ABSTRACT

GÜNAY, MELİH. Characterization and Quantification of Woven Fabric Irregularities using 2-D Anisotropy Measures. (Under the direction of Dr. Warren J. Jasper and Dr. Moon W. Suh.)

It is a well known fact that the quality of a fabric is tied to the non-uniformity of fabric properties. Although methods have been suggested to measure certain physical properties of woven or knit fabrics (mass, handle, strength, comfort, permeability), there has been no single method that is industrially accepted to characterize and quantify distribution of some of these fabric properties or non-uniformities. Therefore, the purpose of this research was to investigate and suggest a new method to fill this need. During this research, data about fabric properties were obtained either directly from images of fabric appearances or indirectly from on-line measurements of yarn diameters. The yarn diameters captured through a line-scan camera were mapped into a 2-D fabric matrix by assigning each point of the yarn to a specific location (x, y) within the 2-D fabric matrix. The gray-scale image of a 2-D fabric matrix was called a virtual fabric and provided the basic information on the uniformity of the fabric property. Variance-area curves were developed to characterize and quantify non-uniformity of actual and virtual fabrics in two dimensions. Certain irregularity features such as vertical and horizontal streaks and random cloudiness produced variance-area curves that are dependent on the shape of the unit area. Thus the difference between these curves became a new way to measure isotropy features of fabric properties. Theoretical relationships between yarns and their virtual fabrics were derived using only the internal correlation information of the given underlying yarns.
Dedication

This thesis is dedicated to my mom Nuray, my dad Hilmi, and my sister Anil Günay.
Biography

Born in Turkey, Melih Günay received a BS in Textile Engineering from Istanbul Technical University in 1997. His interests in automation and computer controlled systems motivated him to pursue graduate education in the field of computers. In 1998, he was awarded a scholarship to continue his studies in the US at North Carolina State University where he earned a Master’s degree in Computer Science. In 1999 and 2000, he worked with Dr. Warren Jasper and Dr. Moon Suh on an NTC funded project that developed an online yarn characterization system. Upon graduation in 2000, he was employed by a software company where he worked until January 2003. With the encouragement of Drs. Jasper and Suh, he became a Ph.D. student in Fiber and Polymer Science at NC State University in July 2003. He is currently the author or the co-author of one book, five conference papers, and two journal articles.
Acknowledgements

I would like to express my sincere appreciation to Dr. Warren Jasper and Dr. Moon Suh, co-chairmen of my advisory committee, for encouraging me to join them in their research and pursue my Ph.D. Their motivation, guidance, and financial support was invaluable at all stages of this research.

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I am indebted to Dr. Demir who has provided me the inspiration and guidance to do my best throughout my career.

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# Table of Contents

List of Tables vii  
List of Figures viii  
List of Symbols xi  
List of Nomenclature xii  
List of Abbreviations xiii  

1 Introduction 1  

2 Review of Literature 4  
2.1 Yarn irregularity and analysis 4  
2.1.1 Sources of yarn irregularity 5  
2.1.2 Analysis of yarn irregularity 11  
2.1.3 Mass, diameter and twist relationships of yarns 21  
2.1.4 Instruments for yarn irregularity measurement 28  
2.1.5 Wavelet-stochastic hybrid model for yarn diameter simulation 34  
2.2 Fabric appearance and irregularity 35  
2.2.1 The analysis of fabric appearance and uniformity 38  
2.2.2 Fabric visualization systems 43  
2.2.3 Anisotropy of 2-D texture images 44  
2.3 Summary of relevant literature review 44  

3 Methodology for this research 48  
3.1 Approach 49  

4 Instrumentation and Experimental Setup 50  
4.1 Yarn Data Acquisition System 50  
4.1.1 Hardware components 52  
4.1.2 Configuration of the measurement system components 55  
4.1.3 Software design for real-time yarn measurement system 60  
4.1.4 Line and area scan images of various yarns and considerations 67  
4.2 Yarn to fabric mapping 69
5 Analysis of Spun Yarn Structure and Generation of Diameter Data 73
5.1 Analysis of yarn cross-section ................................. 74
  5.1.1 Effect of elliptic yarn cross-section on the measurement of actual diameter from projected diameter .......... 76
  5.1.2 Experimental setup to measure the eccentricity of yarn cross-section ........................................ 78
  5.1.3 Measurement of yarn cross-section eccentricity .............. 79
  5.1.4 Rotation of major and minor axes with twist .......... 79
  5.1.5 Relationship between twist, eccentricity and yarn cross-section 83
5.2 Generation of yarn diameter data ................................ 86
5.3 Summary and conclusions ........................................ 89

6 Characterization and Quantification of Woven Fabric Non-uniformities 92
6.1 The variance-length curves and its derivation ............... 93
  6.1.1 Using correlation-length relation of a yarn to obtain B(L) curve ............................................. 95
6.2 Analysis of fabric irregularity using surface area function ........ 97
  6.2.1 Methods for creating variance-between-area, CB(A), curves . 99
  6.2.2 Existence of anisotropy and detection through CB(A) curves . 102
  6.2.3 Quantification of anisotropy ................................ 104
  6.2.4 Justification of anisotropy .................................. 104
6.3 CB(A) curves as a function of correlation for woven fabrics ...... 106
  6.3.1 The relationship between the CB(A) curves of fabrics and B(L) curves of yarns ......................... 106
  6.3.2 The relationship between the CB(A) curves of fabrics and correlogram of yarns .......................... 110
6.4 Relationship between irregularity features and CB(A) curves ...... 116
  6.4.1 Random and evenly distributed large size fabric irregularities: 117
  6.4.2 Periodic irregularities visible in one or more directions: .... 118

7 Conclusions 122
7.1 Contribution of this research ....................................... 123
7.2 Future work .......................................................... 124

List of References 125

A The Data of CB(A) Curve Sets 133
  A.1 The data of actual CB(A) curves shown in Figure 6.15 ........ 133
  A.2 The data of estimated CB(A) curves shown in Figure 6.16 .... 134
  A.3 The data of actual CB(A) curves shown in Figure 6.19 .......... 134
  A.4 The data of estimated CB(A) curves shown in Figure 6.22 .... 135

B Graphical User Interface 136
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Comparison of yarn irregularity measurement systems</td>
<td>31</td>
</tr>
<tr>
<td>4.1</td>
<td>Basic information of actual yarn samples</td>
<td>69</td>
</tr>
<tr>
<td>6.1</td>
<td>Agreement of relative order statistics for CB(A) curves shown in Figures 6.15 and 6.16</td>
<td>111</td>
</tr>
<tr>
<td>6.2</td>
<td>Goodness of fit statistics for CB(A) curves shown in Figures 6.15 and 6.16</td>
<td>112</td>
</tr>
<tr>
<td>6.3</td>
<td>Agreement of relative order statistics for CB(A) curves shown in Figures 6.19 and 6.22</td>
<td>114</td>
</tr>
<tr>
<td>6.4</td>
<td>Goodness of fit statistics for CB(A) curves shown in Figures 6.19 and 6.22</td>
<td>115</td>
</tr>
</tbody>
</table>
# List of Figures

2.1 Spectrogram of a yarn [26] .............................................. 15
2.2 Damped correlogram .................................................. 16
2.3 Undamped correlogram ................................................. 16
2.4 General shapes of V(L) and B(L) ................................. 18
2.5 Twist triangle .......................................................... 21
2.6 Yarn fiber in cylindrical coordinates ............................... 22
2.7 Shape Error Factor (SEF) ............................................. 23
2.8 Emitted light for a yarn with irregular cross-section ......... 28
2.9 Projected yarn diameter using single camera .................. 29
2.10 Projected yarn diameter using two cameras .................. 30
2.11 Zweigle G-580 yarn evenness tester .......................... 32
2.12 Yarn evenness testing with Fresnel Principle [40] ......... 33
2.13 Appearance of some fabric defects [52] ......................... 37
2.14 Influence of wavelength on visibility [52] .................... 37
2.15 CB(L) and CB(A) of a fabric [67] ............................... 41
2.16 Mapping of yarn signal into a woven fabric .................. 45
2.17 Mapping of yarn signal for another woven fabric ........... 45

4.1 Measurement system setup for simultaneous diameter and mass measurement. .............................................. 52
4.2 Lawson-Hemphill CTT ................................................. 53
4.3 Makeshift jig [Thanks to Nonwovens Research Center, NCSU for providing this instrument.] ...................................... 55
4.4 Camera configuration CommCamm for 1024 resolution and free mode ......................................................... 56
4.5 Yarn profile with light meter set to 2.0 ......................... 58
4.6 Yarn profile with light intensity set to 7.0 ..................... 59
4.7 Yarn profile with light intensity set to 10.0 .................... 59
4.8 Wire with diameter 0.91 mm ........................................ 59
4.9 Wire with diameter 0.87 mm ........................................ 59
4.10 High level software architecture ................................... 60
4.11 Time-line of software developed .................................. 61
4.12 GUI software architecture ........................................... 63
4.13 Diameter calculated using Lawson-Hemphill approach .... 64
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.14</td>
<td>Setting an improper threshold value may yield inaccurate yarn diameter measurements</td>
<td>64</td>
</tr>
<tr>
<td>4.15</td>
<td>Yarn diameter defined with the first method</td>
<td>65</td>
</tr>
<tr>
<td>4.16</td>
<td>Two methods of pixel set selection for method 3</td>
<td>66</td>
</tr>
<tr>
<td>4.17</td>
<td>Different methods of pixel set selection produce different signals</td>
<td>67</td>
</tr>
<tr>
<td>4.18</td>
<td>Picture of a yarn</td>
<td>68</td>
</tr>
<tr>
<td>4.19</td>
<td>Corresponding line-scan image of the yarn</td>
<td>68</td>
</tr>
<tr>
<td>4.20</td>
<td>Picture of a yarn</td>
<td>68</td>
</tr>
<tr>
<td>4.21</td>
<td>Line-scan image of a yarn</td>
<td>68</td>
</tr>
<tr>
<td>4.22</td>
<td>Area-scan image of a yarn</td>
<td>69</td>
</tr>
<tr>
<td>4.23</td>
<td>Mapping of warp and weft yarns into a fabric</td>
<td>70</td>
</tr>
<tr>
<td>4.24</td>
<td>Virtual fabric constructed using actual yarn signals and methods for selecting unit areas</td>
<td>71</td>
</tr>
<tr>
<td>4.25</td>
<td>Virtual fabric of size 400 x 400 pixels (warp = yarn#12, weft = yarn#12)</td>
<td>72</td>
</tr>
<tr>
<td>4.26</td>
<td>Virtual fabric of size 500 x 500 pixels (warp = yarn#12, weft = yarn#12)</td>
<td>72</td>
</tr>
<tr>
<td>5.1</td>
<td>Fitting an ellipse to a yarn cross-section</td>
<td>75</td>
</tr>
<tr>
<td>5.2</td>
<td>Yarn eccentricity histogram for NE 17</td>
<td>75</td>
</tr>
<tr>
<td>5.3</td>
<td>Yarn and camera position</td>
<td>76</td>
</tr>
<tr>
<td>5.4</td>
<td>Yarn profile and detected edge</td>
<td>79</td>
</tr>
<tr>
<td>5.5</td>
<td>Yarn eccentricity along its length</td>
<td>79</td>
</tr>
<tr>
<td>5.6</td>
<td>Elliptic yarn profile projection</td>
<td>80</td>
</tr>
<tr>
<td>5.7</td>
<td>Fitting model to a section of yarn</td>
<td>81</td>
</tr>
<tr>
<td>5.8</td>
<td>Two diameter readings of a yarn, the yarn is rotated by 30 degrees before second reading</td>
<td>82</td>
</tr>
<tr>
<td>5.9</td>
<td>The effect of elliptic cross-section rotation with twist</td>
<td>82</td>
</tr>
<tr>
<td>5.10</td>
<td>Fitting model to a section of yarn to estimate twist</td>
<td>83</td>
</tr>
<tr>
<td>5.11</td>
<td>Twist triangle</td>
<td>84</td>
</tr>
<tr>
<td>5.12</td>
<td>The perimeter of an ellipse as eccentricity increases</td>
<td>84</td>
</tr>
<tr>
<td>5.13</td>
<td>Change in yarn cross-section eccentricity as additional twist is introduced</td>
<td>85</td>
</tr>
<tr>
<td>5.14</td>
<td>Change in yarn cross-section diameter as additional twist is introduced</td>
<td>86</td>
</tr>
<tr>
<td>5.15</td>
<td>Actual warp yarn</td>
<td>88</td>
</tr>
<tr>
<td>5.16</td>
<td>Virtual warp yarn</td>
<td>88</td>
</tr>
<tr>
<td>5.17</td>
<td>Actual weft yarn</td>
<td>88</td>
</tr>
<tr>
<td>5.18</td>
<td>Virtual weft yarn</td>
<td>88</td>
</tr>
<tr>
<td>5.19</td>
<td>The correlogram of the warp yarn signal</td>
<td>89</td>
</tr>
<tr>
<td>5.20</td>
<td>The correlogram of the weft yarn signal</td>
<td>89</td>
</tr>
<tr>
<td>5.21</td>
<td>2-D fabric image generated with actual yarn signals (warp = yarn#6, weft = yarn#12)</td>
<td>90</td>
</tr>
<tr>
<td>5.22</td>
<td>2-D virtual fabric with virtual yarn (eccentricity=0.55)</td>
<td>91</td>
</tr>
<tr>
<td>5.23</td>
<td>2-D virtual fabric with virtual yarn (eccentricity=0.05)</td>
<td>91</td>
</tr>
<tr>
<td>6.1</td>
<td>A number of yarn readings and their correlation</td>
<td>93</td>
</tr>
</tbody>
</table>
6.2 Correlogram and CB(L) of sample yarn 1 ........................................... 97
6.3 Correlogram and CB(L) of sample yarn 5 ........................................... 98
6.4 Virtual fabric constructed using actual yarn signals and methods for selecting unit areas .......................................................... 100
6.5 CB(A) curves of the virtual fabrics shown in Figures 4.25 and 4.26 ........ 101
6.6 Virtual fabric (warp = yarn#3, weft = yarn#3) ................................. 103
6.7 CB(A) curves of virtual fabric shown in Figure 6.6 ............................ 103
6.8 Virtual fabric (warp = yarn#12, weft = yarn#12) .............................. 103
6.9 CB(A) curves of virtual fabric sample shown in Figure 6.8 ................. 103
6.10 2-D virtual fabric image generated with actual yarns (warp = yarn#6, weft = yarn#12) ................................................................. 105
6.11 2-D virtual fabric with virtual yarns (eccentricity=0.35) ...................... 105
6.12 CB(A) curve of virtual fabric with actual yarns shown in Figure 6.10 .... 106
6.13 CB(A) curve of virtual fabric with generated yarns shown in Figure 6.11 ................................................................. 106
6.14 Virtual fabric constructed using actual yarn signals (warp = yarn#1, weft = yarn#5) ................................................................. 109
6.15 CB(A) curves of the virtual fabric shown in Figure 6.14 ...................... 109
6.16 Estimated CB(A) from the CB(L) of the yarns .................................. 110
6.17 Estimated CB(A) obtained from the correlogram of the yarns (warp = yarn#1, weft = yarn#5) ......................................................... 113
6.18 Virtual fabric constructed using actual yarn signals (warp = yarn#12, weft = yarn#6) ................................................................. 115
6.19 Actual CB(A) obtained directly from the virtual fabric (warp = yarn#12, weft = yarn#6) ................................................................. 116
6.20 Correlogram and CB(L) of sample yarn#12 ...................................... 117
6.21 Correlogram and CB(L) of sample yarn#6 ...................................... 118
6.22 Estimated CB(A) obtained from the correlogram of the warp and weft yarn samples #12 and #6, respectively ................................. 119
6.23 Actual fabric sample ................................................................. 119
6.24 CB(A) curve of fabric sample shown in Figure 6.23 ......................... 119
6.25 Actual fabric sample ................................................................. 120
6.26 CB(A) curves of fabric sample shown in Figure 6.25 ......................... 120
6.27 Virtual fabric sample (warp = yarn#5, weft = yarn#1) ...................... 120
6.28 CB(A) curve of fabric sample shown in Figure 6.27 ......................... 120
6.29 Virtual fabric sample (warp = yarn#5, weft = yarn#5) ...................... 120
6.30 CB(A) curves of fabric sample shown in Figure 6.29 ......................... 120
6.31 Virtual fabric sample (warp = yarn#8, weft = yarn#8) ...................... 121
6.32 CB(A) curves of fabric sample shown in Figure 6.31 ......................... 121

B.1 GUI showing diameter signals of a yarn captured on-line .................. 137
B.2 GUI showing virtual woven fabric obtained from on-line yarn diameter signals ................................................................. 138
## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{R}_{cd}$</td>
<td>Anisotropy index in CD</td>
</tr>
<tr>
<td>$\mathcal{R}_{md}$</td>
<td>Anisotropy index in MD</td>
</tr>
<tr>
<td>$k$</td>
<td>Shape constant</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>Standard deviation of $x$ or $\sqrt{\text{Var}(x)}$</td>
</tr>
<tr>
<td>$V_x$</td>
<td>Variance of $x$</td>
</tr>
<tr>
<td>$\mu_x$</td>
<td>Mean of $x$</td>
</tr>
<tr>
<td>$x$</td>
<td>A random variable</td>
</tr>
<tr>
<td>$d$</td>
<td>The diameter of a yarn unless otherwise specified</td>
</tr>
<tr>
<td>$e$</td>
<td>The eccentricity of an ellipse unless otherwise specified</td>
</tr>
<tr>
<td>$a$</td>
<td>The major axes of an ellipse unless otherwise specified</td>
</tr>
<tr>
<td>$b$</td>
<td>The minor axes of an ellipse unless otherwise specified</td>
</tr>
<tr>
<td>$T$</td>
<td>The twist of a yarn unless otherwise specified</td>
</tr>
<tr>
<td>$V(\infty)$</td>
<td>Overall standardized variance</td>
</tr>
<tr>
<td>$N$</td>
<td>The yarn count (tex) unless otherwise specified</td>
</tr>
</tbody>
</table>
List of Nomenclature

B(L) : Variance of the means between lengths of $L$ for a yarn

V(L) : Mean of the variances within lengths of $L$ for a yarn

CB(L) : Coefficient of variation between lengths of $L$ for a yarn

CV(L) : Mean of the coefficient of variations within lengths of $L$ for a yarn

B(A) : Variance of the means between areas of size $A$ of a 2-D fabric image

V(A) : Mean of the variances within areas of size $A$ of a 2-D fabric image

CB(A) : Coefficient of variation between areas of size $A$ of a 2-D fabric image

CV(A) : Mean of the coefficient of variations within areas of size $A$ of a 2-D fabric image

U(%) : Uster yarn irregularity index, the mean of absolute differences divided by mean

CV(%) : Percent coefficient of variation or $\frac{\sqrt{Var(x)}}{E(x)}$

Cov(x,y) : Covariance of variables x and y

E(x) : Expected value of $x$

Var(x) : Variance of $x$

$\rho(u)$ : The correlation coefficient between points $u$ apart
List of Abbreviations

MD : Machine Direction (warp direction)
CD : Cross Direction (pick direction)
SEF : Shape Error Factor
Chapter 1

Introduction

Interest in promoting higher quality, lower cost textile products has been the key strategy for survival during the last decade for the retailers and the producers scattered throughout the world. Furthermore, wide adoption of quality management standards such as ISO 9000 required the standardization and automation of design, production, and quality control of textile products. As computing power increases almost daily at lower costs, measurement and digital imaging in textile industry are faced with unprecedented challenges and opportunities. Improving yarn and fabric qualities is the main focus of the new challenge.

Inherently, all yarns are subject to periodic and random variations. However, the effects of variation on the resulting fabric are difficult to predict. The difficulties are due to limitations in measurement technology, computation and especially unpredictable mapping from yarn to fabric. Although there are studies [49, 59] suggesting where a yarn may be located in a fabric, in reality the fabrication process is far from ideal. Until recently, non-uniformity of fabric appearance has been assessed by the standard yarn board that shows yarn variations. In addition to traditional yarn boards, fabric samples were often produced by actual weaving or knitting, although this is expensive and time consuming.

Extensive research work has been carried out by many researchers in the past
to develop a system for characterizing numerous fabric properties, some through the introduction of quality indices and others by new methods of measurement using time series analysis, Fourier transform, and wavelets [12, 13, 69, 70, 51, 61, 74]. These measures, however, have limited ability to assess features of fabric non-uniformity. Methods such as the Kawabata System (KES) and fabric assurance by simple testing (FAST) have been developed for the rating of fabric’s mechanical properties and used widely by fabric manufacturers and testers. These systems combine objective measurements with subjective rating methods and produce indices that may be useful when comparing fabrics.

