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A Heuristic Methodology for Fault Diagnosis using Statistical Patterns

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ABSTRACT

Process fault diagnosis is a complicated matter because quality control problems can result from a variety of causes. These causes include problems with electrical components, mechanical components, human errors, job justification errors, and air conditioning influences.

In order to make the system run smoothly with minimum delay, it is necessary to suggest heuristic remedies for the detected faults. Hence, this paper describes a heuristic methodology of fault diagnosis that is performed using statistical patterns generated by quality characteristics.

The proposed methodology is described briefly as follows: If a sample pattern generated by random variables is similar to the number of prototype patterns, the sample pattern may be matched by any prototype pattern among them to be resembled. This concept is based on the similarity between a sample pattern and the matched prototype pattern. The similarity is calculated as the weighted average of squared deviation, which is expressed as the difference between the relative values of standard normal distribution to be transformed by the observed values of quality characteristics in a sample pattern and the critical values of the corresponding ones in a matched prototype pattern.

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1. Introduction

Process problem-solving is frequently very difficult owing to the complex interactions of manufacturing parameters. Frequently, the expertise required to direct the selection and application of problem-solving techniques is difficult to find[1]. In general, the technique of statistical quality control is used for process problem-solving. Statistical process control is a preventive tool in the manufacturing process, and is utilized to provide early warnings of process variations, which also increases productivity[2]. The aim of statistical process control is not only to bring the output of the process into specification but also to reduce the variation of the process.

The variation of process is caused by the various factors affecting the process balance. Variation in the behavior of values plotted on a control chart may be caused by chance (or random) causes of variation, and/or by assignable causes of variation[3]. One of these factors is considered as system failure. Hence, it is necessary to construct a diagnostic system for discovering any cause of system failure. It is desirable that this diagnostic system is capable of performing its task as fast as possible, since the duration of the system's breakdown is very closely related to productivity[4].

Interpretation of the statistical patterns on control charts is one of the important techniques in statistical process control. The limitation of a control chart is that it tells when to look for the trouble but cannot directly tell where to look for the trouble or what caused the trouble[5]. The interpretation of a particular pattern of observations plotted on the chart in terms of assignable causes requires extensive statistical experiences and heuristic knowledges of the process[6].

In small-batch production, early detection of an out-of-control situation and fast reaction to eliminate the causes for this variation are critical. The action to eliminate the causes of variation must be done before the batch of products is completed. In recent years, the textile spinning process has adopted the process of multi-products small-lot production. Therefore, there is high process deviation and unstable product quality because of lack of experience with a large variety of product mix environments, new products, mechanical faults, and human errors. First of all, mechanical fault is an important factor in process control. It absolutely affects the efficiency of production and the product quality level.

In order to solve the problems described above, this paper especially provides a heuristic methodology for the worsted spinning process control to interpret the statistical patterns generated by product quality characteristics. Also it diagnoses the process deviation and takes appropriate actions to remedy the faults that are caused from quality levels, mechanical faults, and job justification errors.

2. Fault Diagnosis Approach in Textile Spinning Process

A symptom of a fault is observed when the system behaves in a way that is not expected. In other words, a symptom is the discrepancy between the observed or actual behavior and the expected or predicted behavior of the system. Hence, when a symptom exists, there must be a fault(s) which cause(s) the symptom[7].

Diagnosis is the process of finding the location of a fault. The diagnosis can also suggest the remedy for the fault found. Diagnosis can be described as the process of determining the fault or faults responsible for a set of symptoms[8]. Diagnosis is performed in a wide variety of technical fields, such as medicine, manufacturing, and especially in textile spinning facilities.

Process fault diagnosis is a complicated matter because quality control problems can result from a variety of causes. These include problems with electrical components, mechanical components, human errors and environmental influences[9].

Machines play a significant role as the major production resources in the manufacturing environment and all machines are subject to failures. These failures not only add to the downtime and loss of equipment but also impose a cost in time and human expertise required for diagnosing the cause of failures and repairing the machines[10].

