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Laser based inspection and path correction system for automatic sewing apparatus

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Abstract

This paper describes a laser triangulation inspection system which has been integrated into an automatic stitching machine used to stitch overlapping components. The inspection task locates defects that can occur prior to and during the stitching process so that the stitch path can be modified accordingly. The three-dimensional shape of the surface and component edge positions are extracted through the analysis of the laser line images captured by a high frame rate camera. Different stages of the data collection aspect of the inspection process are presented. These include calibration and laser line image processing techniques. The data modelling of the extracted edge points is based on least-square polynomial regression and parametric curve approximation. The obtained data model is used for stitch path planning. These techniques were tested on an automatic stitching machine.

1 Introduction

Computer controlled automatic stitching machines are widely used to stitch along the edge of overlapping leather and textile parts. The conventional method is to sew materials along a path determined by a sewing program without the use of edge position feedback. However leather and textiles are flexible materials which can change their size and position before and during sewing. Consequently, it is possible for the predetermined sewing path not to match the actual path required and the finished work piece has to be rejected on quality grounds.

The conventional "open-loop" approach to automatic stitching requires that the sewn pieces have to be firmly held in position by a workholder called a pallet. Pallets aim to avoid material movement but can not deal with other factors which cause edge position changes in the sewing process. These include material distortion, such as leather shrinkage, badly cut material pieces and pieces which have been poorly loaded into the pallet. A further problem is that to achieve a high throughput high stitching speeds are required and this increases the likelihood of material slippage in the pallet.

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New inspection systems are needed to aid the guidance of leather components such that the sewing path can be modified if any of the problems outlined above occur. Vision systems which can provide 2D and 3D information have been investigated for the handling of limp materials such as leather [1, 2]. Traditional edge segmentation methods which work by detecting a step change of luminance between different regions of an image are not suited to the inspection of overlapping leather components which are of the same colour and have little or no contrast change.

Although the materials commonly sewn in the shoe and garment making industries have a wide variety of colours, textures and thickness, when two or more such materials overlap topological features are always present. Laser triangulation is a technique used to extract topological features from surfaces [1]. This paper is concentrated on the application of laser triangulation inspection methods and processing algorithms in multi-directional sewing including calibration.

The challenge of applying laser inspection methods to multi-directional sewing is that of obtaining high spatial resolution combined with high speed with materials which are flexible and have different reflectivity. High spatial resolution is required for the inspection of localised defects on leather components such as notches or small perforations. High speed is a required in order to keep the time overhead to a minimum.

The system discussed in this paper can be used for extraction of topological features of overlapping components. Calibration of a camera and laser model is required prior to the inspection task in order to accurately calculate the positions of observed surface topological features. Furthermore, optical settings of the camera lens (aperture level and focusing distance) are calculated using the projected laser line.

2 System Overview

The simplified mechanical system configuration is shown in Figure 1. It comprises the following components :

1. X/Y table
2. Inspected component
3. X and Y servo motors
4. Line generating laser diode
5. State-of-the-art high frame rate camera

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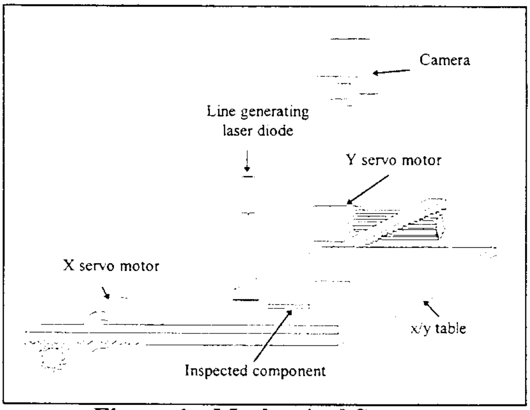

Figure 1 : Mechanical System

Components are moved along a pre-programmed path such that the material edge to be inspected is presented to the field of view of the camera. The principle of laser triangulation can be used to extract edge points from overlapping materials. Laser projection can also be used for gap measurement in situations where two edges are butted against one another. The features of the inspection system are :

1. Camera model calibration using calibration grid
2. Automatic focusing and optimal aperture setting using the projected laser line
3. Novel algorithms for real-time image segmentation, laser line thinning and edge extraction
4. Arrangement to overcome the problem which arises when the edge orientation is same as that of the laser line
5. Mathematical modelling of the inspected surface topological features (e.g. edges)
6. Stitch line correction using a derived mathematical model.

