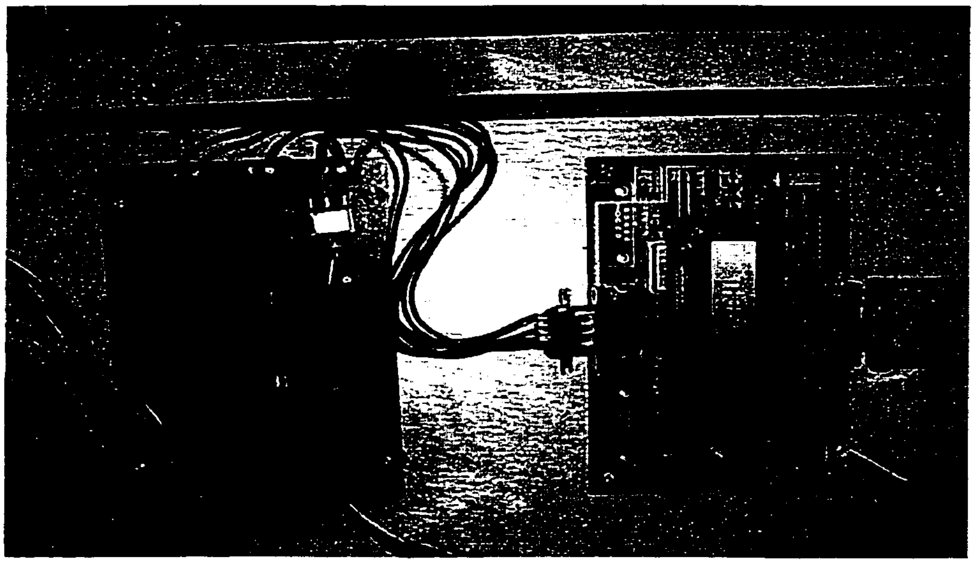

Figure 5- 8: Data acquisition card and drive board

CONCLUSION AND SUGGESTION

Summary

Machine vision systems have been developed to sort, check, separate and classify discrete products for several decades. They generally employ visual detection methods to deal with a difference in gray level (monochromatic method), color (polychromatic method) or image shape. This non-contact method of detection is suitable for high-speed production of variable objects, particularly in food production. Applications include sorting of coffee beans, fruits or removing black defects in rice, etc. Most of the machines and related articles concentrate on discrete or granular products.

Most recent vision machines systems employ CCD sensor technology integrated into the camera to capture and send image signals to a DSP controller (Digital Signal Processor), which is well suited to image processing applications but does not constitute a cheap solution.

In this study a machine vision system was developed to automate the process of removing defects from a flow of apple sauce. The designed system has the ability to fulfill the required productivity of 15 cubic meter per shift. The system development is achieved by the following steps:

- Realization of a two-camera system, which is not only used to improve the adaptive control capabilities of the machine, but also to add the self-test function to deal with variants in the product. The first camera detects defects and supplies the control signal to remove the defect. The second verifies whether or not the defect has been actually removed thus providing a measure of the process quality.

- Configuration of the control system based on FPGA and MCU technologies instead of a high cost DSP product. The high-speed processors perform in real time and result in a reliable control system. They not only control the machine operation, but also achieve redundancy and testing with the appropriate program.

- An experimental investigation of the behavior of apple sauce flow through a rectangular conduit. The experiments measured the moving time of flow passed a specified point and were useful in evaluating the flow profile. Despite the edges, the flow profile is nearly uniform which is an advantage in this application. The moving time of defects is a critical control parameter (see details in chapter 4).

- Investigation of the behavior of the aspiration valve as a function of the size of the orifice, vacuum pressure, etc. This data is crucial in optimizing the operation of the machine in order to minimize the waste. The measured response time (switch on, switch off) of the valve is independent of the material and can applied to other products. The orifice discharge coefficient for apple sauce was also identified and uses to design the orifice diameter in combination with the vacuum pressure. The details of the aspiration valve study and its behavior is presented in chapter 5.

