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Feature Selection and Categorization to Design Reliable Fault Detection Systems

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ABSTRACT

In this work, we will develop a fault detection system which is identified as a classification task. The classes are the nominal or malfunctioning state. To develop a decision system it is important to select among the data collected by the supervision system, only those carrying relevant information related to the decision task. There are two objectives presented in this paper, the first one is to use data mining techniques to improve fault detection tasks. For this purpose, feature selection algorithms are applied before a classifier to select which measures are needed for a fault detection system. The second objective is to use STRASS (STRong Relevant Algorithm of Subset Selection), which gives a useful feature categorization: strong relevant features, weak relevant and/or redundant ones. This feature categorization permits to design reliable fault detection system. The algorithm is tested on real benchmarks in medical diagnosis and fault detection. Our results indicate that a small number of measures can accomplish and perform the classification task and shown our algorithm ability to detect the correlated features. Furthermore, the proposed feature selection and categorization permits to design reliable and efficient fault detection system.

1. INTRODUCTION

We work in conditional maintenance when the supervision system surveys the fault appearance. In a real supervision system, digital data collection devices and data storage technology allow organizations to store up huge data. The large amounts of data, has created a massive request for new

tools to transform data into task oriented knowledge (The knowledge data discovery, and data mining area). Our work concentrates on real-world problems and fault detection system, where the learner has to handle problems dealing with datasets containing large amounts of irrelevant information [9],[13],[14]. Initial features are often selected subjectively based on human experience. However, when large amount of data are being monitored, expert judgement may be subject to errors and biases. It is therefore desirable to use fully automated feature selection algorithm to overcome these shortcomings.

Over-instrumentation: monitoring too many metrics of a system poses significant problems, as a large number of threshold estimation, quantification, aggregation, situation identification and diagnostic rules exclude reliable manual design and maintenance, especially in evolving applications. On the other hand monitoring too many metrics also causes unnecessary performance overhead on the monitored systems, and data collection nodes especially in case of historic data collection.

Under-instrumentation: the improper reduction of the set of monitored metrics, on the other hand can significantly compromise the capabilities of supervision, manifesting in large reaction times to workload changes, significantly reduced availability due to late error detection and diagnosis. The selection of a compact, but sufficiently characteristic set of control variables is one of the core problems both for design and run-time complexity [43]. Dimension reduction methods are usually divided into two groups: feature extraction and feature selection approaches. Feature extraction aims at applying a projection of the multidimensional problem space into a space of fewer dimensions thus resulting in aggregate measures that did not exist in the measured environment while feature selection is

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finding a subset of the measured variables or a subset of the transformed variables via feature extraction.

Many descriptive features may affect the precision of a classifier and some can even parasitize the processing of data. However, it should be noted that features do not have the same importance/role in the development of the classifier. Therefore it is very useful to be able to identify, within the whole training set, the appropriate features' types to discriminate between the fault detection concepts being considered. Yu et al [25] counted four (4) different features types namely irrelevant ones, strongly relevant, weakly relevant and redundant ones. An entire feature set can be conceptually divided into four (4) basic disjoint parts: irrelevant features (I), redundant features (part of weakly relevant features (WRr1 and WRr2)), weakly relevant but non-redundant features (WRnr), and strongly relevant features (predominant). Fig. 2 illustrates this hierarchy. The optimal subset essentially contains all predominant features, WRnr and WRr1 or WRr2. WRr1 is a subset of weakly relevant features having their redundant or equivalent features in WRr2.

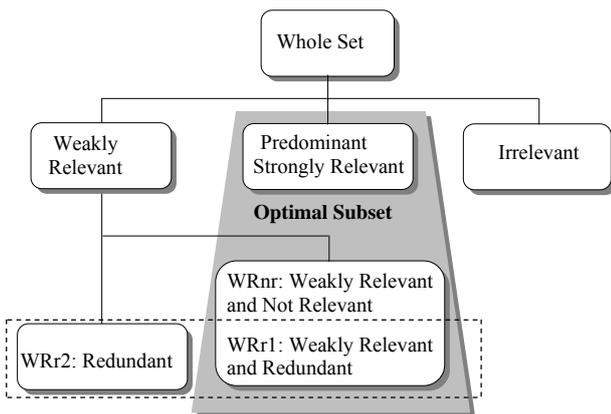


Figure 1. Hierarchy of feature's relevance and redundancy

First of all, we have to reduce the number of sensors/metrics considered in order to avoid over instrumentation and to simplify the classification problem. The filter algorithm STRASS [22] is initially used to select relevant information, construct a robust fault detection model and speed up training time. Moreover the proposed feature selection algorithm is based on two criteria of relevance which provide a useful features' categorization (Fig. 1): the strongly, weakly relevant features and the redundant ones. This features' categorisation is based on criteria developed in [22], [35]. In our precedent study [22], we define two complementary criteria, one Myopic and the other Contextual, to take into account partially redundant feature and privilege the quality detection of relevant subset feature. The proposed criteria attempt to explicitly address feature interactions by finding some low-order interactions 2-way

(one feature and the class) and high order interactions k-way (k features and the class) interactions. Those criteria are associated with a greedy algorithm which is noted STRASS (STRong Relevant Algorithm of Subset Selection). STRASS proves its efficiency and effectiveness comparing with five representative algorithms on artificial benchmarks well known for their features interactions. The other paper's contribution is in the exploitation of redundant features to improve fault detection reliability by reducing false alarm and/or missed alarm. Reliability requires the minimization of undetectability and false alarm probability due to sensor readings, which is not only related with sensor readings but also affected by fault propagation. In engineering practice, sensors may often be faulty, meaning that they may fail to give adequate readings or the sensor may give an alarm for a normal operation state, known as a false alarm. We should therefore allow for some redundancy in sensors in case of failures. A robust strategy to identify faulty sensor readings and to discriminate among sensor failure and system failure has been developed.