It is necessary to employ parallel and distributed processing techniques to facilitate the computations required for the real-time inspection and path correction tasks [3]. The block diagram of the hardware components are shown in Figure 2. The choice of the high frame rate digital camera was dictated by the speed and spatial resolution requirements and allows, in general, one edge point to be extracted from one camera frame. In addition, the high frame rate camera eliminates the need for high speed strobe lights to freeze motion.

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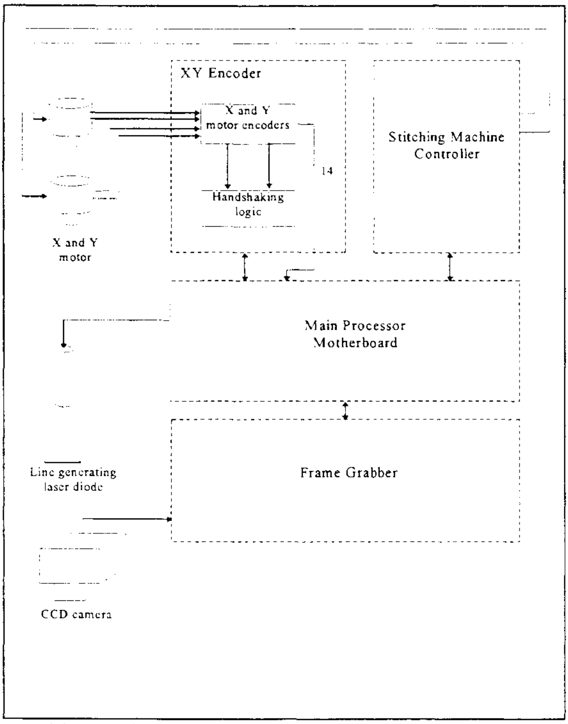

Figure 2 : Block diagram of the hardware

3. Inspection system calibration

Calibration of the inspection system can be divided into two stages :
1. *Camera model derivation* for mapping the image co-ordinates to the real world co-ordinates;
2. *Focusing distance and aperture level adjustment* using the laser line image.

3.1 Camera model calibration

The grey level images of the laser line are captured by the camera and digitally processed. The information extracted from the laser line images can be further processed to obtain specific object features such as surface discontinuity positions and curvature. To obtain the real representation of the measured features of an object a transformation from the image to the real-world co-ordinate system has to be performed. This transformation is based on a camera model [4] and incorporates the camera geometrical and optical parameters. The camera model defines a 3D point projection onto a 2D camera image sensor and incorporates a number of parameters. These parameters are divided into two main groups : extrinsic and intrinsic parameters. Extrinsic parameters define the geometrical position and rotation of the camera whereas intrinsic parameters define the internal camera optical and geometrical characteristics. In order to obtain an accurate camera model it is necessary to calculate these parameters. Normally, it is not very convenient to measure these parameters directly and therefore they are determined indirectly by following a calibration procedure. The calibration procedure involves viewing a calibration grid plate from which all camera parameters can be calculated. Different methods can be applied in the calculation of the intrinsic and extrinsic parameters which involve full-scale or partial non-linear minimisation, perspective transformation or geometric method [4].