The operating principle and design of the machine perform yield significant advantages but there are also limitations, which need to be addressed, as well as modifications to be made.

Advantages

The two vision modules are different in function, but exactly the same in construction. This effectively reduces the quantity of work and cost accordingly. The modularity of the design allows it to be used in a wide range of applications. The principle of operation is relatively independent of the nature of the inspected material.

Each image acquisition module was designed as an autonomous unit, allowing its integration into a more complex control system. This feature enables the application of several different types of industrial processes, such as removal of defective particles, statistical evaluation or quality control of products.

The two-camera system is not only employed for the adaptive control of defective particles removal but also for flow profile testing. Flow test is very important in applications involving a natural material. The self-tuning ability of the system also allows it to be used in a wider range of applications, using products with varying nature and texture.

Disadvantages

Since the camera is located on the opposite side of the light source, the opacity of the inspected media cannot exceed certain limits. The product quantity flowing through the system is directly related to the spacing between the two glass plates, which must be determined as a function of product opacity.

Although the pixel acquisition rate is quite high, the product speed cannot exceed certain limits (section 4.4.4). The faster the product flows, the smaller the margin of time for proper detection, and the lower the detection rate of actual particles flowing through the system.

The short distance separating the camera sensor from the glass plates does not allow a reasonable compromise to be reached between the focus at the center point and focus at the edge points. The die therefore cannot be very large, unless another solution is found, using lenses for example, in order to obtain a focus adjustment that will be suitable for viewing the entire range.

In order for the glass plate to resist the internal pressure of the die, a minimum thickness must be employed. This generates an error in lane width and position, since dioptric diffraction will create the illusion of the outer lanes being further than they really are. This will change the actual position and width of each lane in the pixel array of the camera sensor. Since the separation between each lane is performed by a counter, they are presently equidistance on the camera sensor. This also limits die width. The glass quality is also a topic of importance.

Conclusion

In conclusion, a system for eliminating the dark particles in apple sauce was developed with experimental parameters that are primarily based on meeting the required productivity of 15 cubic meters of apple sauce per single 8 hours shift. The testing principles employed and the devices developed resulted in a successful and viable system. This system can be used not only to produce high quality apple sauce but it is also applicable to other similar foodstuff products such as concentrated orange juice, salad sauce, etc. wherever color is one of the key parameters to classify the quality of the product.

Although tests were not carried out for a large number or a large range of inspected materials, the results from the various experiments prove that the system will operate and function well beyond expectations. A prototype of the machine is being manufactured at Intempco Control Ltd. in order to evaluate the procedures and the entire process. The machine will be available for shipment to the customer after it goes through a period of evaluation and adjustment and will surely provide satisfactory results.

In the designed system, the flat die width relates to the length of the light source and the camera field of view. The cost for a 14" light source is nearly doubles that of the 12". Consequently, the most convenient width for the flat die in this application would be 10". In this case, the problem of image resolution at the edges not longer exists and the number of aspiration valves can be reduced accordingly to 32 which necessitates only 2 drive boards for control. The width reduction requires a corresponding increase in flow speed, but this remains within the acceptable speed range.

Suggestion

The experiments on the prototype prove that the applied principles meet the functional requirement of detecting and eliminating dark particles from base material. The machine is object-oriented in design for the specified productivity. For a successful and convincing application of the project in industry, some modified are necessary:

- Improvements in some of the optical devices in the vision module including a macro lens for the camera to improve the focus and the length of the light source in relation to die width.

- Simplifying the aspiration actuator e.g. direct actuated solenoid coils instead of the pneumatic valves. This would lead to a reduction in cost and a more compact design.

- Speeding up the controller by replacing the MCU with a faster version which would be capable of managing more complex tasks to improve the intelligence of the system.

- Adding a defect injection module and modifying the program to achieve the flow profile test in the machine as a self-test function to better accommodate variations in the materials. The testing device used to measure the orifice discharge coefficient should also be modified to become an accompanying commercial device.