In addition to these various indices and methods, a few yarn quality testing instruments are nowadays equipped with devices for obtaining information on yarn properties on-line or off-line and then mapping them into weave or knit fabric structures in order to help the manufacturer visualize the final product.

A quick review of the literature indicates that methods for analyzing yarn irregularity using spectrograms, correlograms, variance-length curves are advanced. They are widely accepted by yarn manufacturers. On the other hand, widely accepted standardized methods are not available for fabrics. There are several possible reasons why irregularities have not been defined or measured properly in the past for woven, knitted, and nonwoven fabrics:

- the difficulty of measuring fabric properties in 2-D at reasonable cost;
- the difficulty in mapping from materials to fabrics;
- the difficulty in interpreting the information obtained through the measurement sensors.

Therefore, the first goal of this thesis is to suggest a method for characterization and quantification of fabric non-uniformities. The second goal of this thesis is to develop theories for estimating fabric non-uniformity based on yarn irregularity measurements.
Although in this study, fabric irregularity is defined in terms of thickness distribution or appearance, it can be expanded to include mass and other properties of fabrics.

During this study, we have also examined the theory and practical applications of yarn irregularity analysis methods and then have sought ways to expand or carry over some of these ideas into analysis of fabric mass and appearance uniformity.

Since, the major factor affecting fabric appearance is the variation of the underlying yarn in a two-dimensional array, it was important to understand the causes of yarn irregularity and the methods for analyzing them. With this methodology, we hoped to not only understand the yarn formation, especially the random fiber arrangement and the twist distribution within the yarn, but also to expand or carry over some of the yarn irregularity analysis methods to characterize fabric irregularity.
Chapter 2

Review of Literature

The quality attributes of a fabric - whether it is the appearance, strength, dimensional consistency and stability, weight distribution or air and water permeability - are affected by the yarn uniformity and the process variations of fabrication. Among these, yarn uniformity has been recognized as being the most important factor. The unevenness of yarn may occur in the form of twist irregularity, diameter irregularity, and mass irregularity. While yarn irregularity may have a direct impact on the weight, permeability, and strength distributions, it may also indirectly impact the appearance, for example, by causing variation in the dye absorption behavior of the yarn.

In this chapter, the causes of yarn and fabric irregularity and methods for their analysis will be reviewed.

2.1 Yarn irregularity and analysis

Staple yarn production involves twisting of fiber strands that are brought together during the pre-spinning processes, namely, opening, carding, and drafting. If this twisted bundle strand has uniform geometrical and mechanical properties, then the stable yarn may be called regular or perfect. However, the production of a yarn is not completely controllable; the amount of fiber in the processes is variable. Moreover,
the fibers do not have determinate shape and uniform geometry and are also blended with foreign elements. Therefore, the principal causes of yarn irregularity may be summarized as follows:

- variations in fiber characteristics;
- random arrangements of fibers;
- non-random arrangement of fibers caused by faulty production;
- irregular twisting;
- existence of foreign elements in fiber.

2.1.1 Sources of yarn irregularity

As already mentioned, the regularity of a yarn fundamentally depends on fibers and their arrangement within the yarn. However, it is always true that the input variances of fibers and the intermediate products are augmented by the process variances from all stages. Although the output variances of yarns are much larger than the theoretically projected variances, attempts have been made in the past to estimate the variances of yarns using the underlying statistics of fibers and their arrangement [44, 58, 9]. In this section, we will briefly mention the sources of yarn irregularity and discuss some of the estimation models that have been suggested.

Random fiber arrangement and fiber-length effect

Many researchers in the past investigated the irregularity of spun yarns under several assumptions. It was often suggested that the random fiber arrangement and the drafting of shorter fibers are the main causes of yarn mass irregularity. Martindale [44] studied the irregularity of yarn caused by random fiber arrangement by assuming that the fibers are randomly arranged through blending, carding, doubling, roving, and spinning. His model was based on the fact that the probability of a fiber crossing a given yarn cross-section is proportional to the length of the fiber.
His first approach was based on the assumption that a yarn cross-section contains a total of $N$ fibers all with same length. He then gave the probability of a fiber crossing a given cross-section as $P = n/N$ where $n$ is the average number of fibers in the yarn cross-section. As $P$ is very small for yarns, this Bernoulli process was approximated by a Poisson distribution whose mean is $n$ and the standard deviation is $\sqrt{n}$. The coefficient of variation (CV) of yarn was then projected as $\frac{100}{\sqrt{n}}$.

Martindale’s second approach was more advanced in the sense that the fibers are no longer assumed to be the same length. He posited that a yarn cross-section contains a group of $m$ fibers with the lengths $l_1, l_2, l_3...l_m$, each group having $n_1, n_2...n_m$ fibers, where

$$\sum_{r=1}^{m} n_r = n$$

Referring back to his first approach and assuming independence between groups of different fiber lengths, Martindale [44] showed that the standard deviation of the number of fibers in a yarn cross-section is still $\sqrt{n}$ as follows:

$$\sigma_n^2 = \sum_{r=1}^{m} \sigma_r^2 = \sum_{r=1}^{m} n_r = n$$

Thus the coefficient of variation is unaffected by the length characteristics of the fibers.

However, in practice, this was contested by Grosberg [28]. His experience showed that the fiber length and the yarn irregularity are correlated; therefore, one can calculate the yarn irregularity from the mean fiber length, diameter, and count of the yarn. His experiments show that for a given fiber diameter, an increase in the mean fiber length would result in a decreasing coefficient of variation, perhaps as a result of improved orientation.

Martindale’s [44] final approach considered a non-uniform fiber cross-section area.
He split the variation of yarn into the following two components: the variation caused by the non-uniform fiber cross-section area and the non-constant number of fibers in the yarn cross-section. He assumed that the number of fibers in the yarn cross-section has a mean $n$ and variance $\sigma_n^2$ where each fiber has a mean cross-section area $\bar{A}$ and variance $\sigma_A^2$. He obtained the variance of yarn, $\sigma_Y^2$, as follows:

\[
\sigma_Y^2 = \bar{A}^2 \sigma_n^2 + n\sigma_A^2
\]
\[
= n\bar{A}^2 + n\sigma_A^2
\]
\[
= n\bar{A}^2 \left(1 + \frac{\sigma_A^2}{\bar{A}^2}\right)
\]
\[
= n\bar{A}^2 \left(1 + 0.00001CV^2(A)\right)
\]

Note that

\[
CV_A = 100\frac{\sigma_A}{\bar{A}} \quad \text{and therefore} \quad \sigma_A = \frac{A \times CV_A}{100}.
\]

Martindale next defined the limit irregularity of a yarn as

\[
CV(Y) = \frac{100\sqrt{n\bar{A}}\sqrt{1 + 0.0001CV(A)^2}}{n\bar{A}}
\]
\[
= \frac{100\sqrt{1 + 0.0001CV^2(A)}}{\sqrt{n}}
\]

A third component, configuration of fibers, was considered much later [18, 73] in the analysis of yarn irregularity as a result of random fiber arrangement. The irregularity was given as the variation of local linear density, $T(x)$:

\[
= n(x)m_t(x)m_s(x)
\]

where $n(x)$ is the number of fibers, $m_t(x)$ is the mean local linear density, and $m_s(x)$
is the mean local fiber orientation. Assuming independence between these three components and using the additive rule of variances, the yarn CV(\%) was given as

\[ CV^2[T] = CV^2[n] + CV^2[m_t] + CV^2[m_s] \]  

(2.3)

**Effect of drafting waves**

Balls [4] pointed out that fibers move in groups causing non-random wave-like patterns. He called them drafting waves, and showed that they are responsible for periodic thin and thick places over a yarn. He suggested that they are often caused by improper draft zone settings, eccentric top rollers, improper top roller pressures, and high percentages of short fibers in the material.

Later Foster [21] investigated the effect of drafting wavelength on yarn irregularity and noticed that neither the wave nor the amplitude was constant. During the drawing process, three things were happening: drafting was increasing irregularity, the fibers were being parallelized and, the irregularities were reduced by doubling. While the amplitude of the drafting wave increased with the increasing draft, the effect of doubling was to reduce the period of the drafting wavelength. He finally concluded that the irregularities in a cotton yarn are mostly made up of drafting waves introduced at the spinning frames rather than the draw frames. Although the drafting waves introduced in earlier steps are small in amplitude, they are responsible for long-term variations. In addition, the wavelength of a periodic fault would grow in the subsequent drafting. According to Foster, the stretching during winding at the speed and ring frames were also important causes of count variations.

In a follow up study, Foster [22] suggested that when the fiber’s mid-point reaches a certain point, the fiber changes speed from the back roller speed to the front roller speed. This point was called the change point, was said to be located somewhere
between the two rollers, and was perhaps responsible for the drafting waves. Later several researchers including Cox and Ingham [15] investigated the effect of change location on the irregularity of yarns and proposed various estimation models.

An important conclusion of yarn irregularity studies is that evenness deteriorates during processing. There are two reasons for this [66]:

1. The number of fibers in the cross section steadily decreases; therefore, uniform arrangement of the fibers becomes more difficult.

2. Each drafting operation increases the unevenness by adding a certain amount of irregularity to the irregularity of a finished yarn. The resultant irregularity at the output of any spinning process stage is equal to the square root of the sum of the squares of the irregularities of the material and the irregularity introduced in the process.

Mathematically stated, if $CV_o$ is the CV(%) of output material, $CV_i$ is the CV(%) of input material, and $CV_p$ is the irregularity introduced by the machine, then

$$CV_o = \sqrt{CV_i + CV_p}$$

Sung and Suh [38] proposed a technique for separating the input variance and the process variance when a roving is produced from a sliver by a conventional drafting process in ring spinning. They demonstrated that a spline method and a cross-spectrum analysis could be used to estimate the density profiles of rovings from slivers. This provided a mean to separate out the input variances from the process variances.

**Effect of twist variation**

Spun yarn production fundamentally involves twisting of a random fiber array. Twisting tends to concentrate the yarn structure into an irregular close-packed polygonal shape [32], but the cross-section still possesses a concave-convex irregular shape.
Over time, many studies have modeled yarn as a cylinder with a circular cross-section. With the advances in image analysis, Tsai and Chu [64] showed that the cross-sections of ring-spun and open-end-spun yarns are better approximated as an ellipse with an irregular outline. The eccentricities of the best-fit ellipses for ring-spun and open-end-spun yarns were obtained as 0.40 and 0.36, respectively, indicating that the cross-sectional shape of open-end-spun yarns are more circular than the ring-spun yarns. This resulted from the smaller linear density and yarn twist of ring-spun yarns.

In addition, there is a complex relationship between yarn diameter, twist, and mass. Therefore, it is hard to predict the effect of twist on yarn structure. For example, twist is not constant but concentrated in the thinnest parts of the yarn. Therefore, high twist compresses thin places and exaggerates the variations in the apparent diameter [6].

Therefore, careful analysis of yarn irregularity must involve understanding yarn structure, especially the effect of twist on yarn geometry.

**Effect of foreign elements**

Neps are caused by foreign elements, immature raw material, and insufficient and improper cleaning during preparation processes. These faults are usually random and visible to the human eye. They are detected by many evenness-testing instruments. When a cross-section deviation exceeds a preset value, the instrument classifies the imperfection as either a nep, or a thin or thick place. The standard levels are as follows, +200%, −50% and +50%, respectively. The length of the fault is usually in the order of a few centimeters [65].

A yarn’s neps, thin places, and thick places can significantly affect the appearance of a woven or knitted fabric. While the thin and thick places do not lead to processing difficulties, neps on the other hand, do, particularly in knitting [66].
2.1.2 Analysis of yarn irregularity

Coefficient of Variation

Uster® defined yarn irregularity, U(%), as the average of absolute differences between the mean mass, \( \bar{x} \), and the measured mass readings, \( x \), as follows:

\[
U = \frac{1}{n-1} \sum_{i=1}^{n} |x_i - \bar{x}| \tag{2.4}
\]

where \( n \) is the number of readings. Although U(%) has been widely used, the coefficient of variation, CV(%), has now widely been accepted as a measure of expressing yarn irregularity due to ease of statistical manipulation. Using the same symbols, it is defined mathematically by

\[
CV = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}}{\frac{1}{n} \sum_{i=1}^{n} x_i} \tag{2.5}
\]

It can be shown mathematically that CV(%) and U(%) are related by

\[ CV = \sqrt{\frac{\pi}{2}} U \]

if normal distribution is assumed.

Extending the definition of CV(%), Martindale [44] introduced the concept of limit irregularity, \( CV_{lim} \). It was defined as the ratio between the measured irregularity (Equation 2.5) and the limit irregularity (Equation 2.1) given by

\[ I = \frac{CV_{eff}}{CV_{lim}} \]

Note that the closer the value to unity the more regular the yarn would be.

Although CV(%) is simple to obtain and interpret, it does not provide any information on the medium and long term yarn variations. Due to the significance of
these variations on fabric irregularity, the measurement methods discussed below are
developed for yarn evenness testing.

**Time-series modeling and spectral analysis**

A discrete time series is a set of time-ordered data obtained from observations
of some phenomenon over time. If at each time a single quantity is observed, the
resulting set is called a scalar or univariate time series. If at each time several related
quantities are observed, this corresponds to a vector or multivariate time series [68].

The fundamental aim of time series analysis is to understand the parameters of
the observed data to forecast future values of the observations. Since one-dimensional
yarn signals and two-dimensional surface signals are usually correlated among their
observations, textile structures can be represented with datasets of time-series.

Three commonly used linear time series models - Autoregressive, $AR$, Moving
Average, $MA$, and Autoregressive Moving Average, $ARMA$ - are summarized briefly
below.

**Linear time series models:**

The fundamental assumption of time series modeling is that the value of the series
at time, $t$, depends only on its previous values (deterministic part) and on a random
disturbance (stochastic part) [68]. The dependence of $X(t)$ on the previous $p$ values
is assumed to be linear and can be written as

\[
X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + \tilde{Z}_t \tag{2.6}
\]

where $\phi_1, \phi_2, \ldots, \phi_p$ are real constants and $\tilde{Z}_t$ is often referred to as the error at time $t$.

This error usually has two components, a zero-mean uncorrelated random variable,
$Z_t$, and a zero-mean white noise process, $\theta Z$, that is,

\[
\tilde{Z}_t = Z_t + \theta_1 Z_{t-1} + \theta_2 Z_{t-2} + \ldots + \theta_q Z_{t-q} \tag{2.7}
\]
The constants $\phi_1, \phi_2, ... \phi_p$ and $\theta_1, \theta_2, ... \theta_q$ are called AR and MA coefficients, respectively. Combining Equations 2.6 and 2.7 yields

$$X_t - \phi_1 X_{t-1} - \phi_2 X_{t-2} - ... - \phi_p X_{t-p} = Z_t + \theta_1 Z_{t-1} + \theta_2 Z_{t-2} + ... + \theta_q Z_{t-q} \quad (2.8)$$

This defines a zero-mean autoregressive moving average (ARMA) process of orders $p$ and $q$, or $ARMA(p,q)$. ARMA, however, has a short-term memory and therefore may not be suitable for expressing long-term seasonal periods, which is usually the case for yarn signals.

Sung and Suh [38] captured signals from slivers and fit them with the ARMA model to predict the future behavior of the rovings and yarns. Although the signals did not show any obvious trends or cyclic patterns, the time series analysis made it possible to extract patterns as a function of time.

In addition to ARMA, Spectral analysis, which is based on Fourier series, has been applied to analyze periodic yarn mass variations. This computation involves breaking up a yarn signal, $Y(t)$, into a set of frequency components by inverse discrete Fourier transform. The original sequence $Y(t)$ can be represented as a combination of $N$ different frequencies $f$ as

$$Y(t) = \frac{1}{N} \sum_{k=1}^{N} U_N \left( \frac{2\pi k}{N} \right) e^{-i2\pi kt/N} \quad (2.9)$$

The parameter $U_N \left( \frac{2\pi k}{N} \right)$ corresponds to the amplitude of the signal at angular frequency $w_k = 2\pi k/N$.

However, in practice, for a given signal, the power spectrum is used to obtain a plot of the portion of a signal’s power (energy per unit time) falling within given frequency bins [68]. It is given by
\[ P_y(t) = \int_{-\infty}^{\infty} [Y(t) - \bar{Y}]e^{-i2\pi ft} dt \]  

(2.10)

Spectrogram

A spectrogram helps to recognize and analyze periodic faults in a sliver, roving, and yarn by representing the mass variations in the frequency domain in a way similar to time-series analysis. If a yarn with a periodic fault is analyzed using a spectrogram, the wavelength of the periodic fault can be calculated using the relationship

\[ \text{frequency} = \frac{\text{wavelength}}{\text{material-speed}}. \]

Therefore, in textiles, a direct representation of wavelength is preferred over the frequency domain. In a spectrogram, the X-axis represents the wavelengths and Y-axis represents the amplitude of the faults as shown in Figure 2.1. Often a logarithmic scale is given for the X-axis to cover the maximum range of wavelengths. In general, the periodic defects could be sinusoidal or non-sinusoidal. The sinusoidal defects are usually caused by rotating parts such as drafting rollers and are easier to detect. However, the non-sinusoidal defects are harder to detect and difficult to comment on [7]. Based on the characteristics of the period, these defects can be divided into categories as being symmetrical, asymmetrical, or impulsive. In addition, depending upon the wavelength of the periodic fault, the mass variations are classified as

1. short-term variation (wavelength ranges from 1 cm to 50 cm);
2. medium-term variation (wavelength ranges from 50 cm to 5 m);
3. long-term variation (wavelength longer than 5 m).

If yarns with periodic variations in the range of 1 cm to 50 cm lie next to each other and repeat a number of times within the fabric width, a fabric defect called the moiré effect may be formed. This effect is particularly striking to the naked eye if the finished product is observed at a distance of approximately 50 cm to 1 m.
Periodic mass variations in the range of 50 cm to 5 m are not recognizable in every case. Faults in this range are particularly effective if the width of the cloth is the integral (or near integral) number of the periodic fault wavelength. In such cases, weft stripes in woven and rings in knitted fabrics are likely to appear.

Periodic mass variations with wavelengths longer than 5 m can result in quite distinct cross-stripes in woven or knitted fabrics. This is because the wavelength of the periodic fault will be longer than the width of the woven fabric or the circumference of the knitted fabric. In addition, the longer the wavelength, the wider the width of these cross-stripes. Such faults are easily recognizable in finished products, particularly when they are observed from distances further away than 1 m.

A periodic mass variation in fiber assembly does not always affect the CV(%) of the yarn significantly. Nevertheless, such a fault will detract from the appearance quality of a fabric especially after dyeing.

The degree to which a periodic fault can affect the finished product is dependent on its intensity, the width and type of the woven or knitted fabric, the fiber material, the yarn count, and the dye up-take of the fiber. A considerable number of trials have shown that the height of the peak above the basic spectrum should not over-step 50% of the basic spectrum height at the wavelength position where the peak is observed.
A periodic fault, which occurs at some stage during the spinning process, is lengthened by subsequent drafting. For instance, if the front roller of the second draw frame is eccentric, then by knowing the number of drafts in the following processes, the position of the peak in the spectrogram of the yarn measurement can be calculated. Similarly, from the position of the peak in the spectrogram, the location of the defective part can be located using the wavelength reading at the peak and the speed of the rollers [66].

**Correlogram**

A correlogram is the plot of the correlation coefficient, $\rho(L)$, as a function of distance, $L$. A yarn correlogram shows how readings of yarn signals that are, for instance, $L$ apart are correlated with each other. Normally, as $L$ changes, the $\rho(L)$ may vary as demonstrated in Figures 2.2 and 2.3. However, the correlogram is often a damped harmonic curve for a yarn. This usually indicates the existence of 'quasi-periodic' wave in the signal [63]. On the other hand, an undamped sinusoidal curve indicates a strong periodic motion.

It was suggested that a correlogram could be derived from the fiber length distribution by assuming that fibers are randomly distributed in the yarn [57]. Cox and Townsend [63] demonstrated that the correlogram could not always be derived from the fiber length distribution because the assumption that the fibers are distributed randomly is untrue. However, they acknowledged that the fiber length distribution
must nevertheless influence the correlogram, that is; the greater the fiber length, the
greater the value of \( L \) at which \( \rho(L) \) converges to zero.

Even though the contribution of quasi-periods to the visual appearance of yarns
and fabrics was not so clear to Townsend and Cox [63], they suggested that the
correlogram is probably the best method of detecting quasi-periods in yarn signals.

Acknowledging that no single measure is sufficient to assess all features of the yarn
irregularity, Townsend and Cox [63] felt that the \( V(L) \) relation is a more appropriate
measure of yarn irregularity.