3.2 Focusing distance and aperture level settings

Lens calibration is performed by viewing the projected laser line. This calibration stage is used to set the focusing distance and optimum aperture level. It is based on analysing the brightness and sharpness of the viewed laser line using a mathematical model of the laser line cross-section. This method relies on the fact that every observed laser line cross-section can be mathematically modelled using a template function dependant on a number of parameters. By changing these parameters the template function can be made to accurately fit the laser line cross-section. A number of laser line cross-sections are used to derive sharpness and brightness at a particular focusing distance. The focusing distance and aperture level then can be iteratively changed until the best sharpness and optimum brightness are achieved. The type of the template function used for laser line cross-section mathematical modelling depends on a number of factors such as the light distribution of the laser line source, the type of the line generating lens and the geometric position of the camera and the laser source. For example the cross-section of a Gaussian laser source can be modelled using the following template function (see Figure 3):

$$f_o = \begin{cases} A\exp\left(-\left(\dfrac{x-\mu}{\delta}\right)^2\right) + \mathit{offset} & \mathit{for}\ x < \mu \\ A\exp\left(-\left(\dfrac{x-\mu}{\delta\cos(\alpha)}\right)^2\right) + \mathit{offset} & \mathit{for}\ x \geq \mu \end{cases}$$

where the cross-section parameters are :
α - camera pitch angle (i.e. angle of the camera with respect to the x/y plane)
x - pixel co-ordinate
μ - Gaussian peak position
δ - standard deviation (measure of the width of the cross-section)
A - measure of the maximum brightness and
offset - level of the background light intensity

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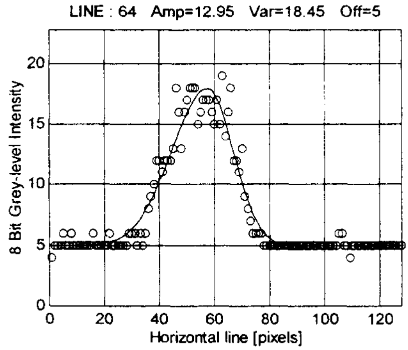

Figure 3 : Gaussian laser line template

4. Laser edge profiling

The principle of laser line triangulation involves projecting one or more laser lines on a surface which can be viewed using an area camera (see Figure 4). The camera is mounted at an appropriate angle to allow inspection of a desired range of material thickness. When an edge is placed in the field of view of the camera each laser line appears to be discontinuous, with the shape of the line being dependent on the characteristic of the edge profile (see Figure 5). Consequently, the laser triangulation method can be used to inspect surface feature characteristic for the shoe industry (e.g. edges, holes and gaps) [5,10].

The surface point of interest (Figure 4) corresponds to the image point marked as a cross in Figure 5. The real positions of the inspected surface feature can be obtained by using the camera model and mathematical model of the laser line. The position of the surface point of interest can be derived by calculating the intersection point between the laser line plane and the image point projection line derived from the camera model (see Figure 6).

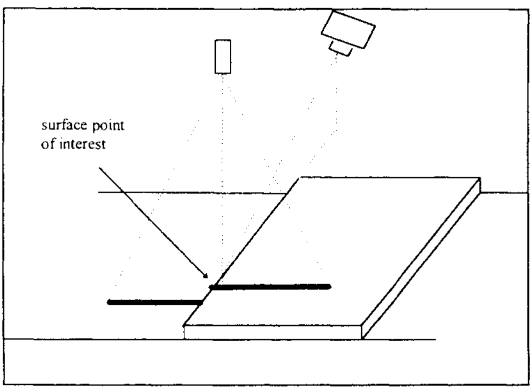

Figure 4 : Horizontal laser line switched on

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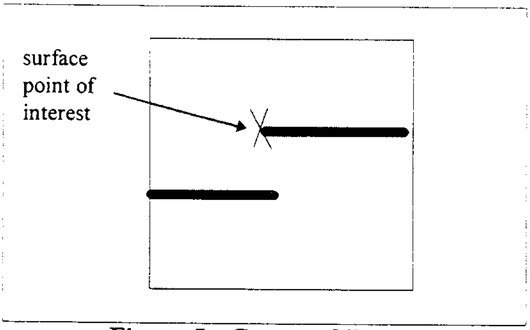