As mentioned above, in spinning process control the discriminant method, whether each process condition is in-control or out-of-control, is determined by measurement of the quality characteristics of the product. Also, the relevant remedies required in process fault diagnosis are performed to analyze the pattern generated by measurement of the quality characteristics.

Any appropriate technique is due to be selected for the relative remedies to each pattern generated combinatively by all the possible combinations of the measured results in statistical process control. This paper presents a heuristic methodology to make appropriate decision statistically for fault diagnosis related an unstable pattern generated by quality characteristics in the worsted spinning process.

3. Proposed Methodology of Fault Diagnosis and Remedies using Statistical Patterns

3. 1 Proposed Methodology[11]

Here, let us define the random variable X_i, $i=1, \cdots, k$, as the quality characteristics in a controlled process and define x_i as the corresponding measurement of random variable X_i. Then, an array can be obtained as follows;

$$\begin{vmatrix} X_1 & X_2 & \cdots & X_i & \cdots & X_k \\ x_1 & x_2 & \cdots & x_i & \cdots & x_k \end{vmatrix}$$

and many different patterns are generated by the measured results of each random variable. Thus, we obtain informations about process conditions through a generated pattern. As a consequence of the acquired information analysis, we have to take relevant actions to remedy the problem when the process conditions are unstable.

Next, let us consider the remedies for each random variable. First, let us assume that each random variable is normally distributed, i.e., $X_i \sim N(\mu_i, \sigma_i^2)$. The remedial zones that take actions are established according to the measured results of random variables under normal distribution. The established zones are referred to the criteria that take relevant actions whether the measurements of quality characteristics are in-control limits or out-of-control ones.

Here, if we define that a_i is referred as the number of remedial zones on each random variable described above, the remedial zones are expressed as pairs of X_i and a_i, i.e., (X_1, a_1), (X_2, a_2), $\cdots$, (X_i, a_i), $\cdots$, (X_k, a_k). And thus the whole sample patterns N can be obtained by the equation(1)

$$N = a_1 \times a_2 \times \cdots \times a_i \cdots \times a_k \, . \tag{1}$$

If the remedial zones on each random variable are more diversified, the generated sample patterns are greatly increased. Hence, it is possible to establish the remedial matters related to the whole sample patterns, but they are much duplicated.

As mentioned above, the proposed problem is very complicated and difficult to adjust with the remedial matters to many components of machines, when we consider the remedial matters on a certain sample pattern among the generated sample patterns.

If we perform all the remedial matters to the troubled machine, the machine is interrupted intermittently. Thus, the machine operating rate is decreased secondary to the interruption. Therefore, let us examine all the remedial matters that have to be performed on the sample pattern described above. In other words, according to inevitable ones among several remedial matters and factors to affect product quality, the relevant remedies are to be considered.

The proposed approach in this study is intended to solve the problems mentioned above. If we analyze the remedial matters of the whole sample patterns generated by measurements of each random variable, several prototype patterns are classified with the basic different remedial matters. When the remedial matters of a sample pattern include the relative remedial matters of two or three prototype patterns, this study presents the heuristic method to take the remedial matters of the matched one among the similar prototype patterns. The concept of matching between a sample pattern and a similar prototype pattern is considered as the similarity between two patterns.

In this study, the concept of similarity is explained as the distance, that is the difference between the criteria of quality characteristics in a prototype pattern and the measured values to be transformed into the standard normal distribution of the corresponding ones. As compared to the distances that are the differences between the values of standard normal distribution referred to the values of random variable on each sample pattern and ones corresponding to two or more similar prototype patterns, a sample pattern is matched by the prototype pattern to minimize the summation of differences. The proposed methodology selects the prototype pattern to minimize the weighted average of squared deviation for each similar one.