**Variance-length curves**

Townsend and Cox [62] showed that the relationship between the mean standard-
ized variance, \( V(L) \), and the length within which \( V(L) \) is measured leads to indices
characterizing types of irregularity that may be of practical importance.

When analyzing the causes of irregularity they preferred to deal with the square
of the CV(\%), namely relative variance, instead of CV(\%) itself. This was because a
moderately small addition of irregularity has a small effect on the total coefficient of
variation, CV(\%).

They proposed two variance-length curves, namely B(L) and V(L), to illustrate
the relationship between the length \( L \) and the standardized deviation. While B(L)
was defined to be the standardized variance between the means of lengths \( L \), V(L)
was defined to be the mean standardized variance within lengths \( L \) of yarn. These
definitions may be expressed mathematically as follows:

\[
B(L_i) = \sqrt{\frac{\sum_{k=1}^{n_i} [x_{ki} - \bar{x}_i]^2}{n_i}}
\]

(2.11)

where

- \( B(L_i) \) is the variance between sections of \( i^{th} \) length cut;
• $x_{ki}$ is the value of the $k^{th}$ section for $i^{th}$ length cut;
• $\bar{x}_i$ is the mean value of the yarn property for $i^{th}$ length cut;
• $n_i$ is the number of yarn segments for $i^{th}$ length cut.

$$V(L_i) = \frac{\sum_{k=1}^{n_i} V(x_{ki})}{n_i} \quad (2.12)$$

where

• $V(L_i)$ is the $i^{th}$ length variance;
• $V(x_{ki})$ is the variance of the property for $k^{th}$ segment;
• $n_i$ is the number of yarn segments for $i^{th}$ length cut.

**Figure 2.4**: General shapes of $V(L)$ and $B(L)$

Townsend and Cox [62] pointed out that

$$V(L) + B(L) = V(\infty) \quad (2.13)$$

where $V(\infty)$ is the overall standardized variance from the simple theory of analysis of variances. Consequently, they provided the general shapes of $V(L)$ and $B(L)$ as shown in Figure 2.4. The $B(L)$ curve starts with an initial value of $B(\infty)$ at small lengths. It falls rapidly at first and then more slowly to an asymptotic value of zero at longer lengths. On the other hand, the $V(L)$ curve starts with an initial value close to zero at small lengths and increases to a limiting value $V(\infty)$ as additional length introduces more opportunity for variation to arise [41].
Townsend and Cox [62] classified the yarns to have either short or long term variation, based on the rapidity of approach to $V(\infty)$. They mentioned that the gradient at the origin of these curves as well as the scatter of variances about their mean could be a discriminating tool for yarns.

Townsend and Cox [62] gave the relationship between the correlogram and the $V(L)$ curve as shown below:

\[ V(L) = V(\infty) \left[ 1 - \frac{2}{L^2} \int_0^L (L - U) \rho(u) du \right] \]  

(2.14)

where $\rho(u)$ is the coefficient indicating the correlation between points $u$ apart on the yarn, $V(L)$ is the mean standardized variance within lengths $L$ of yarn, and $V(\infty)$ is the overall standardized variance. They suggested that variance-length curves may be obtained faster from the correlogram of yarns using Equation 2.14.

In a follow up study, Breny [9] combined the results of Townsend and Cox [62, 63], Martindale [44], and Spencer-Smith and Todd [57] in order to determine $V(L)$ curve using only the following quantities:

1. the fiber length distribution;

2. the mean fiber diameter and its dispersion and;

3. the yarn count.

Letting $l_m$ be the maximum fiber length and assuming $\rho(u) = 0$ for $u > l_m$; $V(L)$ curve was derived as

\[
V(L) = \frac{2(V(\infty))}{L^2} \int_0^{l_m} (L - u)[1 - \rho(u)]du + \frac{2(V(\infty))}{L^2} \int_0^{l_m} (L - u)du
\]

\[= V(\infty)(1 - \frac{A}{L} + \frac{B}{L^2}) \]  

(2.15)

where $A$ and $B$ are determined experimentally or theoretically from fiber length
distribution. Breny [9] conducted experiments to verify the validity of the model, however, by assuming fibers with same length.

Suh [58] statistically derived the most generic expression for the fiber mass contained in length interval $L$ of a fiber array of known thickness as a function of fiber length distribution. Noting that yarn irregularity is the variation of the length aggregate of all fibers $S_T(L)$ within $L$, he derived $S_T(L)$ as a function of fiber length distribution, average number of fibers and length interval $L$. He then derived coefficient of variation of yarn as

$$CV[S_T(L)] = \frac{\sqrt{Var[S_T(L)]}}{E[S_T(L)]} \quad (2.16)$$

from the moments of the $S_T(L)$ by considering the well-defined distributions of fiber length and number of fibers.

Suh’s [58] model provided an easy way to individually separate out the effect of average fiber length and the number of fibers from the total irregularity of the yarn. The expressions obtained for uniform fiber length were compatible with the time-series expression to that derived by Cox and Townsend [63] and Breny [9]. Suh [58] also showed that when $L = 0$ and the fiber diameter is uniform, the expression simplifies to the one obtained by Martindale [44]. Suh [58] finally demonstrated that an increase in $L$ results in a decrease in $CV(\%)$ as expected.

Some connection between the variance-length curve and fractal theory was reported. It was suggested that fractal dimension could be calculated from a variance-length curve by taking the logarithm of the curve to obtain a quality index for quantifying irregularity of yarns [41].
2.1.3 Mass, diameter and twist relationships of yarns

Geometric descriptors of yarn and coordinate system

Some basic concepts regarding yarn coordinate systems and twist geometry will be given in this section in order to provide a common nomenclature. If yarn is assumed to be circular in cross-section, then the unit twist may be given as $\pi d \tan(\theta)$ where $d$ is the diameter of the yarn and $\theta$ is the twist angle as shown in Figure 2.5.

![Twist triangle](figure2.5)

**Figure 2.5:** Twist triangle

On the other hand, in cylindrical coordinates the twist angle, $\tan(\theta)$, may be given as, $r d\theta / dz$. In addition to twist angle, migration angle, $\psi$, of a single fiber shown in Figure 2.6 may be given as [43]:

$$\tan(\psi) = \frac{dr}{dz} \quad (2.17)$$

Combining the twist angle $\theta$ and the migration angle $\psi$, Lieve [43] suggested the coordinate system of a fiber as

$$\frac{dF}{dz} = (\frac{dr}{dz}, \frac{r d\theta}{dz}, 1) \quad (2.18)$$

Twist and fiber strand interactions

Cybulska [16] assessed yarn thickness, hairiness, and twist using image analysis. The study assumed a cylindrical yarn with a variable diameter where the fibers are laid along the helix curves characterizing the twist on the surface. The projection of helix to the image plane was given by
Figure 2.6: Yarn fiber in cylindrical coordinates

\[ y - y_0 = \frac{d}{2} \sin(b_1 x + b_0) \]  

(2.19)

where \( y_0 \) denotes the y-coordinate of the yarn axis, \( d \) is the local diameter of the yarn core, and \( b_1 \) characterizes the spiral lead. The value of \( \tan(\beta) \) was calculated as the slope of the tangent to the helix at point \((x_0, y_0)\) as follows:

\[ \tan(\beta) = \frac{b_1 d}{2} \cos(b_1 x + b_0) = \frac{b_1 d}{2} \]  

(2.20)

Cybulskaya calculated the twist of a yarn using Equation 2.21 and by estimating the parameters of Equation 2.19 from the best-fit sine curve of the projected yarn image.

\[ \frac{1}{T} = \frac{\tan(\beta)}{\pi d} = \frac{b_1}{2\pi} \]  

(2.21)

The results show that the twist varies along a yarn and concentrates in the thin places of the yarn.

Benslimane and Lachkar [50] also estimated the level of twist by finding the best-fit sine curve using Equation 2.19 and genetic based inverse voting Hough transform. Genetic algorithms were used in image space to overcome the memory and computational requirements of Hough transform in parameter space. Using genetic algorithms, a set of best-fit curves was preserved and the others were eliminated in a way similar
to natural selection.

However, Tsai and Chu [64] using image analysis techniques showed that the cross-sections of spun yarns are better approximated as ellipses. This was achieved by measuring yarn cross-sections rotated during the test so that the angle of intersection between the emitted light beam and the fixed axis of the yarn cross-section varies continuously. The eccentricities of the best-fit ellipses for ring-spun and open-end-spun yarns were obtained as 0.40 and 0.36, respectively, indicating that the cross-sectional shapes of open-end-spun yarns are more circular than the ring-spun yarns. This was contributed to the smaller linear density and yarn twist of ring-spun yarns.

Figure 2.7: Shape Error Factor (SEF)

In order to account for the irregular outline of yarn, shape error factor (SEF) was introduced. It was simply given as the ratio of the actual area to the approximated ellipse’s area such as shown in Figure 2.7. SEF was given by

$$SEF = \frac{\pi}{2} \sum_{i=1}^{n} \nu_i \times 100 \tag{2.22}$$

where $\pi ab$ is the area of the best-fit ellipse of a yarn cross-section, $n$ is the number of yarn cross-section readings, and $\nu$ is the area difference. Since, the second moment of a best-fit ellipse equals to that of the cross-sectional shape. The radii $a$ and $b$ were given by
\[ a = \left( \frac{4}{\pi} \right)^{1/4} \left( \frac{I_{\text{max}}^3}{I_{\text{min}}} \right)^{1/8} \]  

(2.23)

and

\[ b = \left( \frac{4}{\pi} \right)^{1/4} \left( \frac{I_{\text{min}}^3}{I_{\text{max}}} \right)^{1/8} \]  

(2.24)

where \( I_{\text{min}} \) and \( I_{\text{max}} \) are the greatest and least moments of inertia, respectively \[71\]. In Equation 2.22, the dividend was multiplied by \( \frac{2}{2} \) to translate absolute irregularity to coefficient of variation with the assumption that the area difference is distributed normally.

Tsai and Chu \[64\] suggested that the cross-sectional shapes of ring-spun and open-end-spun were not identical due to different yarn formation mechanisms. The greater the yarn twist and linear density (tex), the smaller was the ellipticity of the yarn cross-section. In addition, the SEF was greater for ring-spun yarns than open-end-spun yarns owing to the greater ellipticity of the former. Furthermore, the SEF can be applied to both spun yarns because of the low variance (0.005) of the eccentricities between the various cross-sections of the yarns.

On the other hand, several authors \[49, 5\] investigated the relationship between yarn count and diameter with the assumption that the yarn is cylindrical and its linear density is known. While studying the effect of twist on yarn diameter and contraction, Barella \[5\] derived the diameter in terms of yarn count \( N[\text{tex}] \) and yarn density (\( \delta \)) as

\[ d = 2\sqrt{\frac{N}{1000\pi\delta}} \]  

(2.25)

He suggested that when there is no slippage, the yarn density would be equal to fiber density if a force is applied at breaking levels. At that point, the diameter may be called the critical diameter. The relationship between the diameter and force was given by \( d_f = d_o - K\sqrt{F} \). In this relation, \( K \) is a constant that depends on the
yarn type, and $d_o$ and $d_f$ are the diameters of the yarn under no tension and under force, respectively. Taking into account the effect of twist on yarn count through contraction, Barella obtained contraction, $C$, as

$$C = 100\left(1 - \frac{1}{\sqrt{1 + \tan^2 \theta}}\right)$$  \hspace{1cm} (2.26)

where $\theta$ is the twist angle. Correcting diameter for contraction yields

$$d = \sqrt{\frac{\sqrt{1 + \pi \gamma 10^{-2}T^2}}{N\pi(a + bT)}}$$  \hspace{1cm} (2.27)

In this equation, $T$ is unit twist, and $\gamma$ is yarn density and may be given by $c_1 + c_2T$. The constants $c_1$ and $c_2$ are experimentally determined for a given yarn.

A theoretical relationship between mass and diameter was derived by Kim et al. [42] as, $CV(diameter) \approx 0.5 \times CV(mass)$. It was assumed that yarn cross-sections are circular, the yarn linear density is uniform, and mass ($m$) and diameter ($d$) are normally distributed, $N(\mu, \sigma^2)$. By definition, the CV(%) of mass $m$ is

$$CV(m) = \frac{\sqrt{Var(m)}}{E(m)}$$  \hspace{1cm} (2.28)

Since $m = \frac{\rho \pi d^2}{4}$, the expected value and variance of the mass is given respectively by

$$E(m) = E\left(\frac{\rho \pi d^2}{4}\right) = \frac{\rho \pi (Var(d) + E^2(d))}{4}$$

$$= \frac{\rho \pi}{4} (\sigma^2 + \mu^2)$$  \hspace{1cm} (2.29)
\[ V \text{ar}(m) = V \text{ar}(\frac{\rho \pi d^2}{4}) = \frac{\rho^2 \pi^2}{16} (E(d^4) - E^2(d^2)) = \frac{\rho^2 \pi^2}{16} (4\mu^2\sigma^2 + 2\sigma^4) \quad (2.30) \]

Substituting Equations 2.29 and 2.30 into Equation 2.28 yields

\[ CV(m) = \frac{CV(d)\sqrt{4 + 2CV^2(d)}}{CV^2(d) + 1} \quad (2.31) \]

The Maclaurin expansion of Equation 2.31 yields

\[ CV(m) = 2CV(d) + 3/4CV^3(d) + 23/16CV^5(d)\ldots \approx 2CV(d) \quad (2.32) \]

In other words, the measured mass CV(\%) would be twice of the measured diameter CV(\%) for a circular yarn. Barella [6] showed that in practice, however, the variation in diameter is higher than the theoretical approximated one. He suggested that this must be due to the influence of twist on yarn diameter irregularity. He conducted the following three experiments on yarn:

I. tension increased and length kept constant;

II. twist increased and length kept constant;

III. twist increased and yarn allowed to contract.

and observed a decrease in apparent diameter CV(\%) for the three experiments conducted. He explained the decreases in CV(\%) by the following theories:
• in the first case, the tension effected thick places more than the thin places and had a regulating effect;
• in the second case, the increase in twist caused an increase in tension and had a regulating effect;
• in the third case, the tension was constant and the redistribution of twist occurred. This in turn increased the regularity of the yarn.

Barella finally concluded that mass irregularity causes twist irregularity and in turn exaggerates the yarn irregularity. However, his analysis did not take into account the effect of measurement principle and field length.

Kim et al. [42] investigated the effect of measurement field length on yarn evenness by comparing the CV(%) of the measurement obtained from three sensors with different measurement principles. These sensors were: a capacitance sensor with an 8 mm sensing zone; an optical sensor with a 2 mm sensing zone; and a laser scanner with a 1 mm effective sensing zone. They derived the theoretical CV(%) of capacitive and optical sensors by partitioning the measurement field length of the capacitive to the one of the optical as \( M = m_1 + m_2 + m_3 + m_4 \) and assuming independence between partitions. Equation 2.28 was then modified as

\[
CV(M) = \frac{\sqrt{Var(m_1 + m_2 + m_3 + m_4)}}{E(m_1 + m_2 + m_3 + m_4)} = \frac{\sqrt{4Var(m)}}{4E(m)} = 0.5CV(m) \quad (2.33)
\]

Substituting Equation 2.32 into Equation 2.33 yield \( CV(M) = CV(d) \), which means that the CV(%) measured by the optical sensor would be as high as the CV(%) measured by the capacitive sensor. Although measured CV(%)s were in agreement with the theoretically calculated ones for both the optical and the capacitive sensors, the measured CV(%) obtained for the laser scanner was lower than the theoretically calculated one. This was explained by the diminishing effect of correlation between
yarn readings of 1 mm apart for the laser scanner.

2.1.4 Instruments for yarn irregularity measurement

Nowadays, two types of yarn quality assessment systems, one based on capacitive and the other one based on optical measurements, are widely used in the textile industry. Using capacitive measurement, the irregularity of yarn is detected from the variations in electric capacitance generated by the movement of yarn specimen that passes through the gap of a fixed air condenser. On the other hand, using the photoelectric measurement, the irregularity is measured from the fluctuation of the light intensity or shadow on the sensor caused by the beam of light passing across the yarn cross-section.

![Figure 2.8: Emitted light for a yarn with irregular cross-section](image)

Two main factors, the inhomogeneous radiant intensity of the emitted light source and the irregular yarn cross-section, are likely to cause error in the measurement of yarn evenness by the photoelectric method [64]. The effect of an irregular yarn cross-section on yarn evenness measurement is demonstrated in Figure 2.8. For the same cross-sectional area, the projected diameters $d'$ and $d''$ are not equal because of the orientation of the yarn. Tsai and Chu [64] showed that the problem of orientation could be solved if two photoelectric instruments with two incident beams are placed perpendicular to each other. They demonstrated this by first calculating the measured
area from the projected diameter assuming single incident light beam as shown in Figure 2.9. The measured area, $A_o$, is a function of $\psi$ and the semi-major and semi-minor axises, $a$ and $b$ as given below:

$$A_o = \frac{\pi d^2}{4} = \frac{\pi (b^2 + a^2 \tan^2 \psi)}{1 + \tan^2 \psi}$$  \hspace{1cm} (2.34)$$

![Diagram of projected yarn diameter using single camera](image)

**Figure 2.9:** Projected yarn diameter using single camera

They then compared the actual area to the projected area and plotted the difference as an error. As one expects the error was maximum when the major or minor axes were perpendicular to the light beam.

They next introduced another camera into their model as shown in Figure 2.10. The measured area was calculated theoretically by adding the projected areas of the two cameras and dividing the result by 2. The measurement error was plotted for various values of $\alpha$ ($0 \leq \alpha \leq \pi$). It was shown that when two light beams are perpendicular to each other, in other words when $\alpha = \pi/2$, the error was zero, indicating that the measured area was exact and independent of the camera or the orientation of the yarn.

Huh and Suh [33] suggested that if the variations in yarn diameter are correlated, then the sampling interval in optical systems may also affect the measured signal. They observed that the higher the sampled data were correlated with each other, the
higher were the mean thickness and the CV(%). This suggested that the mean and standard deviation of the measured thickness decreases as the yarn speed increases. They concluded that in order to reach the randomness of yarn thickness variation, the yarn must be sampled at further than 2 mm intervals.

The advantages and disadvantages of capacitive and optical systems are listed in Table 2.1. Because of the advantages of optical systems, they are preferred over capacitive ones [8, 47].

**Some of the commercially available yarn irregularity testers**

**Zweigle G-580**

Zweigle G-580 is an optical system for visual assessment of yarns and fabrics [74, 52]. The system operates with the principle of absolute optical measurement using infrared light as shown in Figure 2.11. The structure of a yarn is subject to variations of a periodic or random character. The measuring system compares the yarn diameter with the constant reference mean and records variations in length.

Figure 2.10: Projected yarn diameter using two cameras
and diameter. The reference mean is established in the first 100 m of testing. The G 585/G 588 yarn testing modules use an infrared light sensor operating with a precision of 1/100 mm over a measuring field length of 2 mm and at a sampling interval also of 2 mm. The speed of measurement may be selected on a graduated scale between 100 and 400 m/min. The sensor is unaffected by the aging of the light source, extraneous light, contamination, temperature, and humidity. It is unaffected by such yarn characteristics as color, conductivity, or luster. The defects are classified in respect of their length and their variation of diameter. The system provides a CV(%), a CV(L) curve, a histogram that shows diameter distribution, and a spectrogram that shows wavelengths of the periodic defects in the yarn.

It was reported that [42] the measurements of G-580 should not be compared with the readings of Uster due to the following reasons:

- different principles of measurement (optical determination of diameter, capacitive determination of mass variations);
- different test zone lengths (integration stages), USTER 8 mm, G 585/G

<table>
<thead>
<tr>
<th></th>
<th>advantages</th>
<th>disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical</td>
<td>- sees like eye</td>
<td>- discrete sampling causing lower resolution</td>
</tr>
<tr>
<td></td>
<td>- suitable for hairiness determination</td>
<td>- irregular shape of yarn cross-section</td>
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<td></td>
<td>- more sensitive to diameter variations</td>
<td>- inhomogeneous radiant intensity</td>
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<tr>
<td></td>
<td>- the fiber material does not affect measurement due to conductivity</td>
<td>- sensitive to vibrations during measurement</td>
</tr>
<tr>
<td>capacitive</td>
<td>- continues sampling</td>
<td>- sensitive to both temperature and humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- not suitable for hairiness calculation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- sensitive to fiber material</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of yarn irregularity measurement systems
Figure 2.11: Zweigle G-580 yarn evenness tester

588 2 mm;

**Uster Tester III**

The Uster Tester III is a capacitive type of tester for slivers and yarns. It provides a CV(%), a spectrogram, and a CV(L) curve. The field length $L$ can be adjusted by timing the capacitive reading and the speed of the tested material. For yarns, $L$ typically defaults to 8 mm intervals. The latest model, Uster 4-SX [65], is capable of measuring yarn diameter and hairiness with dual light beams perpendicular to each other. This design reduces shape error caused by irregular yarn cross-sections [64]. Note that the CV(%) was provided directly as opposed to $\%U (= \text{mean irregularity})$ in earlier models.