Although a lot of experiments are required to determine the necessary design data, more theoretical research would serve to consolidate the success of the project.

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ANNEX A

Introduction to control system

CONTROL SYSTEM

Conventional Control Devices:

The overall control system includes a central controller which manages most of the operational tasks. The overall control system is comprised of:

- The control panel which serves as an interface to the operator and which is used to control the operation of machine
- The camera boards whose function is to read, process the information from the cameras and output the lane number containing the defect to the controller
- The controller which communicates with the control panel, computer, drive boards and reads the inputs from the camera boards and flowmeter.
- The drive boards receive the command to activate the appropriate aspiration valve from the controller via an 8-bit bus
- The flowmeter measures the current flow rate and sends this information to the controller to create the look-up table of delay values
- The computer is used to capture data, display results or modify the control algorithm

The schematic layout of the control system is illustrated in Figure A-1. The control panel is designed with buttons, indicators, and a screen to indicate the current status of the machine and to allow the operator to control machine operations.

The camera board reads the pixel values from the camera and compares them with a set of preset values which define a defect. When a pixel value is smaller than the corresponding preset value, the board outputs the lane number containing the defect to the controller. The output of the camera board indicates the position of the defect at that time.

The flowmeter is located in line with the material flow and is used to measure the current flow rate of the material. The measured flowrate is displayed and transferred to the controller to create the look-up table which identifies the delay time to open and close the aspiration valves (see details in chapter 5). The accuracy of the flowmeter is the key to minimizing waste. It must therefore be properly specified.

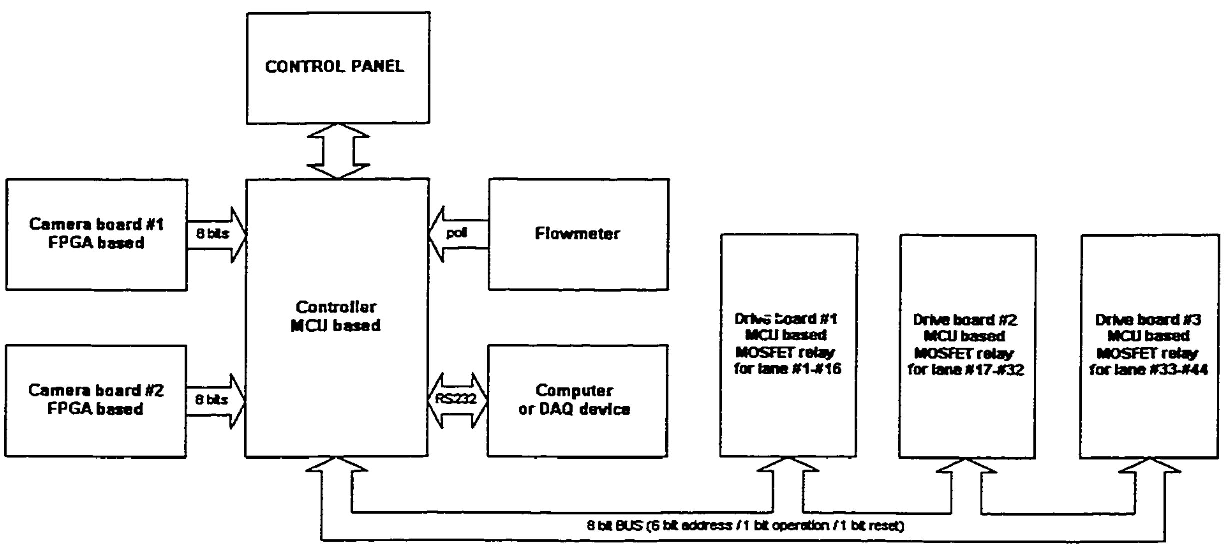

Figure A- 1: Schematic layout of overall control system

The computer or other peripheral device communicates with the controller via a serial port (RS232). This communication is very useful in testing the entire process, especially in terms of a self-test function.