Figure 5 : Captured Image

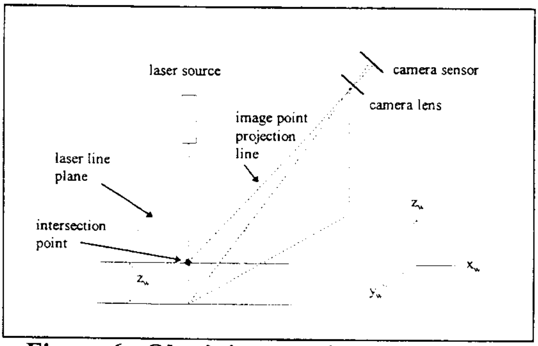

Figure 6 : Obtaining a real world position

In order to obtain the position of the image point from Figure 5 it is necessary to apply the following image processing techniques :

1. Image segmentation
2. Laser line thinning
3. Edge point extraction

4.1 Image segmentation

The captured grey-level camera image consists of a laser line contrasted against a surface background. Segmentation [6] is required to separate the laser line from the background.

The background contribution to the Grey level histogram of a surface is dependent on material characteristics such as colour, reflectivity and surface finish. In general, the histogram shape is dominated by a broad background peak. Pixels of the laser are distributed at the white end of the grey scale and have a small influence on the shape of the dominant background contribution. When the laser line is contrasted against two different materials which overlap the histogram has a complex structure.

The threshold segmentation of the laser line from the background is a non-trivial problem. The grey level histogram is not bimodal or multimodal and therefore the laser line can not be easily separated from the background using shape analysis of the histogram itself. In addition, thresholding has to be done in real time.

Two approaches to the thresholding problem have been devised and investigated. The first method is used to calculate a global threshold value and it is based on analysing the continuity and thickness of the laser line. The second method is used to calculate a number of local threshold values so that the variable surface reflectivity within the camera field of view can be compensated.

A global threshold value calculation is based on the observation that as the threshold value is increased to the white end of the grey scale the laser line thickness decreases and the line begins to break-up as a number of empty vertical gaps appear in the laser line. The laser line parameters, mean thickness (t) and number of vertical gaps (N_g) can be used to optimise the threshold level using an iterative procedure.

The change in threshold, ΔT, is calculated using :

$$\Delta T = K_t\, t - K_g\, N_g$$

where K_t and K_g are scaling factors for the thickness and vertical gap parameters. The threshold value is updated using an variable step size technique. An initial threshold level T is selected such as the mid-value (e.g. T = 128 for pixels represented by 8-bits). A step size increment is calculated as T/2. The sign to determine whether the threshold value should be raised or lowered is determined from ΔT. The threshold level is calculated by iterating the pseudocode:

```
STEP = T/2
SIGN = ΔT/ |ΔT|
T = T + SIGN STEP
```

with a new step size and sign calculated on each iteration. The threshold level calculation finishes when the step size is unity. For an initial threshold value of 128 seven (e.g. $\log_2 2^7$) step iterations are needed.

In the second approach the local threshold values are calculated for a number of observed laser line cross-sections. The number of calculated local thresholds depends on the spatial frequency of the surface reflectivity change. The local threshold (i.e. the threshold value used for the laser line between two analysed cross-sections) is calculated using spatial histograms. The local threshold in this case represents the background intensity level. Since the width of the laser line is small compared to the vertical field of view, the background intensity is taken as the position of the maximum in the spatial histogram.

Both these approaches to calculating the threshold level can be implemented in real-time. In the first method, the choice of scaling factors is very important as the threshold level and therefore the laser line quality is directly dependant on them. The advantage of this approach is that the global threshold can be used until the surface reflection properties change. The local thresholds need to be calculated for every captured image as the position of the surface discontinuity within the camera field of view is not predictable.

4.2 Laser Line Thinning

Once the laser line has been separated from the background using thresholding it is thinned to a single pixel width. Two approaches have been investigated. The first is simply to find the mean value of the laser line width at each point across the frame. Because the laser line is not smooth the resulting pixels vary spatially around the centre line of the laser. The spatial variations of the pixels around a centre line can be considered as noise.

A second approach is to calculate the centre of gravity for each laser line cross-section. The positions of the calculated centroids of each of the cross-sections form a thinned laser line. This method provides better results than the mean approach but it is computationally more expensive.