**Lawson-Hemphill EIB**

Lawson-Hemphill $EIB^\text{®}$ is an optical system with a line-scan camera. It scans every 0.5 mm with a speed of 100 m/min. The diameter was defined to be the distance between the pixels near a user-set threshold level. Because optical readings are from a single angle, they are subject to shape errors. The yarn vibration is prevented by guiding the yarn through a measurement zone. In addition, the Constant Tension Transport (CTT) unit prevents variations that might be introduced by irregular yarn
Keisokki KET-80 and Laserspot

Keisokki KET-80 and Laserspot [40] are two types of evenness testers based on capacitive and optical measurement principles, respectively. Like Uster Tester III, KET-80 provides a U% and CV(%), a CV(L) curve, and a spectrogram. It also provides a deviation rate, a DR%, which is defined as the percentage of the summed-up length of all partial irregularities exceeding the preset cross-sectional level to the test length. In practice, however, the yarn signal is primarily processed by the moving average method for a certain reference length. As a result, long-term irregularities are likely to be detected.

The Laserspot evenness and hairiness instrument uses laser beam and is based on the Fresnel diffraction principle. With this principle the yarn core is separated from hairs, allowing yarn diameter and hairiness to be measured at the same time. See Figure 2.12.

![Figure 2.12: Yarn evenness testing with Fresnel Principle [40]](image)

Flying Laser Spot Scanning System

The Flying Laser Spot Scanning System [33] consists of three parts: the sensor head, the specimen feeding device, and the data analysis system. When an object is placed in the scanning area, the flying spot generates a synchronization pulse...
that triggers the sampling. The width between the edge of the first and the last light segment determines the diameter of the yarn. Depending on the spot size and specimen feeding speed, the measurement values may vary. Therefore, it is important to calibrate the system for the feeding speed and the spot size.

2.1.5 Wavelet-stochastic hybrid model for yarn diameter simulation

Fundamental problems of on-line yarn monitoring systems are the storage and handling of vast amounts of data. Kim et al. [41] developed a system for characterization of yarn properties (mass, diameter) using a wavelet-stochastic hybrid method. According to the method developed only the essential statistical information and significant events are recorded, and vast amounts of normal data are filtered out. While the stochastic models facilitate detection and identification of the spinning faults, wavelet analysis allows the compact representation of the necessary information with up to a 99.9% data reduction rate. It was shown that a variety of virtual yarns could be generated with the algorithm developed for data reduction.

Data screening and reduction

The spun yarn was considered an assembly of fiber with random thick places and nepes. The parameters of these imperfections were the amplitude of the fault, the length of the fault, and the arrival time of these faults. For the arrival time of these faults, the Poisson process was chosen. The Gamma and generalized Pareto distribution functions were chosen for the length and the amplitude of the thick places, respectively [41]:

The procedure for data screening and reduction was as follows:

I. capture yarn diameter signals until a base parameter set is formed;
II. capture yarn diameter signals continuously in a block and estimate the parameters of the block;

III. compare the parameters of the block with the base parameter set;

IV. if there is a significant change, record the location of the current block along with its parameters, before compressing them using wavelet transform;

V. otherwise discard the current block data;

VI. continue processing from step 2 as needed.

In a follow up study, Snyder et al.[55] tried to develop a fabric quality rating system using wavelet methods and CYROS® in conjunction with human judgment. Yarn signals captured from a traditional evenness tester were first broken down into twelve sub-signals using wavelet decomposition and multi-resolution analysis (MRA) with successively decreasing frequencies. The variance profiles of these twelve sub-signals were then obtained and compared with various yarns having specific fabric defects. The correlation between the defects and these sub-signals is determined and used to develop visual quality rating system in conjunction with subjective (human) evaluations of CYROS® fabric images.

2.2 Fabric appearance and irregularity

The appearance of fabrics is mainly affected by the uniformity of the underlying yarns and fabrication process problems. However, when the fabrication process problems are to be examined, it will be seen that many of the failures are also caused by the yarn irregularities. For example, an irregular yarn will have an uneven strength and will likely to disturb the fabrication process because of frequent breakage. This section focuses on the effect of yarn properties on fabric appearance.
Fabric defects caused by irregular yarns may be grouped in two categories: random and periodic fabric irregularities. While random fabric irregularities may occur at any location in a fabric, periodic irregularities may create visible patterns in certain directions.

The following list is intended to classify most common fabric appearance problems according to the two main categories defined above. The irregularity definitions are taken from ASTM [3].

I. Random fabric irregularities

A Yarn related

Random yarn irregularity may cause rough fabric appearance.

Cloudiness, rough, fuzziness is a fabric condition characterized by a hairy appearance due to broken fibers or uneven twist.

B Fabrication process related

Irregular reed marks are due to cracks between warp ends at random intervals for short distances.

Missing or faulty yarns are visible at a portion of the fabric.

Holes, cuts, knots or slubs are local defects mainly caused by mechanical problems.

II. Periodic fabric irregularities

A Yarn related

Bárré is a striped effect in a fabric caused by a series of picks, which have apparent difference in color or luster that is repeated at intervals in the warp direction. See Figure 2.13.

Warp streak is characterized by a narrow bar running warp-wise and has difference in color from neighboring ends.
Filling bar is a weft that runs parallel with the picks and that is different in material, linear density, twist, and luster from the adjacent wefts.

Diamond bar/Moiré is caused by sinusoidal periodic thickness variations in weft yarn whose wavelength is less than twice the width of the cloth [11, 25]. See Figure 2.13. Figure 2.14 shows the influence of the wavelength on the visibility of a periodic defect on fabric.

B Fabrication process related

Reed marks, unlike irregular reed marks, occur in regular intervals and run along the pick.

Skewing, bowing, non-symmetric placements are usually caused by excessive tension in fabrication.

![Figure 2.13: Appearance of some fabric defects [52]](image)

![Figure 2.14: Influence of wavelength on visibility [52]](image)

Farger et al. [19] studied the effects of yarn irregularity in dyeing and finishing. They examined the effect of weight irregularity, twist irregularity, and the fiber characteristic variation. Their study showed that:

I. The yarn mass variation effects the weight distribution and cover of fabrics, which in turn may affect the dyeability and the finishing behavior of fabrics.
This was because liquors used in processing penetrate differently depending on the accessibility of the material.

II. The yarn twist variation causes packing density variation, which in turn effects the penetration of liquids. In addition, highly twisted portions of the yarn are raised more slowly than the portions of low twist, and this causes variations along the cloth causing waisting, puckering, and pile variations.

III. The variation in fiber characteristics is responsible for irregular natural shade.

Prevention of defects that occur during weaving or knitting, in other words, during the fabrication process, requires on-line monitoring of the raw fabric. On the other hand, the yarn related defects could be prevented by inspecting the yarns as thoroughly as possible. While most of the defects may be identified right after fabrication, some yarn related irregularities appear after dyeing and finishing.

2.2.1 The analysis of fabric appearance and uniformity

It was suggested that [67, 46] the quality of fabric can be predicted from the coefficient of variation, the CV(%), of the yarn that is used. However, in industry, the evaluation of fabrics is still commonly done by the experts through eye and hand judging. This is primarily due to the fact that the CV(%) is grossly insufficient to predict the features of irregularities, since it is not location specific within the fabric.

Several researchers in the past tried to characterize numerous fabric properties, some through introduction of quality indices and others by new methods of measurement using time series, Fourier transform, and Wavelets. Consequently, methods such as the Kawabata System (KES) [61], fabric assurance by simple testing (FAST), and the Total Quality Index [55] have been proposed for total appearance rating. Nowadays yarn quality testers are equipped with devices for obtaining information
on yarn properties on-line or off-line and then mapping them into weave or knit fabric structures in order to help visualize the final product [74, 48, 59].

**Kawabata system and FAST**

The operation of these systems includes the measurement of certain fabric properties and the interpretation of the data to predict the tailorability, appearance, feel, and handle [61].

Kawabata system suggests several indices, such as the Total Appearance Value (TAV) and Total Hand Value (THV), for fabric properties. These indices are calculated by combining measurements made on several parameters, some of which are: elongation, linearity, tensile energy, resilience, shear stiffness, hysteresis, bending rigidity, compressional energy, thickness, roughness, and friction. Depending on the requirements, importance is attached to properties affecting feel, handle, and appearance. Due to the complexity and expensiveness of the instrument, some mills use FAST (fabric assurance by simple testing), which is simpler and less expensive.

**Surface-variation function**

In mid 1980s, Wegener [67] introduced a surface variation function to estimate the irregularity of the textile surfaces. He suggested that the variance-area relation of fabrics characterizes the variation of a property in its dependence on the measured area similar to variance-length relation of linear fiber assemblies. Analogous to within and between length variations of variance-length curves, internal and external surface variation function, as well as a total coefficient of variation, were discussed in his paper. He pointed out that the surface variation function can be satisfied for different properties of a fabric such as mass, thickness, reflectivity, absorption, and air and water permeability. However, he suggests that mass distribution acquires practical importance due to following reasons:
mass per unit area is often used in irregularity measurement of textile fabrics;

- the mass for unit area and its scatter are experimentally easy to determine.

The surface coefficient of variation CB(A) of the masses $G_i(g)$ of $N$ square fabric samples of area $A(cm^2)$ was determined as follows:

$$CB(A) = \frac{100}{G} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (G_i - \bar{G})^2}$$

(2.35)

where $G_i$ = mass of the $i^{th}$ sample of size $A$ within the fabric,

$\bar{G}$ = average mass of samples of area size $A$, and

$N$ = total number of fabric samples with size $A$.

Defining the ideal weaving process as a process in which the yarns are uniformly spaced, the thick and thin places in the yarn are randomly distributed in the fabric, the yarn tension and weaving conditions are constant, and the fabric contains no faults, Wegener [67] suggested that the irregularity of warp yarn and weft yarn and the deviation from an ideal manufacturing process causes fabric mass variations. As with between length variation curves, between area variation curves decrease as section size or cover increases. This can be explained by the doubling law but in two dimensions and is given by

$$CB^2(A) = \frac{CB^2(L_1)z_1(e_1TG_1)}{e_2TG_2} + CB^2(L_2)z_2$$

$$\sqrt{A[\frac{e_1TG_1}{z_1} + z_2]^2}$$

(2.36)
where $A$ is the sub-sample area of a square fabric,

$CB(L_i)$ is the length variation of yarn $i$,

$L_i$ is the extended sample length of the part of yarn $i$ in the fabric,

e$_i$ is the crimp % of yarn $i$,

$z_i$ is the thread density of yarn $i$,

$TG_i$ is the count of yarn $i$, and

$i=1, 2$ yarn 1 and yarn 2, respectively.

For a fabric having the same structure in the warp and weft directions, the indices of quantities $z$, $e$, $TG$, and $CB(L)$ can be omitted in Equation 2.36 and the surface variation function simplifies to

$$CB^2(A) = \frac{CB^2(L)}{2z\sqrt{A}}$$  \hspace{1cm} (2.37)

![Graph showing CB(L) and CB(A) for a fabric.]

Figure 2.15: CB(L) and CB(A) of a fabric [67]

As seen from Equation 2.37, $CB^2(A)$ is less than $CB^2(L)$ by the factor of thread density and sample area. Consequently, the CB(A) curve has greater negative slope than the CB(L) curve for small values of $L$ and $A$. Therefore CB(A) approaches zero faster than CB(L) as shown in Figure 2.15.
Wegener conducted experiments that showed that the observed CB(A) in a real weaving process was higher than the theoretically calculated one. According to him the reasons for this disagreement were:

- non-uniform thread spacing;
- non-random distribution of thick and thin places in the fabric;
- tension differences and faults (knots).

It was suggested that the surface coefficient of variation contains irregularity contributions of warp and weft as

\[
CB(A) = \frac{\sqrt{Var_w(A) + Var_p(A)}}{X_w + X_p}
\]

(2.38)

where \(X_w\) and \(X_p\) are the mean masses of individual warp and weft contributions. Therefore \(X_w + X_p = \bar{G}\), and \(Var_w(A)\) and \(Var_p(A)\) are the variance contributions of individual warp and weft masses.

Wegener finally derived the surface variation function for an ideal knitting process assuming single-yarn system and setting warp-thread density to zero as follows:

\[
CB^2(A) = \frac{CB^2(L_s)}{z_s \sqrt{A}}
\]

(2.39)

where \(z_s\) = stitch density of fabric,

\(L_s\) = is the yarn length in a row of stitches.

As in woven fabrics, he observed that the surface variation function of a knitted fabric was also higher than the theoretically calculated one.

**Variance-area curves**

Han et al. [31] developed two prediction models for fabric quality based on 2-D and 3-D electronic fabric images. These fabric images were obtained by mapping yarns into specific locations in a 2-D matrix array. Han et al. suggested two types
of variance-area curves, $CV(A)$ and $CB(A)$ curves, to quantitatively judge the fabric quality in its dependence on the measured area. It was shown that the variance-area curves approach their limits asymptotically as the unit area increases similarly to the variance-length curves. Han et al. [31] also demonstrated that a larger $CB(A)$ value implies a greater appearance variation especially in the form of scattered fabric non-uniformity such as cloudiness and bárre.

Han et al. [31] finally investigated the invariance property of the variance-area curves within a fabric by arranging the weft yarns to either random or specific locations within the fabric. They concluded that as long as the original yarn data sets remain the same, the variance-area curves would be identical regardless of the way weft yarns are arranged.

### 2.2.2 Fabric visualization systems

Until recently, no commercial system existed for predicting or visualizing fabric qualities directly from the yarn diameter or mass measurements taken on-line. There are now several systems, such as $CYROS^\text{®}$, $USTER^\text{®}$, $EXPERT^\text{®}$ and $OASYS^\text{®}$, that visualize yarn and fabric qualities through various types of images created directly from the yarn profiles captured from certain measurement sensors. However, these systems are not completely satisfactory because of the way the yarn data are converted into fabric images. These images also require subjective visual judgment in the absence of a quantitative measure.

More importantly, none of the existing systems maps or fingerprints the quality of a woven or knitted fabric for an entire roll. Therefore, there exists no method for judging and ranking the visual or physical qualities of fabric rolls produced from a given machine at different time points or from different yarns, or from more than one machine. Other difficult technical issues include how to define and measure yarn signals optically, capacitively or opto-capacitively. The optical method or the
The capacitive method currently being used is known to be grossly inadequate due to
distortion of actual yarn images within a fabric. Until recently, no technology existed
for fusing the two independent datasets (capacitive and optical readings). Now there
are commercial systems for making more than one measurement within a given tester
(Uster Tester 4-SX using OM sensors, Keisokki opto-capacitive dual sensor system).

2.2.3 Anisotropy of 2-D texture images

C. T. J. Dodson investigated the uniformity and anisotropy of 2-D texture im-
ages of structures such as paper, nonwoven materials, and medical images. Dodson
[54] gave definitions of anisotropy and isotropy as follows, respectively: the random
field is anisotropic if adjacent pixels have a stronger correlation along one direction
than another direction; if the correlation between grey-levels decreases equally in all
directions, then the random field is isotropic.

In addition, Dodson et al. [53] suggested an index called anisotropy for the quan-
tification of anisotropy in 2-D structures. According to his approach, an ellipse was fit-
ted to a number of variance-between-area readings at different angles. The anisotropy
index was then defined to be the function of eccentricity of the best-fit ellipse for each
unit area size. If the correlation between the points of a fabric decreases equally as
a result of isotropy, then the ellipse will be a circle, and if they are highly correlated
then the ellipse will be highly elliptic. However, since a woven fabric is made of
mainly two groups of yarns, warp and weft, it may not be necessary to investigate
other directions.

2.3 Summary of relevant literature review

Extensive research work, such as the introduction of quality indices, time series
analysis, Fourier transform, and Wavelets have been carried out to develop systems for
characterizing numerous fabric and yarn properties. Several authors [67, 46] suggested that the quality of fabric can be predicted from the CV(%) of the yarns that are used within the fabric. However, the CV(%) is grossly insufficient to predict the features of irregularities, as it is not location specific within the fabric.

In addition to the CV(%), several methods are developed to evaluate fabric qualities that are based on the actual fabric. The Kawabata System (KES) [61] and fabric assurance by simple testing (FAST) are among the ones that are industrially accepted. They provide indices for quantification of various fabric qualities. Recognizing the difficulty in assessing fabric irregularities from a single number, it was suggested that the aesthetics and appearance qualities of fabrics could be visualized with the information obtained on yarn properties without having to weave or knit a fabric. This prediction is usually achieved by collecting on-line or off-line mass and/or diameter information of yarns and simply mapping them into a 2-D matrix, such as shown in Figures 2.16 and 2.17, through a simulation technique [74, 48, 59].

While the existing visualization methods (CYROS®, etc.) do not quantify irregularity, the fabric evaluation systems (KES®, FAST®) on the other hand provide an index for quantifying quality. However, information on the irregularity features of fabrics cannot be obtained from a single number.

Townsend and Cox [62] suggested that the relationship between the coefficient of
variation and the length within which the variance is measured leads to indices char-
acterizing the types of yarn irregularity that have practical importance. They char-
acterized the uniformity of the yarn along the yarn axis, and expanded the CV(%),
a point estimate, to a series of numbers expressible in two curves also known as
variance-length curves. They showed that the variance-length curves provide a much
more powerful method for discriminating the irregularity features of the spun yarns
than any other method.

Wegener [67] introduced the surface variation function, which is determined by
partitioning the 2-D fabric into subsections and calculating the mass variation between
these sections. In addition, he derived the relationship between variance-length and
the surface-variation function for square unit-areas. He finally concluded that the
surface-variation of a fabric could be estimated from the variance-length relationship
of the yarns that are used; therefore, it is not necessary to obtain the surface variation
function of a fabric.

Fundamental problems of on-line yarn monitoring systems are the storage and
handling of vast amounts of data. Kim et al. [41] developed a system for characteri-
zation of yarn properties (mass, diameter) using a wavelet-stochastic hybrid method.
According to the method developed only the essential statistical information and sig-
nificant events are recorded and a vast amount of normal data is filtered out. While
the stochastic models facilitate detection and identification of the spinning faults,
wavelet analysis allows the compact representation of the necessary information. It
was shown that a variety of virtual yarns could be generated with the algorithm devel-
oped for data reduction. Generation of vast amounts of simulated yarn data, however,
requires a better understanding of yarn geometry. Most studies, which describe the
geometry of yarn and fabrics, assume a circular cross section for the yarn. With
advances in image processing and computing, it was demonstrated that the shapes of
yarn cross-sections could be better approximated as ellipses [64]. However, the interactions between the twist and the elliptic cross-section of the yarn, the distribution of eccentricity, and the orientation of the major axes with respect to the twist of the yarn have not yet been addressed. Attempts have been made to estimate the twist of yarn by finding the slope of this best-fit sine curve of the fibers laid on the surface [16]. Because yarn has an elliptic cross-section, the sine curve approximation must be revised in order to improve this estimation.
Chapter 3

Methodology for this research

Variance-area curves are developed for studying the non-uniformity of fabric properties in two-dimensions, analogous to variance-length curves of spun-yarns in a unidimension. The CV(%) of fabric thickness and appearance are be expanded to a series of variance components, which, in turn, form CV(A) and CB(A) curves. These two curves are be used for characterizing and discriminating the aesthetics and thickness of fabrics. However, unlike the case for variance-length curves the calculation of variance-area involves infinite choices when it comes down to the selection of the shape for a given area of the fabric. These different options for choosing the sub area in fact may lead to a powerful tool for characterizing the appearance uniformity of the fabrics unless the fabric is perfectly isotropic. As part of this research, the opportunities that might be brought about by the existence of two-dimensional anisotropy are examined. In addition, the circumstances that lead to invariance properties of fabrics due to two-dimensional anisotropy are studied within a theoretical framework.

It is believed that the interaction between the elliptic shape of a yarn cross-section and the yarn twist may also play an important role in the construction of the variance-area curves. Therefore, the complex relationship between the twist and the distribution of the eccentricity of the elliptic yarn profile are modeled mathematically. By this, we hope to suggest a more deterministic yarn simulation technique, which
takes into account irregular twist, eccentricity, and diameter distribution.

The objectives of this research are:

- to characterize and quantify irregularity features of fabric properties;
- to develop a better algorithm for determining and measuring yarn diameters;
- to develop methods for mapping yarns into fabrics;
- to develop a prediction model for the existence of isotropy or anisotropy in fabric properties based on yarn measurements;
- to suggest a model for the generation of more deterministic yarn data;
- to investigate the effect of elliptic yarn cross-sections on fabric appearance.