Here, let us define each random variable of quality characteristics, X_1, X_2, $\cdots$, X_k and then the measurements of each random variable are x_1, x_2, $\cdots$, x_i, $\cdots$, x_k. And the measurements of each random variable are transformed into the standard normal distribution, Zx_1, Zx_2, $\cdots$, Zx_i, $\cdots$, Zx_k. If a sample pattern is similar to m-number of similar prototype patterns, the similarity is calculated as the weighted average of squared deviation, which is expressed as the differences between the relative values of standard normal distribution to be transformed and the observed values of a sample pattern and the critical values of a similar prototype pattern.

The weighted average of squared deviation is calculated as the equation(2).

$$WD_j = \frac{\sum_{i=1}^{k} \frac{1}{W_i} [\, Zx_i - Rx_i^{(j)} \,]^2}{\sum_{i=1}^{k} \frac{1}{W_i}} \tag{2}$$

where,

WD_j : the weighted average of squared deviation of m-numbers of prototype patterns

W_i : the weight on each random variable.

Zx_i : the relative values of standard normal distribution on each random variable

j : 1, 2, $\cdots$, m

$Rx_i^{(j)}$: i-th criterion of j-th prototype pattern

Here, if x_i is included within the criteria of the j-th prototype pattern, the deviation is equal to zero.

If the weighted average of squared deviation calculated by the equation(2) is arranged to ascend, the equation(3) is obtained by

$$WD_{(1)} \leq WD_{(2)} \leq \cdots \leq WD_{(j)} \leq \cdots \leq WD_{(m)} \tag{3}$$

Here, $WD_{(1)}$ is illustrated at the minimum of WD_j .

If a sample pattern is highly matched the prototype pattern related to $WD_{(1)}$, we perform the remedial matters related to $WD_{(1)}$ on the machine. If we do not satisfy the remedial matters related to $WD_{(1)}$, the remedial matters related to $WD_{(2)}$ are performed on the machine. The procedures like these are performed continuously to find out a matched prototype pattern.

The weights W_i used in the equation(2) are empirically distributed by domain-expert. Thus in this study, the sensitivity analysis is performed by Monte Carlo's simulation, how affect these weights to select the prototype pattern.

The results demonstrate that the distribution of weights does not affect the selection of the prototype pattern.

Table 1. Parameters of mean and variance for each random variable.

Random variable \ Parameter	μ_i	σ_i^2
X_1	5.51	0.316^2
X_2	0.27	0.0036^2
X_3	1.33	0.336^2
X_4	64.00	3^2

Table 1 illustrates an example of the parameters of mean and variance for each random variable under normal probability distribution. Two kinds of weight groups used for simulation are shown in Table 2.

Table 2. Weight groups used for simulation.

Random variable	X_1	X_2	X_3	X_4
Weight group I	100	90	60	55
Weight group II	100	85	70	55

Table 3 illustrates the experimental output for simulation by means of input data as shown in Tables 1 and 2.

Examination of the experimental results in Table 3 shows that the different kinds of weight group do not affect the similarity, since a sample pattern is matched by all the same prototype pattern regardless of the weight group.

Table 3. Simulation output.

Weight	Mean value of X_4 : 59.0		Mean value of X_4 : 69.0	
	Prototype pattern 1	Prototype pattern 2	Prototype pattern 1	Prototype pattern 2
Group I	4	0	4	0
Grpup II	4	0	5	0
Sub total	8	0	9	0

Figure 1 illustrates the flowchart of simulation for weight value sensitivity.