4.3 Edge Extraction

Edge extraction is required to transform a frame which has undergone thresholding and line thinning into an edge point. The input binary image can contain single pixel width line noise. To find an edge point requires searching for a discontinuity in the laser line ignoring noise. Partially occluded lines are dealt with by ensuring that the segment of the laser line in the highest z-plane always falls within the field of view of the camera.

Three approaches have been investigated which are based on the following methods;

(i) Spatial pixel histogram
(ii) Hough transform
(iii) Polynomial regression

The first approach involves calculating the discrete spatial pixel histogram. This represents a plot of the number of pixels in each horizontal line of the binary image against line number (i.e. y position). The histogram is either bimodal or multimodal with each peak representing a line segment. Lines through the peak maxima are projected and an edge point is calculated as the end point of the laser segment in the highest z-plane. This method relies on the a priory knowledge of the orientation of the laser line.

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The Hough transform [6,7] can be used to detect straight lines in a frame. The advantage of this approach is that edge extraction is not too sensitive to imperfect data or noise and no prior knowledge of line rotation or region position is required. To overcome the difficulties of vertical line detection a parametric form of the Hough transform method has been implemented. The parametric equation used to represent a laser line is :

$$r_0 = x\cos\theta + y\sin\theta$$

where r_0 and θ are the parametric parameters. The basic idea of the method is that a noisy or approximately straight line is transformed into a cluster of points in parameter (r_0,θ) space (also called accumulator space). The centre of gravity of the cluster can be considered as the straight line representation. Detecting the local maxima in parameter space can be achieved with an algorithm which tracks maximum values as the accumulator is updated. The computational complexity of the Hough transform means that a distributed processing system is required for real-time implementation.

The third approach investigated for edge extraction is that of polynomial regression. A second order polynomial is regressed through pixel values which represent the laser line until a calculated error exceeds a pre-specified limit. This point represents a boundary discontinuity the cause of which can be either an edge or a noise variation. If the regressed segment is very short the discontinuity is considered as noise and ignored. The process is repeated until the last point in the image is reached and all boundary positions are found. Polynomial segments representing the laser line are joined at the calculated boundary positions. The first derivative at each boundary is evaluated and its sign can be used to distinguish between either a rising or falling edge.

4.4 Butted edges

Laser line projection can also be used for detecting any deviation of a material edge butted against a pallet border. With-out a material piece inserted, the pallet border edge is scanned and treated as a reference line data set. With a material piece inserted, edge points which deviate from the pallet border are measured.

In the ideal case, the camera observes two segments in the same z-plane on the right and left parts of the gap and a discontinuity segment which falls in the gap itself. This results in a spatial histogram (i.e. a plot of the number of pixels in each horizontal line of the binary image against line number) having two peaks. If the pallet and leather component are not at the same height but the gap segment is still observed the spatial histogram has three peaks.

The laser line component which falls in the gap can be occluded from the camera by the pallet border or the edge itself depending on how the gap is orientated relative to the camera. With the pallet and leather at the same height a spatial histogram which has one peak results in this case. In the situation, where the two laser lines falling on the left and right sides of the gap are not in the same z-plane and the gap segment is occluded a spatial histogram having two peaks results. The two peaks have a different spacing to those obtained in the ideal case.

The algorithm to calculate an edge deviation point due to a gap analyses the shape of the spatial histogram to determine which of the situations described above occurs. This information is used to identify the position of the gap.

Two data sets are collected using this method. The first is a fully complete data set representing the boarder of the pallet edge. The second is a sparse data set representing any deviation of the material edge from the pallet boarder edge. Both sets have the same position dependence and can therefore be fused together. This is achieved by replacing reference pallet line data with edge deviation data at defected positions.

5. Accuracy and Repeatability of the Inspection System

The algorithms used to extract the edge data points have been tested for accuracy and repeatability. One of the tests involved scanning a standard in the form a circle with a radius variation which was smaller than the resolution of the inspection system.