3.1 Approach

The following tasks are carried out to achieve the objectives of this research:

I. experimental measurement of yarn eccentricity, cross section, and core diameter;

II. acquisition or generation of a sufficiently large yarn data base for fabric simulation;

III. development of mapping techniques where yarn data are used to construct virtual fabrics;

IV. development of quantitative methods for prediction and/or evaluation of fabric uniformity;

V. development of a theoretical framework to understand the circumstances that lead to invariance properties (thickness, mass, etc.) of fabrics.
Chapter 4

Instrumentation and Experimental Setup

This chapter details information on the instruments and experimental setup employed in this study. Pertinent information about individual devices and procedures is provided as needed in the following chapters.

As previously stated, the main objective of this research is to predict and quantify the visual and physical properties of fabrics from actual yarn signals. This process requires the determination of yarn properties and the mapping of them into virtual fabrics. While the former required the establishment of a yarn data acquisition system, the latter was accomplished by implementing several MATLAB scripts for mapping yarn information into a 2-D fabric image and analyzing them. The following subsections describe the yarn data acquisition setup and yarn to fabric mapping in detail.

4.1 Yarn Data Acquisition System

Two systems were developed for capturing yarn profiles. In the first system, a linescan camera and a mass sensor capture yarn data in real-time. For each millimeter of yarn, the counter generates a pulse, triggering the camera and the mass sensor. The data from the camera and mass sensor are collected and stored in an array. The size of the array is cross-checked with the location information provided by the counter.
Although data fusion has been implemented in many engineering systems, it has not been widely used in textiles because of the non-linear interactions of multiple inputs to multiple outputs. Additionally, different sensors have different sampling rates, precision, accuracy, bandwidth, etc., that make combining measurements difficult. We have developed a new hardware system at NC State University that enables us to control the input tension and speed while simultaneously measuring output tension, yarn diameter (every 1 mm) and capacitance (every 8 mm). Previous work [36] suggests that the diameter and mass variation of a yarn is correlated. Therefore, we did not think it was necessary to combine these two readings to produce a set of new signals to predict both the appearance and the physical properties of yarns.

In addition, in order to understand the relationship between a given yarn cross-section and the twist of the yarn, it was necessary to continuously capture yarn images in three dimensions without distorting the structure of the yarn. Therefore, a second imaging system was developed using an area-scan camera and a makeshift jig [37]. This system allows one to take two-dimensional pictures of yarns off-line while the yarn is rotated around its axes at twelve 30-degree steps.

Moreover, software was also developed that communicates with the hardware to collect data and store them in a file for further analysis. The text below, details the two systems briefly mentioned above.

This chapter is organized in the following order:

I. the hardware components specifications and capabilities are detailed;

II. the configuration of the measurement system components are described;

III. the software architecture and the algorithm developed to capture yarn information in real-time is explained;

IV. samples of the experimental results are presented.
4.1.1 Hardware components

Real-time yarn measurement with a line-scan camera

The real-time yarn measurement system is comprised of a Lawson-Hemphill CTT, an encoder connected to a counter board, a Thompson CCD line-scan camera, a DIPIX vision board, and a Keisokki capacitance sensor connected to an ADC board as shown in Figure 4.1. The data gathered from the line-scan camera and the capacitance sensor are synchronized with the encoder signal. A Graphical User Interface (GUI) was developed to control the system for data acquisition and basic analysis.

The GUI, the Linux drivers of the counter, and the ADC board was developed at NCSU [35]. While the vision board image library, XVL, was obtained from DIPIX, the Linux driver of the vision board was obtained from the open source community.

Lawson-Hemphill CTT and the Encoder:
This system was built on a Lawson-Hemphill Constant Tension Transport (CTT) unit
in order to ensure constant tension during yarn transportation as shown in Figure 4.2. The vision board was first installed on a Pentium II PC running Linux 2.2 Kernel and later upgraded to a PC with AMD Athlon 3.2 GHz processor, running Linux 2.4 Kernel. Lawson-Hemphill CTT came with two encoders. Encoder signals were input into a PCI-CTR05 Counter Board and the DIPIX Vision Board.

Detailed descriptions of some of the hardware components are given below.

**Figure 4.2: Lawson-Hemphill CTT**

**Thomson-CSF CCD TH78CA14 Linear Camera**

Thomson CCD model TH78CA14 is a digital output camera with two resolution settings: 1024 pixel and 2048 pixel [2]. At a 1024-pixel resolution, the frame scan rate is 38000 lines/sec. At a 2048-pixel resolution, this rate reduces to 19000 lines/sec.

The configuration is stored in an EEPROM controlled by a RS232 serial interface. This interface controls:

- gains (analog and digital);
- offset;
• trigger mode;
• output mode (dual, single, or binning);
• external or internal clock choice.

Although five different modes are available for triggering, only the following two
modes are used: free-run mode and external-triggered mode. While in free mode no
external trigger is used to control the integration time. In trigger mode, an external
signal can be used to trigger on an external event and control the integration time.

**DIPIX FPG-44 Power Grabber Vision Board**

This is a frame grabber and high-speed image processing board for PCI bus PCs.
It supports simultaneous image acquisition and processing up to 20 MHz for analog
inputs or up to 32 Mbytes/sec for digital inputs. The vision board grabs images from
the line-scan camera. Image acquisition can be triggered by an external or an internal
source. In this system, the camera serves as the internal source, and the encoder of
the Lawson-Hemphill CTT serves as the external source.

**PCI-CTR05 Counter Board**

The function of the Counter/Timer is to measure frequency by event counting. In
our setup, the event is generated by the encoder of the CTT.

**PCI-DAC 16/330 Analog to Digital Board**

The output of the Keisokki capacitance sensor is connected to this ADC board. The
analog signal, which contains the mass information of the yarn, is digitized and stored
in an array along with the diameter information of the yarn.

**2-D yarn measurement with an area-scan camera**

Our three-dimensional yarn profile analysis system is comprised of a Pulnix TM-
1020-15 progressive scan camera, an Engineering Design Group (EDT) frame grabber
board and a makeshift jig.

Detailed descriptions of the components are provided below.
Pulnix TM-1020-15

Pulnix TM-1020-15 is a progressive scan camera connected to an Engineering Design Group (EDT) frame grabber board. It has an interline CCD with pixels of 1024(H) by 1024(V), of which 1008 x 1018 are active. The camera is capable of taking 15 frames per second, and has a shutter speed of up to 1/16,000 sec. The video output is BW 8-bit RS-422 with a S/N ratio of 50 db.

Makeshift Jig

A makeshift jig, seen in Figure 4.3, was built to be placed in front of a camera. It allows yarn to be tightened from both ends by clamps as it was rotated along its axes at six equal angles (0, 30, 60, 90, 120, and 150 degrees). In order to avoid yarn distortion and preserve yarn’s twist, a metal bridge was also installed that rotates both clamps together. When the optional metal bridge is removed and one clamp kept constant, twist can be inserted or removed with the rotation of the other clamp.

![Figure 4.3: Makeshift jig [Thanks to Nonwovens Research Center, NCSU for providing this instrument.]](image)

4.1.2 Configuration of the measurement system components

Our experiments required the configuration of the camera using the *CommCamm* camera software, modification of the DIPIX XVL library camera configuration file, *TH78CA14.cpf*, determination of the optimum light intensity, determination of the
pixel width, and optimization of the XVL software library and FPG driver.

Camera configuration

The line-scan camera can be set to capture images in one of the two resolutions, 1024 or 2048. While the latter setting includes all the pixels that are captured, in 1024 resolution, the even pixels are skipped and only odd pixels (1, 3, 5, ..., 2047) are recorded. As one would expect, higher resolution would result in better yarn image, but reduced performance due to limited bandwidth.

![Camera configuration CommCam](image)

**Figure 4.4**: Camera configuration CommCam for 1024 resolution and free mode

In addition to resolution, the event type which triggers the camera for image capture must be selected. One can select the appropriate choice from the *timing* combo box in the application software shown in Figure 4.4. Two options, *free mode* or *external trigger mode* are available. In free mode the vision board triggers the camera for the next picture whereas in external trigger mode, an external event triggers the camera to capture the next yarn image. An encoder pulse was used as an external trigger. Some of other configuration parameters that need to be set using
the software shown in Figure 4.4 are described below:

**Internal clock** is used to set the internal clock frequency. The possible values are either 40 MHz or 20 MHz. The setting is ignored if an external trigger is used to initiate the image acquisition.

**Timing** is used to set the source trigger type. For external sources, the external trigger mode must be selected, whereas for internal sources the free mode must be selected.

**Multiplexing** sets the resolution to 2048, otherwise the resolution defaults to 1024. Setting internal clock to 40 MHz at 2048 resolution is not allowed.

**Binning By 2** is selected if the camera feeds more than one frame grabber. However, this is not germane to the system developed.

**Camera configuration files**

The DIPIX libraries are equipped with several JED files as well as an executable file called 'fpg.out’. The executable file was used to initialize the frame grabber. The accompanying catalog does not explain the function of the JED files, but suggests that the *A12082.JED* should be chosen if the FPG is to supply a trigger signal to the camera and that the *A12082NC.JED* should be chosen if encoder is to supply a trigger signal to the camera in the DIPIX XVL library camera configuration file, *TH78CA14.cpf*.

**Determination of the optimum light intensity**

The vision system consists of a camera and a light source as shown in Figure 4.4. The intensity of the light source can be adjusted between 0 and 10 by varying the lamp voltage.
In addition, the camera produces 12 bit data per line-scan where each bit may take one of the two values, that is 0 or 1. Consequently depending on the light intensity, the output is expected to have a range between 0 and $2^{12} - 1 = 4095$. If the light is blocked from reaching the camera, the observed intensity should be zero and if the light is allowed to reach the camera at full intensity, then the pixel value should reach up to 4095.

Using ANSI C and MATLAB, two program were written to understand the effect of light intensity and environment on the image acquired. The program written in C grabs a frame and stores the pixel intensity data in a file. The program written in MATLAB simply plots the pixel intensity values. In addition, it also prints out their statistics and the location of the pixels whose intensity values are not 4095. The light meter voltage was first set to 2, and the pixel intensity values were plotted as shown in Figure 4.5. As can be seen, the intensity values varied around 2400 with fluctuations near the first and last pixels.

The testing continued by incrementing the voltage by one up to 10. It was observed that until the voltage reached 7, the pixel light intensity values consistently increased. The pixel light intensities for voltage level 7 are shown in Figure 4.6. One can see that a straight line formed at level 4095. However there were still some points where the intensity values were not 4095. As the voltage increased most of these points
disappeared and finally, at light-meter voltage 10, the plot shown in Figure 4.7 was obtained. Except for three pixels, the light intensity values for all pixels were 4095.

Two other experiments were also conducted by turning on and off the room light while the light-meter was turned off. It was observed that the light intensity values were at a level close to zero and were not affected by the ambient of the room light.

**Pixel width determination**

Two metal wires of known diameters (0.91 mm and 0.87 mm) were placed in-between the light source and the camera. The line-scan of wire profiles is shown in Figure 4.8 and 4.9. The distance between the two sides of the valley at the threshold intensity level 3000 was measured in terms of pixels for each wire. The pixel widths
(225 and 216 dots) were then divided to actual diameters of the wires to obtain pixel widths in mm. The pixel width was found to be approximately 0.004 mm.

4.1.3 Software design for real-time yarn measurement system

The real-time yarn measurement software was developed using both ANSI C and JAVA. It is currently installed on a PC with an AMD Athlon 3.2 GHz processor running Linux Kernel 2.4. While the user interface was implemented using JAVA, the computation intensive image processing parts were implemented using C. The bi-directional communication between JAVA and ANSI C was achieved through JNI (Java Native Interface).

![High level software architecture](image)

**Figure 4.10:** High level software architecture

Figure 4.10 shows the high-level software architecture. The software resides in two spaces, the kernel space and the user space. The user space consists of three
major components: the Graphical User Interface (GUI), the Yarn Processing Engine (YPE), and the XVL Libraries. The kernel space contains the drivers of the vision board, ADC board, and the counter board. As seen from Figure 4.10, the user interface interacts with the YPE, and the YPE interacts with the XVL Libraries, the ADC/DAC and the counter drivers. Notice that the vision board drivers are not accessed directly but only through the XVL Libraries.

**Data acquisition software design details**

![Diagram](image)

**Figure 4.11**: Time-line of software developed

Once one clicks the start button on the GUI shown in Appendix B, the YPE is called in order to capture a real-time yarn image. The YPE next calls the XVL Libraries, the ADC board, and the counter board drivers. The XVL Libraries, in turn, call the XPG driver. Finally, the drivers command the hardware and return data back to the user space. As data arrives to the YPE, the user interface is notified with the new yarn data. In the user interface, the event listeners are awakened, and the GUI panels are refreshed.

The real-time yarn measurement begins with the initialization of the YPE. The
engine falls in a loop and waits for the first yarn image data to arrive. However, image acquisition will not occur until the vision board and the camera are triggered by an external source from the encoder. As yarn moves through the CTT, the encoder triggers the vision board and the yarn image acquisition begins. With the arrival of yarn data in every millimeter (the default setting), the YPE calls one of the yarn analysis sub routines and returns the diameter and also the hairiness information of the yarn. In addition to yarn image acquisition, the capacitive and the counter readings are done at the same time. While, the capacitive reading is used to determine the mass information, the counter reading is for the verification of the current yarn location. As yarn properties are determined, they are forwarded to GUI to be displayed.

**GUI software design details**

The Model-View-Controller software design pattern shown in Figure 4.12 was implemented in the graphical user interface. The yarn attributes are wrapped by a data entity (model) and shared between the viewer and the controller. The duty of the controller is to establish communication between the GUI and the YPE through JNI.

Once the application shown in Figures B.1 and B.2 starts, the main function creates a viewer and a controller. The viewer constructs the GUI and registers two listeners to detect start and stop button clicks. If the user chooses to start the application, a listener, which is responsible for directing data into panels as received from YPE, is registered. In addition to the listeners, a buffer is created to store data, and a thread is initiated to allow asynchronous communication between GUI and YPE. As data arrives at GUI from YPE, they are stored in the buffer until the number of items in the buffer exceeds a preset number. Once the buffer overflows, all the panels are notified to refresh themselves in order to display the latest data.
Diameter calculation algorithms

Lawson-Hemphill diameter calculation algorithm

The Lawson-Hemphill method determines the diameter of a yarn profile as shown in Figure 4.13 as the distance between the first and last intersections of the yarn signal with the threshold line. This distance is shown in Figure 4.13 with the symbol \( c \). Using this method, the hairier the yarn profile is, the greater the imprecision in the measured diameter of the yarn. See Figure 4.14. A closer look at figure 4.13 shows that the actual diameter of the yarn profile is better indicated by symbol, \( d \), the distance between the intersection of the deepest parabola and the threshold line. Our method allows for a more accurate measurement of the diameter of the yarn profile.

Implemented diameter calculation algorithms
The following three methods were developed to determine a yarn diameter from a typical yarn line-scan image as shown in Figure 4.15

**Method-1:** Two assumptions were made:
the minimum light intensity valued pixel (core pixel) is located at the core of the yarn body;

- the yarn diameter is located at a threshold line, which is chosen to be 3/4 of (minimum + maximum) pixel values.

The implementation of this method seeks two pixels, one on the left hand side and the other one on the right hand side of the core pixel, which are closest to the threshold line. The search begins from the core pixel and continues on both sides until the threshold line is approached. The diameter is defined to be the distance between these two pixels (see $d$ in Figure 4.15). The running complexity of this algorithm is $O(n)$ where $n$ is the number of pixels in the
line-scan yarn image (1024 or 2048 in our case).

![Intensity vs. Pixel](image.png)

**Figure 4.15**: Yarn diameter defined with the first method

**Method-2**: This method is the same as the first method except that the threshold line is lifted to the maximum possible light intensity value, that is 4095. At this level, diameter definition becomes easier and requires less computation. The running complexity of the function is still on the order of $O(n)$. Unfortunately, for a yarn profile such as shown in Figure 4.15, this method will overestimate the actual diameter. There is also no guarantee that the diameter can be defined at this high threshold level (see Figure 4.15, symbol c).

**Method-3**: After examining several yarn profiles, it was observed that hairs in yarn were often counted as part of a yarn body when using the first two methods (see Figure 4.15). Accurate measurement of yarn cross-section requires exclusion of these hairs from yarn diameter measurement.

Assuming that the minimum light intensity valued pixel is located at the core of the yarn body, this method locates two pixels for the boundaries of a yarn body. According to this technique, pixels are grouped in sets of 5 in both sides
of the yarn core. Beginning from the core of the yarn, a best-fit trajectory (linear line) is determined for each set in both sides and the slope of that line is compared with the experimentally determined threshold slope (40). If the slope exceeds the threshold slope, then the latest included pixel in the set is recorded for diameter calculation otherwise the process repeats with new sets of pixels until the experimentally determined threshold slopes are reached in both sides. The selection of the sets were done in two ways as shown in Figure 4.16 and described below:

I. each set are formed from completely new pixels;

II. each set contained 1 new pixel and 4 pixels of the adjacent set, also known as FIFO (First In First Out) technique.

The diameter signals of a yarn obtained using both pixel set selection methods are shown in Figure 4.17. As seen from the plots, FIFO technique produced more stable and more accurate diameter readings. This is due to the smoothing effect of FIFO implementation. The significant variation between these two yarn signals also emphasizes the importance of accurate yarn diameter measurement. When comparing yarns, it is advised to be consistent with the diameter
Figure 4.17: Different methods of pixel set selection produce different signals

calculation method.

4.1.4 Line and area scan images of various yarns and considerations

Figure 4.18 and 4.19 show pictures of a typical yarn and its typical line-scan image. The yarn cross-section blocks the light and causes a clear valley-like line-scan image as seen from Figure 4.18. On the other hand, as the yarn shown in Figure 4.20 was not densely packed, the light penetrated through it, and the line-scan image of the yarn was like the one shown in Figure 4.21. It is therefore recommended that if there is any doubt that the yarn body is not densely packed, the line-scan of yarn profile must be inspected at various random locations and a decision must be made whether or not the yarn is the right choice for the measurement system.

Figure 4.22 shows the area-scan image of a typical ring-spun yarn obtained using the area-scan camera described in section 4.1.1.
Figure 4.18: Picture of a yarn

Figure 4.19: Corresponding line-scan image of the yarn

Figure 4.20: Picture of a yarn

Figure 4.21: Line-scan image of a yarn
4.2 Yarn to fabric mapping

In this study in addition to actual fabric images, virtual woven fabric images are constructed from a pool of ten cotton spun-yarn samples as described below. For each yarn sample 500 meters of yarn was tested [31]. This corresponds to 500,000 data points, because the sampling done in one millimeter increments. Basic information about these samples is given in Table 4.1.

<table>
<thead>
<tr>
<th>Yarn sample #</th>
<th>Yarn Count (NE)</th>
<th>Twist (tpi)</th>
<th>Mean Diameter (mm)</th>
<th>CV(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.4</td>
<td>16</td>
<td>0.25</td>
<td>18.7</td>
</tr>
<tr>
<td>2</td>
<td>28.7</td>
<td>21</td>
<td>0.21</td>
<td>24.38</td>
</tr>
<tr>
<td>3</td>
<td>40.5</td>
<td>23</td>
<td>0.17</td>
<td>19.07</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>10.5</td>
<td>0.5</td>
<td>18.82</td>
</tr>
<tr>
<td>5</td>
<td>10.1</td>
<td>12</td>
<td>0.37</td>
<td>21.81</td>
</tr>
<tr>
<td>6</td>
<td>19.6</td>
<td>16</td>
<td>0.27</td>
<td>21.99</td>
</tr>
<tr>
<td>7</td>
<td>12.4</td>
<td>11.5</td>
<td>0.38</td>
<td>19.19</td>
</tr>
<tr>
<td>8</td>
<td>24.4</td>
<td>17.5</td>
<td>0.23</td>
<td>18.85</td>
</tr>
<tr>
<td>9</td>
<td>34.4</td>
<td>5.5</td>
<td>0.20</td>
<td>23.03</td>
</tr>
<tr>
<td>10</td>
<td>18.8</td>
<td>17.5</td>
<td>0.25</td>
<td>16.33</td>
</tr>
</tbody>
</table>

Table 4.1: Basic information of actual yarn samples

The actual yarn signals are mapped into a two-dimensional fabric matrix array by assigning every piece of yarn diameter information to a specific location (x, y) within a virtual fabric.
For a woven fabric, the warp yarn signals are laid side by side in machine direction (MD) and the weft yarn signals are laid side by side in cross-direction (CD). Consequently the density/thickness at a location \((x,y)\) in the virtual woven fabric is the sum of the warp and the weft yarn diameters in that cell as demonstrated in Figure 4.23.