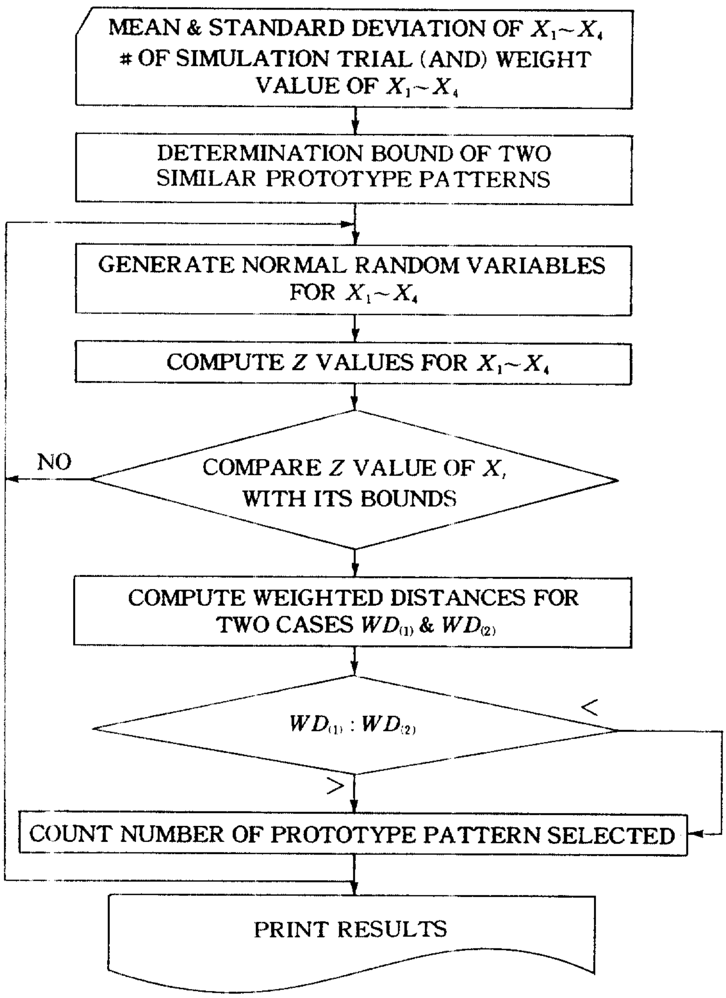

Figure 1. Flowchart of simulation for weight value sensitivity.

3. 2 Numerical example

There are several important quality characteristics in the textile spinning process control. Among them, there are especially four important quality characteristics affecting yarn spinning, i.e., product evenness U%, product weight per meter g/m, coefficient variation of product weight g/m_CV% and fiber length Hmm. Here, let us define that product evenness is replaced by random variable X_1, product weight per meter to X_2, coefficient variation of product weight to X_3 and fiber length to X_4.

Let us assume that X_1 is equal to 5. 84%, X_2 to 0. 258 g/m, X_3 to 2. 01% and X_4 to 66mm According to the measurements obtained above, let us assume that a generated sample pattern corresponds to the 22nd sample pattern in Table 4. The remedial matters related to the 22nd sample pattern are included in the 2nd and 7th sample patterns. The remedial matters related to the 2nd sample pattern in Table 4 are corresponding to the prototype pattern II and the 7th sample pattern to the prototype pattern IV in Table 5.

Table 5. Matching classification between sample pattern and prototype related to remedies.

Prototype patterns	Remedies	Inter-matched sample patterns
Type of I	①	1
Type of II	⑩∨⑨	2, 4, 12, 16, 20, 22, 24
Type of III	②∧(⑩∨⑨)	13, 14, 15, 16, 19, 25, 26, 27, 28, 31, 32, 33, 34
Type of IV	⑥∨⑤	7, 8, 9, 10, 11, 12, 19, 20, 21, 22, 23, 24, 31, 32, 33, 34, 35
Type of V	⑦∨⑧	3, 5, 6
Type of VI	①	36
Type of VII	④	37
Type of VIII	②∧⑧	17, 18, 29, 30, 35

Thus, we use the equation(2) and weight group I in Table 2 to solve the problem, which any prototype pattern of two is the 22nd sample pattern matched similarly.

where,

$$\sum_{i=1}^{4} \frac{1}{W_i} = 0.056$$

then,

Table 4. Generated each pattern and its remedies (Note : ∧ ; AND ∨ ; OR).