An accuracy test was performed based on the Hough transform. The Hough transform was employed to locate the circle shape in a scanned set of edge data (see Figure 7) and calculate its radius and centre point. An absolute radius error at each position around the circle was calculated as the difference between the measure radius at that angle and the calculated Hough radius. The results are shown in Figure 8. Using this approach it was found that the maximum radius error in the circle was 0.27mm. A scanned set of data consisted of approximately 4500 edge points which represents a resolution of 0.054mm and an x-y table speed of 40mm/s. This test was repeated 50 times and the standard deviation of the centre point was found to be less than 0.03mm.

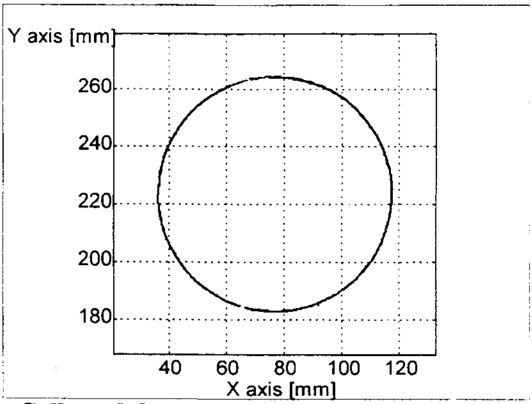

Figure 7 : Collected data points from scan of the circle standard

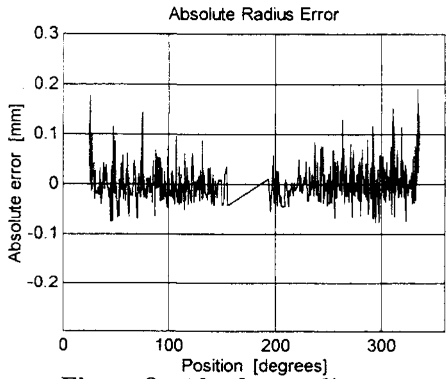

Figure 8 : Absolute radius error

6. 3D Measurements

The sewing process requires point to point movements of the material workpiece. This is because to maintain stitch quality in materials such as leather, the work piece must remain stationary for 50% or so of the cycle for which the needle penetrates it. The dwell time represents the time the needle spends in the leather piece before it is moved to the next position and is directly related to material thickness.

Figure 9 shows a 3D representation of a leather piece obtained using the triangulation technique. 3D information can be used during the sewing cycle for the dynamic control of dwell time and x-y table speed.

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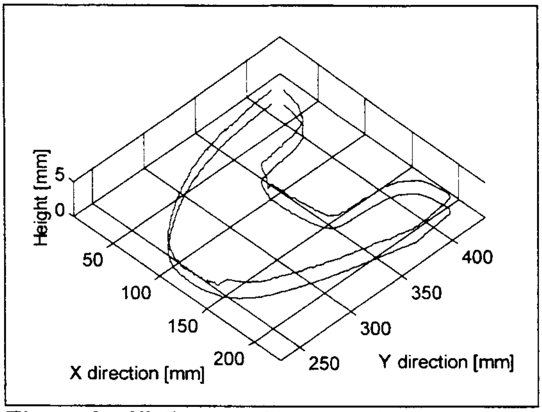

Figure 9 : 3D Image of inspected leather piece

7. Stitch Path Correction

Different methods have been investigated for stitch path correction using scanned edge point data sets of various path outlines. The most common path outlines in shoe manufacturing are obtained from either continuous edge lines or gimped (e.g. sawtooth) edge lines. In each case, the data sets collected from the inspection system are noisy and can also be sparse due to changes in the x-y table speed.

The main steps for stitch path correction are the:

(i) smoothing of the scanned edge point data
(ii) calculation of a line parallel to the edge
(iii) stitch assignment on the parallel line such that the number of stitches per unit length remains constant between start and end locations called corner points.

The basic approach to smoothing the edge point data is that of calculating the edge line using piecewise cubic least squares regression [8]. To overcome the problem of vertical line detection (e.g. large gradients) the Cartesian axis set are flipped by 90 degrees according to the value of the line gradient angle. The regression equations are therefore

$$y = a + bx + cx^2 + dx^3$$

for the x-y plane and

$$x = A + By + Cy^2 + Dy^3$$

for the y-x plane.