![Figure 4.23: Mapping of warp and weft yarns into a fabric](image)

Although we have not mapped yarns for knit fabric visualization, this mapping could be achieved by simply laying yarn signals in the MD.

In order to visualize and understand the irregularity features of a virtual fabric, the 2-D matrix array is plotted as a gray-scale image as shown in Figure 6.4 using MATLAB. While the darker regions represent the higher densities, the brighter regions represent the lower density areas. This transformation will be called basic mapping. Although, basic mapping assumes zero percent filling crimp and warp contraction, it can easily be modified to simulate various yarn sizes, warp and filling shrinkage, cover factors and crimps for woven fabrics, and various stitch lengths and courses and wale counts for knitted fabrics.

Mapping of yarn signals into virtual woven fabric is particularly important when
the yarns used in a woven fabric have periodic irregularities. This is because the nature of fabric variation is likely to be determined by the wavelength of the periodic irregularities and the cloth geometry. Figures 4.25 and 4.26 show 2-D images of two fabrics constructed with different dimensions (pixel) but with the same yarn signals. As clearly seen from the virtual fabric created, the irregularity features of two fabrics are different. One of the main objectives of this study is to devise a method to detect and predict these different irregularity features.
Figure 4.25: Virtual fabric of size 400 x 400 pixels (warp = yarn#12, weft = yarn#12)

Figure 4.26: Virtual fabric of size 500 x 500 pixels (warp = yarn#12, weft = yarn#12)
Chapter 5

Analysis of Spun Yarn Structure and Generation of Diameter Data

A major difficulty in fabric visualization is the necessity of acquiring and storing vast amounts of yarn data. Kim et al.[41] suggested a wavelet-stochastic hybrid model for yarn diameter simulation to overcome these difficulties. According to the method developed, only the essential statistical information and significant events are recorded, and majority of the nominal data are filtered out. While stochastic models facilitate detection and identification of spinning faults, wavelet analysis allows the compact representation of the necessary information with up to a 99.9% data reduction rate. It was shown that a variety of virtual yarns could be generated with the algorithm developed for data reduction.

Data reduction was achieved by considering the spun yarn as an assemblage of fibers with random thick and thin places and neps [41]. The parameters of these imperfections are the amplitude of the fault, the length of the fault, and the arrival time of the fault. The Poisson process was used to characterize the arrival time of a fault. For the length and the amplitude of thick/thin places, Gamma distribution and Generalized Pareto distribution were chosen respectively. When one considers theories about the mechanics of yarn structures, it is also possible to suggest a more deterministic yarn simulation algorithm. In this study, a deterministic yet simple
yarn generation algorithm is proposed. This required the detailed understanding of
the yarn structure.

5.1 Analysis of yarn cross-section

One of the most common assumptions in the field of textiles is that a yarn cross-
section is circular. When one considers varying tension, twist, and yarn count, it
might be expected that the yarn cross-section may not be consistently circular. In
actuality, the yarn cross-section tends to concentrate the structure into an irregular
close-packed polygonal shape [32]. It was shown that the cross-section of ring-spun
and open-end (OE) yarns can be approximated as an ellipse, even though the actual
shape may have an irregular outline [64].

The estimation of yarn cross-section by conic sections requires the aid of current
research in computer graphics. One difficulty in finding the best-fit ellipse is that
there are few direct methods for estimating (in a least squares sense) an ellipse from
noisy data. Two common techniques involve solving a generalized eigenvalue problem
with an associated non-convex constraint or by iteration minimizing the cost function
for optimum solution. Techniques also vary in terms of the fit being arithmetic [27]
or geometric [20].

It must be remembered that the eccentricity \( e = \sqrt{1 - \frac{b^2}{a^2}} \), which is essentially
the ratio of minor axis to major axis, equals '0' if the conic is a circle, '1' if the conic
is a parabola, and between \( 0 < e < 1 \) if the conic is an ellipse.

The process of obtaining accurate measurements of yarn cross-sections presents a
difficulty because the process itself may distort the yarn. It is also impractical to cut
the yarn at various locations and examine the cross-section without distorting the
yarn; however fast and accurate determination of yarn cross-section can be achieved
indirectly by rotating the yarn segment along its center.
Figure 5.1 shows a typical yarn cross-section that is obtained using a line-scan camera. The dots in Figure 5.1 mark the measured diameters for various angles. The yarn’s irregular cross-section is shown to be approximated with a best-fit ellipse with an eccentricity of 0.46.

Several yarns were examined using a line-scan camera. The typical yarn was found to have an elliptic profile with varying eccentricity along its length. The eccentricity value for the majority of the strands of yarn fall between 0.4 and 0.65.

Figure 5.2 shows the distribution of eccentricity values of 30 random locations for a ring-spun yarn with a yarn count of 17 Ne. The distribution is normal with a mean of 0.50 and a standard deviation of 0.12.

These results indicate that an elliptic, rather than a circular, cross-section is a
better approximation to the actual cross-section of the yarn.

5.1.1 Effect of elliptic yarn cross-section on the measurement of actual diameter from projected diameter

Figure 5.3: Yarn and camera position

Figure 5.3 shows the projected diameter $d$ when light is shined on a strand of yarn with semi-major and semi-minor axes, $a$ and $b$, respectively. The actual diameter, $d$, can be derived in terms of $a$, $b$, and $\alpha$, is as follows [37]:

Let $\mathbf{r}$ be a radial vector from the origin to a line tangent to the ellipse, and let $\mathbf{v}$ be the vector tangent to the ellipse.

\[
\mathbf{r} = r\hat{\mathbf{r}} \\
\mathbf{v} = \frac{dr}{d\alpha}\hat{\mathbf{r}} + r\frac{d\hat{\mathbf{r}}}{d\alpha}
\]

The cosine of the angle $\beta$ between the vectors is given as

\[
\cos(\beta) = \frac{\frac{dr}{d\alpha}}{\sqrt{\left(\frac{dr}{d\alpha}\right)^2 + r^2}}
\]
where in polar coordinates:

$$r = ab \sqrt{\frac{1 + \tan^2(\alpha)}{b^2 + a^2 \tan^2(\alpha)}} \quad (5.4)$$

Substituting Equation 5.4 into Equation 5.3 and simplifying yields

$$\cos(\beta) = \frac{ab \tan(\alpha)(1 + \tan^2(\alpha))(a^2 - b^2)}{\sqrt{\frac{1 + \tan^2(\alpha)}{b^2 + a^2 \tan^2(\alpha)}}(b^2 + a^2 \tan^2(\alpha))^2 \sqrt{\frac{b^2(1 + \tan^2(\alpha))^2 a^2 (a^4 \tan^2(\alpha) + b^4)}{b^2 + a^4 \tan^2(\alpha)}}} \quad (5.5)$$

From Figure 5.3, one can see that

$$d = 2r \cos(\delta) \quad (5.6)$$

$$= 2r \sin(\beta) = 2r \sqrt{1 - \cos^2(\beta)} \quad (5.7)$$

$$= 2ab \sqrt{\frac{b^2 + a^2 \tan^2(\alpha)}{b^4 + a^4 \tan^2(\alpha)}} \quad (5.8)$$

Equation 5.8 shows the projected diameter of an ellipse as it is rotated through an angle $\alpha$. It can be shown that the angle $\alpha$ is related to the angle $\gamma$ by the following relationship:

$$\tan(\alpha) = \frac{b^2}{a^2} \cot(\gamma) \quad (5.9)$$

Substituting Equation 5.9 into Equation 5.8 yields the following result given in [64]:

$$\frac{d^2}{4} = \frac{b^2 + a^2 \tan^2(\gamma)}{1 + \tan^2(\gamma)}$$
5.1.2 Experimental setup to measure the eccentricity of yarn cross-section

Two imaging systems were developed for analyzing yarn profiles. Although, these systems are described in detail in Chapter 4, in this section they are briefly summarized.

The first system measures yarn cross-section in a constant speed/tension zone. The system is comprised of a Thompson CCD line-scan camera, a DIPIX Video Board and a Lawson-Hemphill CTT (Constant Tension Transport) machine. An encoder pulse from the CTT is generated every millimeter to trigger the line-scan camera to capture a yarn image. The Thompson CCD line-scan camera can take images at 500 Hz (approx. 24 m/min), with a resolution of 1024 pixels/scan. A software program was developed to interact with the camera and to transfer the captured image to a computer running Linux/RT-Linux for further analysis.

To capture two-dimensional continuous images, a second imaging system was developed. This system is comprised of a Pulnix TM-1020-15 progressive scan camera connected to a Engineering Design Group (EDT) frame grabber board. It has an interline CCD with pixels of 1024(H) by 1024(V), of which 1008 x 1018 are active. The camera is capable of taking 15 frames per second, and has a shutter speed of up to 1/16,000 sec. The video output is BW 8-bit RS-422 with a S/N ratio of 50 db.

It is important that the yarn not be distorted for accurate cross-section determination, therefore a makeshift jig was built and placed in front of the high resolution area camera. The yarn was then tightened from both ends as it was rotated along its axes at 6 equal angles (0, 30, 60, 90, 120, and 150 degrees). In every position, the image of the yarn was taken and, using image processing techniques, the diameter of the yarn was determined. Figure 5.4 shows one such image and the detected edge using an edge detection technique.
5.1.3 Measurement of yarn cross-section eccentricity

A 105 tex 2-ply yarn was measured with both imaging systems. Using the area scan camera, the projected diameter was measured at six different positions by rotating the yarn about its axes. The six positions, because of symmetry, generated 12 data points for each cross-section. A best-fit ellipse, in a least squares sense, was determined using each of these points.

Two techniques, namely arithmetic and geometric fitting of an ellipse, were implemented with MATLAB [34]. It was found that as long as the points were distributed evenly, both methods gave identical results. Figure 5.5 shows the eccentricity of the yarn calculated for each of the points along the strand. The mean eccentricity value found to be around 5.5 with standard deviation 1.121.

5.1.4 Rotation of major and minor axes with twist

As a result of twisting the stream of straight and parallel fibers during the process of yarn formation, the fibers are laid along the helix [16]. On the basis of this observation, we investigated if in fact the elliptic yarn cross-section actually rotates with
the twist. Careful analysis of the yarn revealed that the semi-major and semi-minor axes in fact rotate periodically with the yarn’s twist. The period $\omega$ of this rotation is given by $\omega = 1/\text{turn per unit length}$.

Figure 5.6 simulates the projection of the profile of an ideal strand of yarn. The ideal strand in this case is assumed to be an elliptic yarn whose semi-major axis $a$ and semi-minor axis $b$ rotate about its geometric center. The wave shape seen in Figure 5.6 is constructed using Equation 5.8 where $0 < \alpha < 2\pi$ and $d(\alpha) = d(\alpha + 2n\pi)$ for any integer $n$.

Figure 5.7 shows a section of yarn and the best-fit curve based on Equation 5.8. In order to find the best-fit curve, the yarn diameter profile is first partitioned into sections and then the parameters $a, b, \alpha$ are estimated, while minimizing the cost function given below:

$$\sum_{i=1}^{\text{partition size}} \|d_{\text{data}} - d_{\text{model}}\|^2$$ (5.10)

As is clearly seen, the model seems to fit the data with very small residual. In addition, Figure 5.7 shows the eccentricities calculated for each neighbor peak and valley. For selected segments (1/2 inch of yarn), the mean eccentricity was predicted to be 0.53, which is fairly close to the value of 0.55 found from image analysis for this particular yarn.

In addition, Figure 5.8 shows the projected diameter of the yarn. The solid line
Figure 5.7: Fitting model to a section of yarn

shows the projected diameters at two different angles that are 30 degrees apart. The cross-correlation of the two lines shows a maximum correlation at 16 pixels. The dashed line results from back shifting the measurement at 30 degrees by 16 pixels. This shows that the effect of eccentricity may be the major source of diameter variation experienced when the profile is observed from only a single angle. The theoretical CV for this yarn, assuming the twist, the eccentricity and the mean diameter being constant, was calculated as 7.2%, which is the result of the rotation of the semi-major and semi-minor axes. The experimentally measured CV was found to be 9.0% using the line-scan camera and measuring the diameter of the yarn at 1 mm intervals. It must also be noted that the CV of the yarn would be higher as eccentricity increases.

Figure 5.9 show the same effect in 2-dimensions for 5 angles. The grey-scale represents the contour effect along the yarn for each of these angles. A clear shift toward the left in the image is also a result of eccentric cross-section’s rotation with
**Figure 5.8:** Two diameter readings of a yarn, the yarn is rotated by 30 degrees before second reading.

the twist of the yarn.

**Figure 5.9:** The effect of elliptic cross-section rotation with twist

**Estimation of twist**

Since the eccentric yarn cross-section rotates with the twist of the yarn, one can directly estimate twist by tracing this rotation. Figure 5.10 is obtained by finding the best-fit period using the mean eccentricity value given previously. While the period of this rotation is a function of twist, the shape of the curve is a result of Equation 5.8.

Since the period (\( \omega \)) of the twist is given by

\[
\omega = \frac{1}{\text{turn per unit length}}
\]

One can estimate the twist directly by
twist = \frac{1}{\omega}

For this segment of the yarn, we in fact found the actual twist to be twelve turns, which correlates with the actual value of twist measured with the traditional method for this particular yarn.

Figure 5.10: Fitting model to a section of yarn to estimate twist

5.1.5 Relationship between twist, eccentricity and yarn cross-section

As already mentioned in section 2.1, Balls [4] suggested that during drafting fibers move in groups causing non-random wave-like patterns in the resulting sliver or yarn. He called these movements drafting waves and showed that they are responsible for periodic thin and thick places over the yarn. Later Foster [24] investigated the effect of drafting wavelengths on yarn irregularity and noticed that neither the wave nor the amplitude was constant. With this background, the theoretical relationship between the twist of a yarn and its diameter may be established as follows:

Unit twist can be given as $P \tan(\theta)$ where $P$ is the circumference of the yarn and $\theta$ is the twist angle as shown in Figure 5.11. During staple yarn production,
the twist given per unit length of yarn is kept constant, hence the parameter $S$ in Figure 5.11. As a result of drafting waves, when a thick or thin place is encountered, the change in the circumference of yarn, $P$, must be compensated by the change in unit twist, $T = P \tan(\theta)$. The unit twist, $T$, decreases as $P$ increases (a thick place), and $T$ increases as $P$ decreases (a thin place). This was also suggested by Barella [6] as: *Twist is not constant, but concentrated in the thinnest parts of the yarn. Therefore, high twist compress thin places and exaggerates the variations in the apparent diameter.*

![Figure 5.11: Twist triangle](image)

In addition, a relationship between twist and eccentricity may also be established with the following simple reasoning. Assume that there are several yarns $(y_1, y_2, y_3, \ldots, y_n)$ with the same yarn count and packing densities, and hence the same cross-sectional area. Assume also that these yarns have elliptic cross-sections and are ordered with increasing eccentricities, $e_i$ where $0 \leq e_1 < e_2 < e_3 < \ldots < e_n < 1$. For the equivalent cross-sectional area, increase in eccentricity causes an increase in

![Figure 5.12: The perimeter of an ellipse as eccentricity increases](image)
the circumference \( P \) of the yarn as shown in Figure 5.12. In order to keep the same level of twist, \( S \), the unit twist, \( T \), therefore should decrease.

The complex relation between twist, eccentricity, and a yarn cross-section may be highlighted as follows:

I. in thick places of yarn, the twist is lower and eccentricity is higher;

II. in thin places of yarn, the twist is higher and the eccentricity is lower.

The relationships given above assume that the packing densities are equal, however in reality, as the twist increases, the packing density increases and causes the yarn cross-sectional area to decrease. This also forces yarn to become more round and the eccentricity to drop.

These expectations are also in agreement with the remarks stated by [64]: *the greater the twist and linear density (tex) the smaller the ellipticity of the yarn-cross section.*

![Extra Twist vs. Eccentricity](image.png)

**Figure 5.13:** Change in yarn cross-section eccentricity as additional twist is introduced

An experiment with highly twisted 2-ply yarn was conducted to test these logical conclusions. The eccentricity of cross-sections was measured at several locations of the yarn, and the mean eccentricity was found to be around 0.52 with little standard deviation (< 0.03). The yarn was next tightened from both ends to the clamps of the
makeshift-jig described in detail on page 55. The yarn was then rotated once along its axes to estimate the initial eccentricity of the cross-section measured. Afterwards additional twist was introduced through the makeshift-jig, and the eccentricity was estimated. The last step was repeated, and twist versus eccentricity and diameter were plotted as shown in Figures 5.13 and 5.14, respectively. It was observed that as the twist increased, both the eccentricity and the diameter of the yarn cross-section decreased.

5.2 Generation of yarn diameter data

It is now possible to generate more accurate yarn signals as we understand more about the interaction between the yarn cross-section, eccentricity, and twist. At this stage of the research, several virtual yarns were generated and mapped into a 2-D fabric matrix array to form virtual fabrics. Virtual fabrics formed with these virtual yarn signals were next compared with the virtual fabrics constructed with actual yarn signals. In addition, the effect of twist, eccentricity, and wavelength of drafting waves on virtual fabric appearances were investigated by varying the parameters of virtual yarns.

The generation of yarn data was accomplished with the following steps:
I. a sine wave signal with non-constant period and amplitude was generated to simulate the non-random wave-like fiber movement (drafting wave). Each point of this signal was assumed to represent only 1 mm interval of a yarn (low resolution);

II. each semi-period was next expanded to a higher resolution signal at 0.1 mm;

III. based on the amplitude, the eccentricity and twist values were calculated for each semi-period;

IV. a new projected yarn signal was generated with the consideration that the elliptic yarn cross-section rotates with twist;

V. the high resolution signal was reduced back to the low resolution by extracting only the signals at 1 mm intervals;

Figures 5.15 and 5.18 show the actual warp and weft yarn signals, and Figures 5.16 and 5.17 show the corresponding virtual yarn signals.

Foster [23] has shown that correlograms of the thickness of drafted cotton rovings are of the damped harmonic form and has associated the quasi-periods with drafting waves. It has also been suggested that correlograms can be used to detect the presence of such waves in the final yarn [63]. Therefore, we determined the wavelength of the low resolution sine wave from the correlogram of the yarns shown in Figures 5.19 and 5.20. Assuming the first quasi period (twice the length of the first reading of zero at the correlogram) correlation locations to be the mean periods of the drafting sine wave of the virtual signals generated, 46 mm was chosen to be the period of the warp and 144 was chosen to be the period of the weft yarn signal. Several values were next tested to determine an appropriate value for the mean and standard deviation of the amplitude of the low frequency sinusoidal drafting waves. The goal of these tests was to bring the level of the variations of the sinusoidal drafting waves close to the ones
of the yarns. Once the drafting wave of the virtual yarn signal was obtained, the next step was to vary the eccentricity and the twist values for each semi-period based on the amplitude of the drafting wave of that section. At this stage, the low resolution signal was expanded to a high resolution signal, and the effect of the rotating elliptic yarn cross-sections with twist was embedded. At the final stage, the low resolution signal was extracted from the high resolution signal at 1 mm intervals.

Figures 5.21 and 5.22 show the virtual woven fabric images constructed using the actual and virtual yarn signals, respectively. For the virtual fabrics generated, the mean eccentricities and twists of both weft and warp yarns were chosen to be 0.55 and 18 tpi, respectively, but varied with the amplitude of the drafting wave. As the amplitude of the drafting wave increased, twist decreased and eccentricity increased, and vice versa.

In addition, the mean eccentricity and twist were varied to 0.05 and 22 tpi and the appearance of the virtual fabric image was observed. Experiments show that the changes in twist and eccentricity did not in fact affect the virtual fabric image significantly. See Figure 5.23. This is because the virtual yarn was sampled and
mapped at only 1 mm intervals. The rotation of the elliptic yarn cross-section with twist was not visible at that low resolution.

### 5.3 Summary and conclusions

Several yarn profiles were examined, and it was determined that their cross-sections can best be approximated with an ellipse where the semi-major and semi-minor axes of the ellipse rotate with the twist. With a better understanding of twist, eccentricity, and non-random fiber arrangement, an attempt was made to generate virtual yarn signals using deterministic models. The virtual yarn signals generated were then mapped onto virtual fabrics to simulate the effect of elliptic yarn cross-sections on the resulting fabric. It was expected that when the appearance of a fabric is viewed from a single angle, the rotation of elliptic yarn cross-sections must influence the appearance of the fabric. However the virtual fabrics constructed were not affected significantly by the changes in twist and eccentricity at these low resolutions (every 1 mm).