	X_1	X_2	X_3	X_4	Remedies
1	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$X_3 \le CV_{.75}$	$59 < X_4 < 69$	①
2	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$X_3 \le CV_{.75}$	$X_4 < 59 \vee X_4 > 69$	⑩∨⑨
3	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	⑦
4	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	⑦∨(⑩∨⑨)
5	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	⑧
6	$X_1 \le U_{.75}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	⑧∨(⑩∨⑨)
7	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	⑥∨⑤
8	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	(⑥∨⑤)∧(⑩∨⑨)
9	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	(⑥∨⑤)∧⑦
10	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	(⑥∨⑤)∧⑦∧(⑩∨⑨)
11	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	(⑥∨⑤)∧⑧
12	$X_1 \le U_{.75}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	(⑥∨⑤)∧⑧∧(⑩∨⑨)
13	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.75}$	$59 < X_4 < 69$	②
14	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.75}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑩∨⑨)
15	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	②∧⑦
16	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧⑦∧(⑩∨⑨)
17	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	②∧⑧
18	$U_{.75} \le X_1 \le U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧⑧∧(⑩∨⑨)
19	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.75}$	$59 < X_4 < 69$	②∧(⑥∨⑤)
20	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.75}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑥∨⑤)∧(⑩∨⑨)
21	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	②∧(⑥∨⑤)∧⑦
22	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑥∨⑤)∧⑦∧(⑩∨⑨)
23	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	②∧(⑥∨⑤)∧⑧
24	$U_{.75} \le X_1 \le U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑥∨⑤)∧⑧∧(⑩∨⑨)
25	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.75}$	$59 < X_4 < 69$	②
26	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.75}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑩∨⑨)
27	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	②∧⑦
28	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧⑦∧(⑩∨⑨)
29	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	②∧⑧
30	$X_1 \ge U_{.95}$	$LCL \le X_2 \le UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧⑧∧(⑩∨⑨)
31	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.75}$	$59 < X_4 < 69$	②∧(⑥∨⑤)
32	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.75}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑥∨⑤)∧(⑩∨⑨)
33	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$59 < X_4 < 69$	②∧(⑥∨⑤)∧⑦
34	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$CV_{.75} \le X_3 \le CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	②∧(⑥∨⑤)∧⑦∧(⑩∨⑨)
35	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$59 < X_4 < 69$	②∧(⑥∨⑤)∧⑧
36	$X_1 \ge U_{.95}$	$X_2 \le LCL \vee X_2 \ge UCL$	$X_3 \ge CV_{.95}$	$X_4 < 59 \vee X_4 > 69$	①
37	$X_1 \ge U_{.95}$				④

$$WD_2 = \{\frac{1}{100}(1.044-0.67)^2 + \frac{1}{90}(-3.333-(-2.25)^2) + \frac{1}{60}(2.025-0.67)^2 + \frac{1}{55}\times 0\} / 0.056 = 0.804$$

$$WD_7 = \{\frac{1}{100}(1.044-0.67)^2 + \frac{1}{90}\times 0 + \frac{1}{60}(2.024-0.67)^2 + \frac{1}{55}(2-0)^2\} / 0.056 = 1.875$$

In examining the calculated results described above, the 22nd sample pattern is matched more similarly by the 2nd sample pattern, since the value of WD_2 is less than the one of WD_7.

Therefore, the inevitable remedial action for the 22nd sample pattern is the one of prototype pattern Ⅱ.

We hope that you refer to the other numerical example besides this one and to the more detailed contents related with this study in the reference[12].

4. Conclusions

The proposed methodology in this study represents a heuristic method to select appropriate and effective remedial actions for detected faults. Numerical examples are reviewed to demonstrate the effectiveness of this approach in the field of textile spinning process control. We propose that this methodology can be applied to similar problems in other industrial fields.

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