The drive board is the device which receives the command from the controller via the common bus. It is used to activate the aspiration valve according to the lane number where the defect is detected via an electronic relay (MOSFET). The drive board is based on an MCU and is protected by opto-isolated transistors to sure that there is no damage caused by the power devices (solenoids).

The controller is an MCU based board which is used to create the look-up table from the flowmeter information. It also reads and compares the data from camera board #1 with the look-up table and sends the appropriate command to the drive boards via the parallel bus. The first 6 bits of the 8-bit bus are used to address the lane number (address of aspiration valve to activate). One bit is used to specify on/off and the last bit is the bus-reset bit generated by the drive board. The controller can be also programmed to operate as a data acquisition card as described in chapter 4. The self-test function of machine is an additional valuable function of the control system.

The controller also interfaces to the second camera board to obtain information regarding the non-removed defects. This information is not only displayed on the control panel screen, but also processed in the controller to self-adjust the appropriate control parameter if necessary. In this case, a higher speed MCU is required to accomplish the more complex task (for example, 10 MHz instead of a 1.79 MHz MCU). The specified program upgrades the system as an adaptive control system according to certain criterion, such as acceptable percentage of non-removed defects after processing.

Proposed Control System

In the above design, the MCU based controller realizes many functions including reading the two camera boards and the flowmeter, communicating with the PC and the control panel, processing the information, giving the command to the drive boards and managing 88 timers. This could seriously impede communication and may cause undesirable delays in the control sequence. In this case, the command to activate the valve is not real-time.

The FPGA camera board has the ability to solve this problem by integrating the function of reading the cameras, comparing preset values to determine whether a defect is present and directly sending the defect lane number to the drive boards to activate the valve as a real-time process. This is one of the reasons why FPGA are used in the control system of the project. The new concept of the control system is presented in Figure A-2.