In the following chapter, the characterization and quantification of virtual fabric appearances or thickness distributions will be investigated. While some of the virtual
Figure 5.21: 2-D fabric image generated with actual yarn signals (warp = yarn#6, weft = yarn#12)

Fabrics use actual fabric pictures, others use either actual yarn signals or virtual yarn signals.
Figure 5.22: 2-D virtual fabric with virtual yarn (eccentricity=0.55)

Figure 5.23: 2-D virtual fabric with virtual yarn (eccentricity=0.05)
Chapter 6

Characterization and Quantification of Woven Fabric Non-uniformities

During the last decade, the textile industry has been under pressure to produce high quality products by improving yarn and fabric qualities. Of the many quality characteristics, perhaps none is more important than the uniformity of fabric properties. It has been widely accepted that the properties of yarn greatly affect the properties of fabrics, particularly the visual appearance of woven and knitted fabrics. Some researchers [67, 46] have even suggested that the CV(%) of the yarns is sufficient to quantify the uniformity features of a fabric. However, there has not yet been any statistical model proposed to handle uniformity of a fabric with multiple yarns. Moreover, as the CV(%) of the yarn is not location specific within the yarn and hence within the fabric, it is grossly insufficient in predicting the features of irregularity within a fabric.

With advances in measurement technology and computing, it has been shown [59, 74, 48] that the uniformity of a given fabric can be visualized by information obtained from the on-line or off-line measurement of yarn properties without having to weave or knit the fabric. Apart from the visualization of fabric properties, an extensive amount of research was also carried out to develop an advanced system for characterizing numerous fabric properties. The tools included various quality indices,
random field theory, Fourier transform, and image analysis [54, 12, 13, 69, 70, 51, 55]. However, the methods of visualization and the tools mentioned above neither suggest a practical characterization method for uniformity features of fabrics, nor provide standards for judgments about the uniformity of fabrics.

When one considers the methods for yarn irregularity analysis [62, 63, 9, 58], it will be recognized that the variance-length curves that show the relationship between the coefficient of variation and the length within which the variance is measured are location specific and lead to indices characterizing the types of yarn irregularity that have practical importance [62]. Consequently, the variance-length curves became a common measure for expressing the irregularity features of spun yarns.

6.1 The variance-length curves and its derivation

Assume that \( n \) readings of yarn diameter, \((d_1, d_2, \ldots, d_n)\), are apart by unit length \( \Delta x \) as shown in Figure 6.1. Moreover, assume also that the mean and the variance of these yarn diameters are known and are \( \mu \) and \( V \), respectively. Since yarn is continuous these readings are correlated and stationary ergodic. The variance of means of these \( n \) readings, \( B(n) \), can be given by

![Figure 6.1: A number of yarn readings and their correlation](image-url)
\[ Var\left( \frac{x_1 + x_2 + \ldots + x_n}{n} \right) = Var\left( \frac{x_1}{n} \right) + Var\left( \frac{x_2}{n} \right) + \ldots + Var\left( \frac{x_n}{n} \right) + \frac{2}{n^2} \left[ Cov(x_1, x_2) + Cov(x_1, x_3) + \ldots + Cov(x_1, x_n) + Cov(x_2, x_3) + \ldots + Cov(x_2, x_n) + \ldots + Cov(x_{n-1}, x_n) \right] \] (6.1)

On the other hand, the correlation between any two readings is given by

\[ \rho_{xy} = \frac{Cov(x, y)}{\sigma_x \sigma_y} \]

Because the variables have equal variances, \( \sigma_x = \sigma_y = \sqrt{V} \), the correlation between any two points that are \( x = k\Delta x \) apart, where \( k \) is an integer shown in Figure 6.1, may be stated as

\[ \rho(k\Delta x) = \frac{Cov(x_i, x_{i+k})}{V} \] and
\[ Cov(x_i, x_{i+k}) = V \rho(k\Delta x) \]

(6.2)

When Equation 6.2 is substituted into Equation 6.1, the variance of the means is obtained in Equation 6.3 as the one given by [72] and [14]:

\[ Var\left( \frac{x_1 + x_2 + \ldots + x_n}{n} \right) = \frac{V}{n} + \frac{2V}{n^2} \left[ (n-1)\rho(\Delta x) + (n-2)\rho(2\Delta x) + \ldots + \rho((n-1)\Delta x) \right] \]
\[ = \frac{V}{n} + \frac{2V}{n^2} \sum_{k=1}^{n} (n-k)\rho(k\Delta x) \]

(6.3)

The Equation 6.3 may also be rewritten by substituting \( n \) with \( L/\Delta x \) as follows:
\begin{align*}
    &= \frac{V \Delta x}{L} + \frac{2V \Delta^2 x}{L^2} \sum_{k=1}^{n} \left( \frac{L}{\Delta x} - k \right) \rho(k \Delta x) \\
    &= \frac{V \Delta x}{L} + \frac{2V}{L^2} \sum_{k=1}^{n} (L - k \Delta x) \rho(k \Delta x) \Delta x
\end{align*}

In the interval \( L \) shown in Figure 6.1, as \( \Delta x \to 0 \), then \( n \to \infty \) and in the limit form the discrete interval becomes continuous and the integration replaces summation:

\begin{align*}
    &= \lim_{\Delta x \to 0} \frac{V \Delta x}{L} + \frac{2V}{L^2} \int_{x=0}^{L} (L - x) \rho(x) \, dx
\end{align*}

Finally, when the limits are taken the Equation 6.4 yields the following result given in [63]:

\begin{equation}
    B(L) = \frac{2V}{L^2} \int_{u=0}^{L} (L - u) \rho(u) \, du \quad (6.4)
\end{equation}

### 6.1.1 Using correlation-length relation of a yarn to obtain \( B(L) \) curve

In this section, the derivation of a \( B(L) \) curve of a yarn from the correlogram of the yarn is demonstrated.

As we already know from Equation 6.4, increase in the correlation between successive yarn points increases the correlation coefficient, \( \rho(u) \), of Equation 6.4. Consequently \( B(L) \) increases. Therefore, highly correlated yarn diameter signals will produce \( B(L) \) curves that approach zero more slowly than the ones that are less correlated. On the other hand, the variance-within-length, \( V(L) \), will diminish as the correlation among the neighboring yarn points increases. This relationship can be
expressed mathematically by the following equation:

\[ V(L) = V(\infty) - \frac{2V}{L^2} \int_{u=0}^{L} (L - u)\rho(u)du \]  

(6.5)

When Equations 6.4 and 6.5 are combined, the relationship between \( B(L) \) and \( V(L) \) is established in conjunction with total variance as follows:

\[ V(L) + B(L) = V(\infty) \]  

(6.6)

The equations stating the relationship between the variance-length and the correlogram of the yarn derived here were also given by Townsend and Cox [63]. However, the derivation of this relationship was not provided in their paper. Because of its significance in understanding the characteristics of yarn irregularity in one dimension and fabric irregularity in two dimensions, in depth analysis of Equation 6.4 was necessary.

Using the Equations 6.4 and 6.5 and the computing power available today, it is now possible to estimate the variance-length curves of a yarn using only its correlation information in a relatively short time.

Figures 6.2 and 6.3 show the correlogram and the \( B(L) \) curves of two different yarns. The actual correlogram was plotted for a number of points and is therefore discrete. This discrete correlogram was then transformed into a continuous one by a best-fit spline. This best-fit spline was next used to estimate the \( B(L) \) curve of the yarn. The estimated and the actual \( B(L) \) curves are shown in the sub-plots titled variance-length curve of yarn. As is clearly seen, this approximation is almost perfect. In addition, Figures 6.2 and 6.3 also demonstrate that the yarn sample 5 has higher correlation than the yarn sample 1, therefore as expected the \( B(L) \) curve of latter reduces faster than the former.

So far, we have demonstrated the significance of yarn correlation in one-dimensional
Figure 6.2: Correlogram and CB(L) of sample yarn 1

variance-length relationships. In the rest of this chapter, we will discuss how variance-length curves can be expanded to variance-area curves and how they can be used effectively for characterizing and analyzing irregularity features of fabrics. In addition, we will establish a link between the correlation features of a yarn and the variance-area curves of the resulting fabrics.

6.2 Analysis of fabric irregularity using surface area function

Wegener [67] suggested that the variance versus the measured area relation of fabrics may be used for characterizing the variation of certain fabric properties as a function of the measured area. This is similar to the variance-length relation found in spun yarns. He also pointed out that the surface variation function can be applied to characterize the non-uniformity of such fabric properties as mass, thickness, density,
and air and water permeabilities.

For a fabric having identical structure in the warp and weft directions, Wegener defined the surface-variation function using the variance-length relationship of the warp and weft yarns and finally concluded that the variance-length relationship of yarns are sufficient to predict the irregularity features of fabric properties using Equation 2.37

While Wegener’s assertion holds for fabrics produced from yarns with no periodic irregularities, his prediction model may not hold for fabrics produced from yarns with non-random or periodic oscillation of physical properties such as thick and thin places [60]. The study suggests that the periodicity of the yarn properties and the geometry of the fabric construction determined by the width, yarn thickness, and crimp cause non-unique fabric appearances due to variable mapping.

Wegener’s study was an initial attempt at characterizing fabric irregularity as a function of the measured area. His work, however, did not extend to the two-dimensional aspects of fabric irregularities. More specifically, the methods of selecting
different shapes within a given unit area were not considered for further characterization and quantification of certain fabric properties.

6.2.1 Methods for creating variance-between-area, CB(A), curves

Recognizing the proven values of variance-length curves, this study investigated whether they can be expanded to two dimensions. The concept and terminology of classical variance-length curves are adapted for a two-dimensional fabric area, \( A \), and are called 'variance-area curves'. As in classical variance-length curves, the variance-area relation of fabric thickness distribution or fabric appearance was subdivided into two variance components, \( CV(A) \) and \( CB(A) \) curves corresponding to variance-within-area and variance-between-area curves respectively. They are equivalent to \( \frac{\sqrt{V(A)}}{\mu_A} \) and \( \frac{\sqrt{B(A)}}{\mu_A} \), respectively, and are different from the traditional mathematical forms given by \( V(A) \) and \( B(A) \).

Simply put, the variance-area curves are obtained by calculating the variances of a measured fabric property based on varying unit sizes within a 2-D woven fabric matrix. This 2-D woven fabric matrix is constructed either from actual fabric images or virtual fabric images that are obtained from actual yarn signals as described on page 4.2. Although the mapping is exercised for woven fabrics, the study is not confined to only woven fabrics. As long as one can map a property of a textile into a 2-D matrix array, then the variance-area curves of that textile can be calculated. For instance, one could map the 2-D filtration efficiency of a nonwoven textile onto a 2-D matrix and obtain the variance-area curves of it.

Unlike in Wegener’s surface variation function [67] and Han et al.’s variance-area curves [31], the unit areas in this study are not only squares but also rectangles.

It was demonstrated both experimentally and theoretically how different choices of unit area could potentially lead to a powerful tool for diagnosing certain irregularity
features of fabrics. It is noted that the variance-between-area curve, CB(A), has been
the primary tool for differentiating the fabric non-uniformities.

Figure 6.4: Virtual fabric constructed using actual yarn signals and methods for selecting unit areas

Formation of variance-between-area curve

Let $L$ be the length and $W$ be the width of the entire virtual fabric formed by basic mapping. The fabric is first partitioned into unit areas (an example for unit area is marked with a box in Figure 6.4) of size $A_i$ where $i = 1..n$ and $A_i \leq L \times W$. The variance-between-area curve, CB(A), is the plot of the coefficients of variation for varying unit areas ($A$) versus the magnitudes of the unit areas. Mathematically, this relation is formulated with Equation 6.7 where each unit area size equals $w_i \times l_i$.

$$CB(A_i) = \frac{100}{G(A_i)} \left( \frac{1}{m_i n_i - 1} \sum_{r=1}^{m_i} \sum_{c=1}^{n_i} [G_{rc}(A_i) - \bar{G}(A_i)]^2 \right)$$  \hspace{1cm} (6.7)
where \( CB(A_i) \) is the variance between area among the unit areas of size \( A_i \),

\[ m_i \] is the number of segments in the machine-direction, that

\[ m_i = L/l_i , \]

\[ n_i \] is the number of segments in the cross-direction, that is \( n_i = W/w_i \),

\( G_{r,c}(A_i) \) is the \( i^{th} \) value of the property for the unit area \( A \), of at row \( r \) and column \( c \) (for example; the thickness of the unit area for given dimensions),

\( \bar{G}(A_i) \) is the mean value of the property for all unit areas;

\[ \bar{G}(A_i) = \frac{\sum_{r=1}^{m_i} \sum_{c=1}^{n_i} G_{r,c}(A_i)}{m_in_i} \]

\( m_in_i \) is the total number of unit areas within a designated fabric area.

As the size of each unit area increases, the variance within the unit areas increases, but the coefficient of variation between area, \( CB(A_i) \), decreases asymptotically to zero eventually. While the initial values of the \( CB(A) \) curve indicate the level of overall irregularity, the rate with which it approaches the asymptotic value is determined by the variance among the unit areas.

![Figure 6.5: CB(A) curves of the virtual fabrics shown in Figures 4.25 and 4.26](image)

When two sides of the unit areas, \( A_i \), are equal, \( l_i = w_i \), then Equation 6.7 is equivalent to the external surface variation function of Wegener’s [67]. These type of
variance-between-area curves are, in fact, usually sufficient in detecting the irregularity features caused by the alias between the wavelength of the periodic irregularities and the fabric construction (width, length) as shown in Figures 4.25 and 4.26. The CB(A) curves shown in Figure 6.5 correspond to these virtual fabrics and demonstrate the effectiveness of these curves in detecting appearance differences between these virtual fabrics.

### Three kinds of CB(A) curves

When a two-dimensional fabric surface is considered, there are many ways to choose unit areas having equal sizes [29]. In this study, the shape of unit areas was chosen to be rectangular. In addition, the ratio between the sides of a rectangle is referred to as the shape constant and is symbolized with the letter $k$. Mathematically, it is designated as $k = \ell_i/\omega_i$. In this study, when we refer to a CB(A) of a fabric, three CB(A) curves will be considered, where one of them is plotted for $k = 1$, and the other two are plotted for $k = i$ and $k = 1/i$ where $i > 1$. However during this study we first limited the possible values of $i$ to 2, 3, 4, 5, 6 and then finally decided on $i = 6$ as this produced sufficient discrimination among three CB(A) curves. Note that when $k = i$ or $k > 1$, the unit area is oriented in the Machine Direction (MD), and when $k = 1/i$ or $k < 1$, the unit area is oriented in the Cross Direction (CD), and finally when $k = 1$, the unit area is square in shape. This is demonstrated in Figure 6.4.

### 6.2.2 Existence of anisotropy and detection through CB(A) curves

If a property of a fabric is invariant in all directions, then no matter how one chooses the value of the shape constant $k$, the three CB(A) curves should be identical, overlapping. Any difference between these curves will be due to the existence of
asymmetry in the fabric irregularity and will be the indication of anisotropy of that property within the fabric [30].

The virtual fabric shown in Figure 6.6 is quite uniform and has no directional irregularity or visible pattern, therefore the corresponding CB(A) curves overlap as shown in Figure 6.7.

On the other hand, the CB(A) curves in Figure 6.9 of a virtual fabric sample shown in Figure 6.8 do not overlap. This is because of the absence of isotropy of the virtual fabric. Experiments lead us to conclude that the further apart these curves
are from each other, the more anisotropic the visual appearance of the virtual fabric is.

6.2.3 Quantification of anisotropy

In order to quantify anisotropy, two indices, one for the MD and the other for the CD, were developed. These indices are calculated by approximating the area underneath each of the CB(A) curves and calculating the ratio of the rectangular unit area CB(A) curves to the square unit area CB(A) curves.

The method can mathematically be formulated as follows:

\[ \varepsilon_{md} = \frac{\int_{x_1}^{x_f} CB(A_{k>1}) dx}{\int_{x_1}^{x_f} CB(A_{k=0}) dx} \]  \hspace{1cm} (6.8)

\[ \varepsilon_{cd} = \frac{\int_{x_1}^{x_f} CB(A_{k<1}) dx}{\int_{x_1}^{x_f} CB(A_{k=0}) dx} \]  \hspace{1cm} (6.9)

Again, there are three possibilities, \( \varepsilon = 1, \varepsilon < 1 \) or \( \varepsilon > 1 \), for the values of anisotropy indices. This yields a total of nine possible outcomes when both \( \varepsilon_{cd} \) and \( \varepsilon_{md} \) are considered.

6.2.4 Justification of anisotropy

Anisotropy, defined with CB(A) curves, is basically a function of correlation among the sections of a 2-D fabric image. As fabrics are made of yarns the correlation between sections are in fact determined by the correlation information of the yarns. In addition, since variance-area curves are the extension of variance-length curves, the relationship between variance-length curves and the correlation information of the yarn is expected to hold for fabrics as variance-area curves are functions of correlation.
among the sections of a fabric.

The relationship between variance-between-length, B(L), and the correlogram of a yarn was given earlier by Equation 6.4. As is clearly seen the higher the correlation between adjacent yarn points, the higher the values of B(L) would be and vice versa. If these conclusions are to expanded for variance-between-area curves, one would expect that the highly correlated adjacent sections in a particular direction would produce a dominant CB(A) curve over the CB(A) curves of the other directions. The CB(A) curves of the virtual fabric samples do in fact exhibit this behavior.

![Figure 6.10: 2-D virtual fabric image generated with actual yarns (warp = yarn#6, weft = yarn#12)](image1.png)

![Figure 6.11: 2-D virtual fabric with virtual yarns (eccentricity=0.35)](image2.png)

Virtual fabric images shown in Figures 6.10 and 6.11 were generated with actual and artificial yarn signals, respectively. The artificial yarns are produced with the correlation information obtained from the actual yarns of the fabric shown in 6.10 as described on page 88. Both fabrics show visible stripes in CD. Therefore, the CB(A) curve of \( k < 1 \) is dominant over the other ones for both virtual fabrics. The cloudiness effect is, however, more visible for the fabric sample shown in Figure 6.10 than for the fabric sample shown in Figure 6.11. This is also supported by the CB(A) curves as the CB(A) curve for \( k = 1 \) of the former fabric is slightly higher than the CB(A) curve for \( k = 1 \) of the latter. Nevertheless, the experiment mentioned above
underlines the importance of correlation on fabric anisotropy.

![Figure 6.12: CB(A) curve of virtual fabric with actual yarns shown in Figure 6.10](image1)

![Figure 6.13: CB(A) curve of virtual fabric with generated yarns shown in Figure 6.11](image2)

### 6.3 CB(A) curves as a function of correlation for woven fabrics

As mentioned, the shape and characteristics of a CB(A) curve depends heavily on the correlation information of the underlying yarns. Therefore, technically-speaking one could determine CB(A) curves of a woven fabric by using the correlation information of the yarns. We also know that the variance-between-length, B(L), curve of a yarn is a function of the correlogram of that yarn. Consequently, one could predict CB(A) curves of a fabric by only using the B(L) curves of the underlying yarns.

#### 6.3.1 The relationship between the CB(A) curves of fabrics and B(L) curves of yarns

Let us first consider a woven fabric with two different yarns, one for warp and one for weft. As a result of independence, the variance of a single point, \( f(x, y) \), within
a fabric is only the summation of variances of both warp and weft yarns as given by the following equation:

\[
Var_f = Var_w + Var_p \quad \text{and since } CV_x^2 = \frac{Var_x}{\mu_x^2} \quad (6.10)
\]
\[
= CV_w^2 \mu_w^2 + CV_p^2 \mu_p^2 \quad (6.11)
\]

where \( f \) is the point \( f(x,y) \) located at \( x \) and \( y \),

\( w \) is the warp yarn,

\( p \) is the weft yarn.