Each cubic polynomial is regressed through edge points until the standard error of the estimate around the regression line exceeds a pre-specified limit. For the x-y plane the standard error is given by

$$error = \frac{1}{N-(order+1)} \Sigma_{i=0}^{N-1}\left(y_p(i) - y_o(i)\right)^2$$

where $y_p(i)$ and $y_o(i)$ represent a polynomial value and a data value at point i respectively. N is the number of points and order is the order of the polynomial fit (e.g. 3). For the y-x plane $y_p(i)$ is replaced with $x_p(i)$ and $y_o(i)$ is replaced with $x_o(i)$.

This piecewise approach divides the edge line in to a set of segment polynomials. The length of each polynomial segment varies so that the criteria of minimal error is satisfied. To overcome the problem of boundary discontinuity in the first derivative polynomial segment curves are overlapped.

The regression through the data points represents a pre-filter stage. By optimising the pre-set limit for the standard error of the estimate for the line it is possible to obtain a reasonably smooth curve. However, discontinuities at the curve segment boundaries still exist. Consequently, a second smoothing stage is used based on Hermite interpolation.

A parametric form of the Hermite interpolation [9] is used to smooth the line curve defined by the regressed polynomial segments. The parametric cubic spline equations used for the interpolation have the form:

$$x(t) = a_{0x} + a_{1x}t + a_{2x}t^2 + a_{3x}t^3$$
$$y(t) = a_{0y} + a_{1y}t + a_{2y}t^2 + a_{3y}t^3$$

where the parameter t takes the values zero to one in each segment

$$t \in [0,1]$$

The method used for selecting the data points from the polynomial segments is based on calculating the integral of the absolute value of the second derivative.

$$I = \int_0^L abs(f''(t))$$

where L is the length of the segment and

$$f(t) = (x(t), y(t))$$

The second derivative represents curvature and the integral I is used to select the length of segment that the parametric curve successfully describes.

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Once the raw edge data points have been smoothed to a line defined by a parametric equation a line parallel to the edge contour can be calculated. Stitches are assigned to the parallel path. Two approaches can be used for calculating the parallel line. The first is based on a linear approximation between data points on the smoothed edge contour line. The second method uses the line equation of the edge contour.

A linear approximation between line points is valid if the resolution of the smoothed data points describing the edge contour is less than or equal to the resolution of the stitch points. The parallel line is obtained by deriving for each pair of points the line normal to a linear segment joining the two data points. The parallel path is routed through equi-distant points on the normal lines. Computational speed can be increased by calculating the bi-sector line between three points and using a set of bi-sector lines for routing the parallel path.

The second method which can be used for calculating the parallel line requires finding the tangent at points along the parametrically defined curve. Lines perpendicular to the tangents (i.e. normal lines) are used to route the parallel path at a fixed distance from the edge line. The result of calculating a parallel line from a scanned continuous material edge in a leather upper is shown in Figure 10.

Stitch path correction to a complicated edge forms present in shoe industry is a particularly difficult problem.

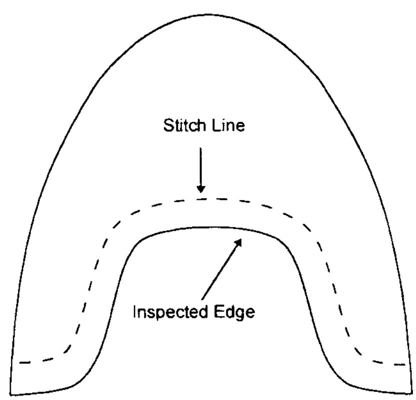

Figure 10 : Calculated stitch line

8. Conclusion

This paper presents a laser-based inspection and path correction system for microprocessor controlled sewing apparatus. Techniques have been developed for laser-based camera calibration, and high speed, high spatial resolution edge detection of flexible components which can be different in colour and texture. Algorithms for thresholding, laser line thinning and edge extraction for achieving good results in real-time have been discussed. Path correction methods have been developed which are based on the collected edge data. The ideas developed as the result of research work into the laser-based inspection system have lead to international patent application [5].

Acknowledgement

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