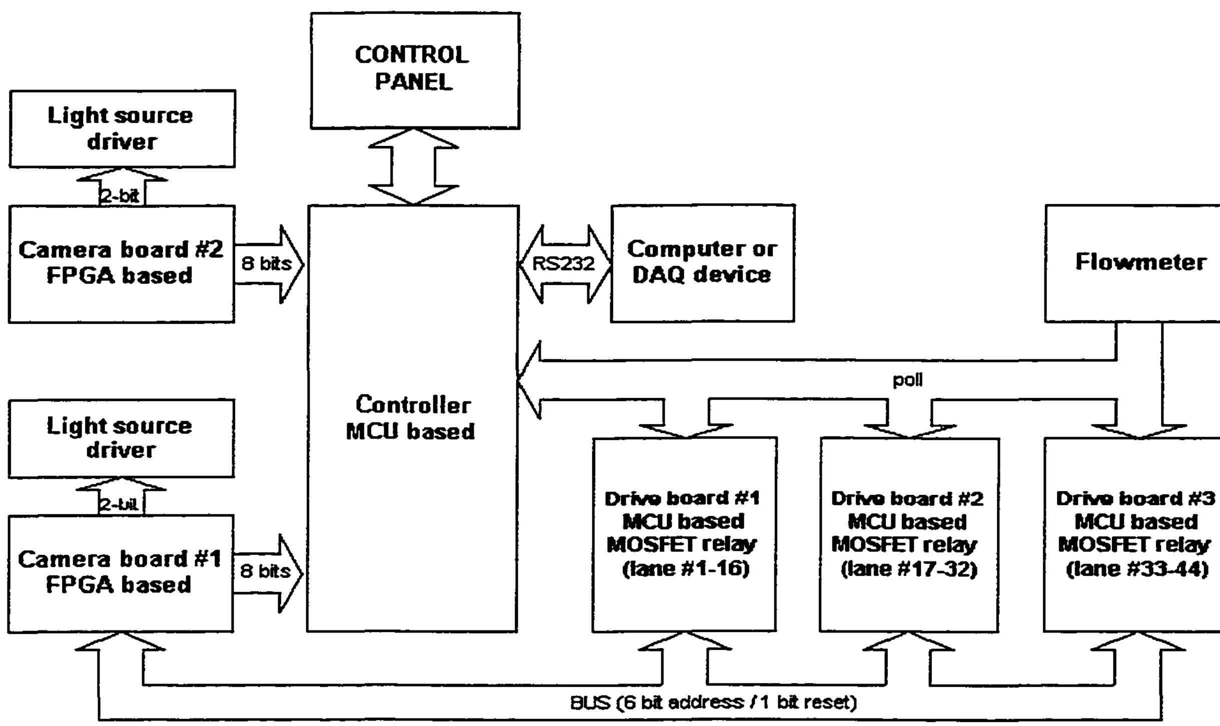

Figure A- 2: Concept of proposed control system

The FPGA camera board is designed to read the 8-bit pixel value from the camera and identify the lane number by means of a counter. The pixel value is compared with the supplemental constraints (according to the lane number as described in chapter 3) to determine the presence of a defect. If a defect is detected, the lane number information is sent via the bus to the drive board. This lane number is also sent to the controller for statistical purposes and data acquisition. The drive board sends a signal to reset the bus to prepare for the next operation after it receives the lane number information. The process of reading pixel values, comparing and outputing the defect lane number is achieved within the FPGA of the camera board. This is a real-time process.

The flowrate is transferred to all drive boards and is used to create the look-up table of aspiration times as per the description above. When the drive board receives the lane number information corresponding to a defect, it activates the valve accordingly to remove the defect. This means that each drive board only manages a maximum of 32 timers at the same time.

In this configuration, the controller only acquires the defect data from the camera boards to verify the process, transfers the data to the PC via the serial port and manages the communication with the operator control panel.

Response Time of Control Boards:

The camera board speed has to be high enough to read the data from the camera so as to ensure that there is no lost data. The camera board is based on a high speed FPGA (minimum 20 MHz to manage of 4096 pixels/line x 4800 lines/second), and the decisional tasks lasts only a small number of FPGA operation cycles (each only 0.05 microsecond). Consequently, the delay time of the process is negligible.

The information on the bus is immediately read by an interrupt of the MCU. If the MCU with clock of 1.79 MHz is employed in this application, the loop operation code in the drive board lasts about 300 clock cycles. The response time of the drive board MCU in this case is about 0.15 millisecond. By employing a high speed MCU, the response time of the boards can be improved significantly. For example, the response time is only about 0.03ms with 20 MHz MCU.

In the chain of electronic delay time, another considerable value is the response time of the electronic relay, which consists of an opto-isolator and a MOSFET in series.

The selected photo-transistor ECG3044 has maximum delay time of 13μs (microsecond). The MOSFET ECG66 has maximum delay time of 0.2μs.

In total, the response time of the overall control system is very small and negligible in compare with the mechanical behavior of the aspiration valves. The proposed control system minimizes the risk of interruptions in the control sequence.

Regulation Board for Light Source:

The control algorithm to regulate the illumination is described in chapter 3. Besides reading and sending the lane number of the detected defect, the camera board can also count the number of saturated pixels and sends it to the illumination regulation board which samples and compares the data with preset values. In this case, a complex regulation board with a 12-bit bus from FPGA camera board is required. The problem can be simplified by integrating this function into the FPGA camera board.

In the FPGA, a compare and counter module is integrated to meet this require. If the read pixel is saturated (its value is 255, or 11111111_2), the counter is incremented by one. At the end of the line scan process, if the counter value exceeds the preset value (optimum percentage of saturation), an output is switched on to decrease the light intensity by the light source regulator. In the opposite case, the output corresponding to increasing the light intensity is switched on when the counter value is smaller than an acceptable value. Consequently, the illumination intensity is appropriately adjusted to match the opacity of the material flow at the scan speed. The high operating speed will yield good results in terms of light source adaptability. The schematic layout of this system is also presented in Figure A-2. The light source regulator is a driver with 2 input bits corresponding to the intensity increase and decrease outputs from the FPGA camera board.