Meanwhile, the CV(%) of the single point is given by

\[
CV_f = \frac{\sqrt{Var_f}}{\mu_f} \quad (6.12)
\]
\[
= \frac{\sqrt{CV_w^2 \mu_w^2 + CV_p^2 \mu_p^2}}{\mu_w + \mu_p} \quad (6.13)
\]

Instead of a single point, if a rectangular region with an area \( A \) and side lengths \( l \) and \( w \) is considered \( (A = l \times w) \), the surface variation function of this region can be estimated using Equation 6.14. Note that Equation 6.14 is the modified version of Equation 6.13 for multiple points. This modification involved finding the mean of the region and taking into account the correlation of the yarns. While the determination of mean is a straight forward process through the multiplication of a single point mean with the area of the region, the effect of yarn correlation on the CB(A) estimation may be a trivial task. However, as the correlation information of a yarn is included in the variance-between-length curve of the yarns, \( CB_{wi} \) and \( CB_{pi} \), this trivial task can be simplified by utilizing this relationship. Consequently, the variance-between-length terms are included in the estimation as shown in Equation 6.14 and divided
by \( w \) and \( l \), respectively, in order to account for the reduction in variation as a result of the doubling law.

\[
CB(A) = \sqrt{\frac{CB^2(l)}{w}(lw\mu_w)^2 + \frac{CB^2(w)}{l}(lw\mu_p)^2} \frac{1}{lw(\mu_w + \mu_p)}
\]  

(6.14)

Substituting \( CB^2(L) \) with \( \frac{B(L)}{\mu^2} \) and simplifying yields

\[
= \sqrt{\frac{B_w(l)}{w} + \frac{B_p(w)}{l}} \frac{1}{\mu_w + \mu_p}
\]  

(6.15)

This simple case can be generalized to account for multiple yarns in both the warp and the weft direction by

\[
CB(A) = \sqrt{\sum_{wi=1}^{n} \frac{B_{wi}(l)}{w} r_{wi} + \sum_{pi=1}^{m} \frac{B_{pi}(w)}{l} r_{pi}} \frac{1}{\sum_{wi=1}^{n} (r_{wi})\mu_w + \sum_{pi=1}^{m} (r_{pi})\mu_p}
\]  

(6.16)

where  \( m \)  is the number of different warp yarns,

\( n \)  is the number of different weft yarns,

\( wi \)  is the  \( i^{th} \) warp,

\( pi \)  is the  \( i^{th} \) weft

\( r_{wi} \)  is the ratio of  \( i^{th} \) warp in the weft direction, and

\( r_{pi} \)  is the ratio of  \( i^{th} \) weft in the warp direction

Note that when there is only one type of yarn for each warp and weft then  \( m, n, r_{wi}, r_{pi} \)  equal one, consequently the Equation 6.15 becomes a special case of Equation 6.16.

Figure 6.16 demonstrates the estimation of CB(A) curves for the virtual fabric shown in Figure 6.14 using only the variance-between-length relationship of the underlying yarns. In this estimation Equation 6.15 was used as the virtual fabric
Figure 6.14: Virtual fabric constructed using actual yarn signals (warp = yarn#1, weft = yarn#5)

Figure 6.15: CB(A) curves of the virtual fabric shown in Figure 6.14

constructed with only two different yarns, one for warp and one for weft.

When the actual CB(A) curves \(^1\), Figures 6.15, and the estimated CB(A) curves \(^2\), 6.16, are compared, it will be seen that the relative order of the CB(A) curves are in agreement. As there is no statistical method to compare a curve set with another curve set based on their orders, we devised the following method, which stems from the differences between the curves of the set. According to the method, the CB(A)

\(^1\)The data of CB(A) curve set is given in Appendix A.1
\(^2\)The data of the CB(A) curve set is given in Appendix A.2
curves are subtracted from each other for both the actual and the estimated set. The differences between the curves of the actual and the estimated sets are compared for goodness as given in Table 6.1. The high $R^2$ values in Table 6.1 verify the validity of estimation model for relative order.

The actual and estimated CB(A) curves are also compared against each other. The closeness of the fit given in Table 6.2 also demonstrates the validity of estimation model.

In addition to the examples presented here, this estimation model was tested with various other yarns and virtual fabrics constructed from them. It was consistently found that the true CB(A) curves can be approximated with the ones estimated from the variance-between-length relations of the underlying yarns. However, this estimation procedure has a limitation when a periodic yarn irregularity together with the cloth geometry determine the characteristics of a fabric irregularity.

### 6.3.2 The relationship between the CB(A) curves of fabrics and correlogram of yarns

In previous sections, we have shown that we can obtain:
<table>
<thead>
<tr>
<th>Actual [CB(A_{k=1}) - CB(A_{k&gt;1})] vs Estimated [CB(A_{k=1}) - CB(A_{k&gt;1})]</th>
<th>$R^2$</th>
<th>$R$</th>
<th>$t - value$</th>
<th>$p - value$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual [CB(A_{k=1}) - CB(A_{k&lt;1})] vs Estimated [CB(A_{k=1}) - CB(A_{k&lt;1})]</td>
<td>0.873</td>
<td>0.934</td>
<td>7.28</td>
<td>0.00008</td>
</tr>
<tr>
<td>Actual [CB(A_{k&gt;1}) - CB(A_{k&lt;1})] vs Estimated [CB(A_{k&gt;1}) - CB(A_{k&lt;1})]</td>
<td>0.869</td>
<td>0.932</td>
<td>7.28</td>
<td>0.00009</td>
</tr>
</tbody>
</table>

**Table 6.1:** Agreement of relative order statistics for CB(A) curves shown in Figures 6.15 and 6.16
Table 6.2: Goodness of fit statistics for CB(A) curves shown in Figures 6.15 and 6.16

- a CB(A) curve from the variance-between-length curves of the yarns and;
- a variance-between-length curve from the correlogram of the yarn.

In this section, both these steps will be linked to demonstrate the determination of a CB(A) curve directly from the correlogram of the yarns. By doing this, the overhead of mapping yarn signals into a 2-D fabric matrix will be avoided. This shortcut not only saves computation time, but also reduces necessary computer resources, in particular, the storage.

For a fabric consisting of multiple yarns the CB(A) curve therefore can be obtained with the following equation:

\[
\text{CB(A)} = \sqrt{\sum_{i=1}^{n} \frac{2V_{wi}}{l^2} \int_{u=0}^{l} (l-u)\rho_{wi}(u)du + \sum_{p=1}^{m} \frac{2V_{pi}}{w^2} \int_{u=0}^{w} (w-u)\rho_{pi}(u)du}
\]

\[
= \sqrt{\sum_{i=1}^{n} (r_{wi})\mu_{w} + \sum_{p=1}^{m} (r_{pi})\mu_{p}}
\]

\[
(6.17)
\]

where

- \( V_{wi} \) is the \( i^{th} \) warp variance,
- \( V_{pi} \) is the \( i^{th} \) weft variance,
- \( \rho_{wi} \) is the \( i^{th} \) warp correlogram,
- \( \rho_{pi} \) is the \( i^{th} \) weft correlogram.

The other symbols are inherited from definitions given by Equation 6.16.
Again, for a fabric of two yarns, that is where warp and weft contains only one type of yarn, the Equation 6.17 simplifies to

\[
\mu_w + \mu_p = \sqrt{\frac{2V_w}{l^2} \int_{u=0}^l (l-u)\rho_w(u)du + \frac{2V_p}{w^2} \int_{u=0}^w (w-u)\rho_p(u)du} \tag{6.18}
\]

Figure 6.17: Estimated CB(A) obtained from the correlogram of the yarns (warp = yarn#1, weft = yarn#5)

Figure 6.17 demonstrates the estimated CB(A) curves obtained directly from the correlogram of the yarns. Once again, the closeness of approximation is outstanding as the goodness of the fits given by \(R^2\) are calculated to be more than 0.99.

Figures 6.18 and 6.19 show another virtual fabric and its actual CB(A) curves, \(^3\) respectively. The estimated CB(L) and CB(A) curves \(^4\) shown in Figures 6.20, 6.21, and 6.22. As seen from both Figures, the relative orders of the CB(A) curve sets are in agreement. This is also supported by the \(R^2\) values as shown in Table 6.3.

The actual and estimated CB(A) curves are also compared against each other. The goodness of fit given in Table 6.4 also demonstrates the validity of our estimation model.

\(^3\)The data of CB(A) curve set is given in Appendix A.3
\(^4\)The data of CB(A) curve set is given in Appendix A.4
<table>
<thead>
<tr>
<th>Actual</th>
<th>CB($A_{k=1}$) - CB($A_{k&gt;1}$) vs Estimated</th>
<th>CB($A_{k=1}$) - CB($A_{k&gt;1}$)</th>
<th>$R^2$</th>
<th>$R$</th>
<th>$t$ - value</th>
<th>$p$ - value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>CB($A_{k=1}$) - CB($A_{k&lt;1}$) vs Estimated</td>
<td>CB($A_{k=1}$) - CB($A_{k&lt;1}$)</td>
<td>0.86</td>
<td>0.9312</td>
<td>7.26</td>
<td>0.00009</td>
</tr>
<tr>
<td>Actual</td>
<td>CB($A_{k&gt;1}$) - CB($A_{k&lt;1}$) vs Estimated</td>
<td>CB($A_{k&gt;1}$) - CB($A_{k&lt;1}$)</td>
<td>0.885</td>
<td>0.94</td>
<td>7.85</td>
<td>0.00005</td>
</tr>
</tbody>
</table>

**Table 6.3**: Agreement of relative order statistics for CB(A) curves shown in Figures 6.19 and 6.22
Figure 6.18: Virtual fabric constructed using actual yarn signals (warp = yarn#12, weft = yarn#6)

<table>
<thead>
<tr>
<th>Actual [CB(A&lt;1)] vs Estimated [CB(A=1)]</th>
<th>$R^2$</th>
<th>$R$</th>
<th>$t-value$</th>
<th>$p-value$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual [CB(A&lt;1)] vs Estimated [CB(A=1)]</td>
<td>0.899</td>
<td>0.948</td>
<td>8.43</td>
<td>0.00003</td>
</tr>
<tr>
<td>Actual [CB(A&gt;1)] vs Estimated [CB(A=1)]</td>
<td>0.898</td>
<td>0.947</td>
<td>8.40</td>
<td>0.00003</td>
</tr>
<tr>
<td>Actual [CB(A&gt;1)] vs Estimated [CB(A=1)]</td>
<td>0.896</td>
<td>0.946</td>
<td>8.34</td>
<td>0.00003</td>
</tr>
</tbody>
</table>

Table 6.4: Goodness of fit statistics for CB(A) curves shown in Figures 6.19 and 6.22

In this chapter we showed that the CB(A) curves of a fabric could be estimated from the correlogram of the underlying yarns of the fabric. This conclusion is also in agreement with Dodson’s work [17], as he pointed out that the areal variance is a known integral of an appropriate sum of covariance functions determined by the geometry of the elements.

This study, however, differs from the Dodson’s research [17, 53, 10, 39] since the variance-between-area curves are obtained as a function of variance-between-length curves. Furthermore, with the mapping method proposed, variance-between-area relations of woven fabrics are obtained virtually. Another difference between the present work and Dodson’s works is the calculation of anisotropy index. While Dodson calculates the anisotropy index for each unit-area size, in this study it is integrated
Figure 6.19: Actual CB(A) obtained directly from the virtual fabric (warp = yarn#12, weft = yarn#6)

over areas and only one index is proposed for the whole 2-D texture image. As there are two main directions for woven fabrics, this calculation of anisotropy index is sufficient. The anisotropy index defined in the present work also contains the direction of irregularity as described in the following section.

6.4 Relationship between irregularity features and CB(A) curves

We were able to relate certain fabric irregularity features with CB(A) curves and anisotropy indices using three choices of $k$. While the anisotropy indices provided a new tool to evaluate the fabric anisotropy quantitatively, the CB(A) curves themselves allowed us to describe distribution of certain fabric properties (thickness) or appearance textures. In this section, illustrations of various virtual fabric irregularities are provided along with their corresponding variance-between-area curves. An attempt is also made to classify these irregularity patterns.
6.4.1 Random and evenly distributed large size fabric irregularities:

Defects such as cloudiness and fuzziness are often randomly distributed throughout the fabric and may be included in this group. Although these defects are verbally described as *patchy and uneven appearance of fabric surface, much like a cloud* [45], there has not yet been a single measure to quantify them.

Upon applying CB(A) curves to fabrics with these defects, it was observed that the CB(A) curve of $k = 1$ is dominant over the other two CB(A) curves of $k < 1$ and $k > 1$. This was demonstrated by the actual fabric sample and the corresponding CB(A) curve shown in Figures 6.23 and 6.24, respectively. This was also reflected by the anisotropy indices as both $\mathcal{R}_{md}$ and $\mathcal{R}_{cd}$ are less than 1.
6.4.2 Periodic irregularities visible in one or more directions:

Streakiness, bárre, and reed marks are typical irregularities of this type. ASTM [3] describes bárre as a striped effect in a fabric caused by a series of one or more wefts which are characterized by an apparent difference in color or luster that is repeated at intervals in the warp direction and streaks as a narrow bar running warp-wise and characterized apparent differences in color from joining ends and reed marks as cracks between warp ends, continuous or at intervals.

Because of the high correlation between adjacent yarn points along a yarn, the property of a fabric may be correlated higher in one particular direction than the other one. This often appears as visible streaks in the virtual fabric in the direction of highly correlated yarn. This in turn causes higher between area variation in the direction of the streak than in the other directions.

The actual fabric image shown in Figure 6.25 illustrates visible streaks in CD. The corresponding CB(A) curve of this actual fabric sample demonstrates that the
**Figure 6.22:** Estimated CB(A) obtained from the correlogram of the warp and weft yarn samples #12 and #6, respectively

**Figure 6.23:** Actual fabric sample

**Figure 6.24:** CB(A) curve of fabric sample shown in Figure 6.23

CB(A) curve for $k < 1$ is dominant over the CB(A) curves of $k = 1$ and $k > 1$. The anisotropy determined from these curves supports this observation as $\kappa_{cd} > 1 > \kappa_{md}$.

On the other hand, the visible streaks seen in the MD of the virtual fabric sample shown in Figure 6.27 are because of the highly correlated MD yarn. This is supported by the CB(A) curve set shown in Figure 6.28 as the CB(A) curve of $k > 1$ is dominant over the other two CB(A) curves. Anisotropy indices also reflect this observation as $\kappa_{md} > 1 > \kappa_{cd}$.

The fabric sample shown in Figure 6.29 illustrates streaks in both MD and CD.
**Figure 6.25:** Actual fabric sample

**Figure 6.26:** CB(A) curves of fabric sample shown in Figure 6.25

**Figure 6.27:** Virtual fabric sample (warp = yarn#5, weft = yarn#1)

**Figure 6.28:** CB(A) curve of fabric sample shown in Figure 6.27

**Figure 6.29:** Virtual fabric sample (warp = yarn#5, weft = yarn#5)

**Figure 6.30:** CB(A) curves of fabric sample shown in Figure 6.29
Since the yarns used in both MD and CD are highly correlated, the CB(A) curves of $k \neq 1$ are dominant over the CB(A) curve of $k = 1$. Consequently, both anisotropy indices $\kappa_{md}$ and $\kappa_{cd}$ are greater than 1.

The results have shown that directional biased selection of unit areas (i.e. rectangular unit area selections with an orientation in the CD or MD direction) were effective in identifying patterns of irregularity features in a particular orientation.

The distance between the two CB(A) curves, $k > 1$ and $k < 1$ also indicates the magnitude of anisotropy within a fabric. As isotropy increases, the fabric becomes more uniform and the CB(A) curves approach each other and converge onto the CB(A) curve of $k = 1$. Meanwhile both anisotropy indices converge to one. This was illustrated with two fabrics samples shown in Figures 6.29 and 6.31. Because the latter fabric sample is more uniform than the first one, the difference between the anisotropy indices are greater for the first one than the second one.
Chapter 7

Conclusions

Characterization and quantification methods were developed for fabric non-uniformity
analysis using 2-D fabric images and the concept of variance-area curves. Although
in this study only the appearance and thickness properties of fabrics were examined,
the methods developed are appreciable to other fabric properties such as mass and
air and water permeabilities.

While the data for fabric appearances were obtained directly from pictures of
fabrics, the data for fabric thicknesses were obtained indirectly from on-line measure-
ments of yarn diameters. For this indirect method, the yarn diameters were captured
through a line-scan camera and translated into a 2-D fabric matrix by assigning each
point of the yarn to a specific location (x, y) within the 2-D fabric matrix, while ig-
noring crimp, yarn count, and thread density. The gray-scale image of the 2-D fabric
matrix was called virtual fabric and provided the basic information on the uniformity
of the fabric properties.

Fabric images obtained directly or indirectly facilitated creation of variance-area
curves by dividing the images into smaller unit areas. Different shapes of the unit
areas, squares and rectangles, were investigated. It was shown that different shapes
of the unit area produce different sets of variance-area curves and provide a tool for
differentiating the appearance or thickness non-uniformity of the fabric. The results
suggest that the variance-area curves were found to be invariant with respect to the
shapes of the area chosen for isotropic fabrics. On the other hand, the different
choices of unit area with varying shape constants were shown to produce different
variance-area curves for anisotropic fabrics or those fabrics with different textures in
the warp or weft direction.

During this research, several yarn profiles were also examined. It was determined
that the cross-section of a yarn can best be approximated with an ellipse where the
semi-major and semi-minor axes of the ellipse rotate with the twists. It was also
determined that some of the optical variations in yarn evenness, especially for plied
yarns with eccentricity greater than 0.5, were due to the rotation of elliptic yarn
cross-sections. It was also shown that by knowing the eccentricity of a yarn, one can
estimate the amount of twist of the yarn by solving the inverse problem (Equation 5.8),
while minimizing the cost function given in Equation 5.10.

Attention must also be given to the fact that the projected diameter of a yarn
does not simply create a sine wave but rather a complex periodic function that can
be modeled mathematically by Equation 5.8.

With this better understanding of yarn structure, an attempt was made to gener-
ate a set of virtual yarn signals using deterministic models. The virtual yarn signals
were then mapped onto 2-D virtual fabrics to simulate the effect of elliptic yarn cross-
sections on actual fabrics. It was found that the ellipticity of a yarn cross-section does
not in fact significantly affect the appearance of a virtual fabric, if the yarn is sampled
at 1 mm intervals.

7.1 Contribution of this research

The contributions of this research are summarized as follows:
• characterization and quantification methods were developed for fabric uniformity analysis;
• a prediction model was suggested for the non-uniformity of fabric properties using only the correlation information of the underlying yarns;
• the yarn cross-section was determined to be elliptic and demonstrated to rotate with the twist of the yarn;
• a deterministic yarn generation method was proposed and validated.

7.2 Future work

While this work provided a new avenue to study the two-dimensional features of fabric appearance and thickness, the time-series aspect of the unit areas has yet to be expanded to two dimensions. The ultimate goal would be to characterize, quantify, and discriminate the fabric properties by merging the results obtained in this study with the theory of two-dimensional random fields.

With the understanding of two-dimensional random field theory, it will also be possible to expand this study into other areas of textiles, in particular to nonwovens. For example, in this thesis non-uniformity features of woven fabrics have been investigated in two main directions (MD and CD). Although this might be enough for a woven fabric, a nonwoven fabric would certainly require investigation of non-uniformity features in several directions.
List of References


[50] A. Lachkar R. Benslimane and et. al. Genetic-based inverse voting hough transform for the assessment of yarn twist level. The restoration of ancient textiles is a projected funded by European Union.


Appendix A

The Data of CB(A) Curve Sets

A.1 The data of actual CB(A) curves shown in Figure 6.15

<table>
<thead>
<tr>
<th>k = 1</th>
<th>k &lt; 1</th>
<th>k &gt; 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0951</td>
<td>0.0883</td>
<td>0.1131</td>
</tr>
<tr>
<td>0.0412</td>
<td>0.0357</td>
<td>0.0532</td>
</tr>
<tr>
<td>0.0295</td>
<td>0.0258</td>
<td>0.0375</td>
</tr>
<tr>
<td>0.0239</td>
<td>0.0205</td>
<td>0.0300</td>
</tr>
<tr>
<td>0.0193</td>
<td>0.0149</td>
<td>0.0269</td>
</tr>
<tr>
<td>0.0177</td>
<td>0.0140</td>
<td>0.0226</td>
</tr>
<tr>
<td>0.0170</td>
<td>0.0122</td>
<td>0.0215</td>
</tr>
<tr>
<td>0.0145</td>
<td>0.0094</td>
<td>0.0197</td>
</tr>
<tr>
<td>0.0138</td>
<td>0.0101</td>
<td>0.0174</td>
</tr>
<tr>
<td>0.0144</td>
<td>0.0113</td>
<td>0.0182</td>
</tr>
</tbody>
</table>
A.2 The data of estimated CB(A) curves shown in Figure 6.16

<table>
<thead>
<tr>
<th>k = 1</th>
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<th>k &gt; 1</th>
</tr>
</thead>
<tbody>
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<td>0.1103</td>
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</tr>
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<td>0.0126</td>
<td>0.0098</td>
<td>0.0160</td>
</tr>
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</table>

A.3 The data of actual CB(A) curves shown in Figure 6.19

<table>
<thead>
<tr>
<th>k = 1</th>
<th>k &lt; 1</th>
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### A.4 The data of estimated CB(A) curves shown in Figure 6.22

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Appendix B

Graphical User Interface
Figure B.1: GUI showing diameter signals of a yarn captured on-line
Figure B.2: GUI showing virtual woven fabric obtained from on-line yarn diameter signals