The rest of the paper is organized as follows: Section 2 overviews the state of art of feature selection techniques for fault detection systems. The study highlights the importance of the pre-processing phase such as feature extraction and selection to improve the classifier. Section 3 introduces the features' categorization technique, the proposed criteria and STRASS features selection algorithm that take into account the type of features in a rather finer way than other methods. It is worth noting that the authors' contribution is not in the filtering algorithm, but rather in the features categorization that has been derived from it to build a reliable fault detection system. In section 4 is devoted to the proposed methodology using feature categorization to design reliable fault detection systems. In Section 5 the proposed algorithm is evaluated and compared with two well-known feature selection algorithms CFS (Correlation Based Feature Selection) [10] and FCBF (Fast Correlation Based Feature Selection) [25] and a feature extraction algorithm the Principal Component Analysis (PCA). CFS and FCBF are considered to be among the best methods for their ability to treat different feature types and consequently provide a finer feature selection based on a minimal subset. Conclusions and recommendation for future work are summarized in Section 6.

2. A SURVEY OF RELATED WORK ON FEATURE SELECTION

Fault detection methods are generally based on either signal processing or physical models. Data-driven techniques for fault detection and diagnosis have also been extensively used. The following is a brief overview of some recently published papers on feature selection techniques for fault detection.

Paljak et al (2009) [31] considered the selection of a compact, but sufficiently characteristic set of control variables which can provide, in a simple way, good parameter estimators for predictive control. Their approach also provides the identification of the operational domain hence facilitating context-aware adaptive control, diagnostic and repair in large Infrastructure Monitoring. They used mRMR (minimum Redundancy Maximum Relevance) feature selection algorithm combined with linear approximation for selecting the few and most significant quantitative aspects of a system for the purpose of supervisory instrumentation. Yang et al (2008) [37] presented a survey on fault diagnosis using Support Vector Machine (SVM) classifiers combined with other methods. For the detection of faults in roller bearing, Jack et al (2002) used Genetic Algorithms to select an optimal feature subset for two SVM and artificial neural network based classifiers. Casimira et al (2006) [6] reviewed various pattern recognition methods for the diagnosis of faults in induction motors' stator and rotor. A set of 31 features were initially extracted by a time frequency analysis of stator currents and voltages and combined with others features. The most relevant features were selected using a sequential backward algorithm. The experimental results demonstrated the effectiveness of the proposed method to improve the k-nearest neighbours classification rate in condition monitoring. The work by Sugumara et al (2007) [38] focussed particularly on fault conditions in the roller bearing of a rotary machine. They used vibration signals from a piezoelectric transducer in different functional mode (good bearing, bearing with inner race fault, bearing with outer race fault, and inner and outer race fault). First, a set of 11 features were extracted by time frequency analysis. Among these, the 4 best features were selected from a given set of samples using the popular C4.5 decision tree algorithm. Second, Proximal Support Vector Machine (PSVM), was used to efficiently classify the faults using statistical features. Torkolan et al (2004) [23] constructed a driver's assistance system. This system uses feature selection to identify which sensors are needed for the classification of 12 manoeuvres (changing left, crossing shoulder, on road...). Sensor data like accelerator, brake, speed, etc. were collected from a driving simulator and a total of 138 features were extracted from this data set. The authors used Naïve Bayes and Random Forest classifiers. They combined CFS feature selection algorithm and Random Forest with various measures to calculate new features and evaluate which among the derived features were relevant to this problem in addition to selecting the best sensors. The results indicated that to some extent new sensor hardware can be exchanged with a software version by computing new variables based on existing ones. Feature selection in this case allows controlled collection of data using a desired number and type of sensors.

Among existing feature selection methods applied to fault detection system, earlier methods often evaluate variables without considering feature-feature correlation and interaction. They rank feature according to their individual relevance or discriminative power to the targeted classes and select top-ranked features. These methods are computationally efficient due to linear time complexity in terms of dimensionality. However, (1) they cannot give the feature categorization that we have cited and (2) they cannot remove partially redundant features.

3. FEATURE CATEGORISATION: CONCEPT AND CRITERIA OF RELEVANCE AND REDUNDANCY

3.1. Feature Categorisation

Definition 1: Irrelevant

A feature is useful if it is correlated with or predictive of the class; otherwise it is irrelevant [10].

Definition 2: Weakly relevant

A feature x_i is weakly relevant to a sample N of instances and distribution D if it is possible to remove a subset of the features so that x_i becomes strongly relevant (Blum and Langley [4]).

Definition 3: Strongly relevant

A feature x_k is strongly relevant to sample N if there exist examples A and B in N that differ only in their assignment to x_k and have different labels (or have different distributions of labels if they appear an N multiple of times). Similarly, x_k is strongly relevant to target c and distribution D if there exist examples A and B having non-zero probability over D that differ only in their assignment to x_k and satisfy $c(A) \neq c(B)$ (Blum and Langley definition's [4]).

Definition 4: Redundant

A feature is said to be redundant if several features taken together play the same role as the underlying feature (they discriminate the population studied by the considered feature).

3.2. Criteria of Relevance and Redundancy

Two criteria have been introduced to categorise a whole set of features (Senoussi et al [22]). These criteria were elaborated from the discriminatory power in a pair-wise data representation approach. The categorized features types depend on: predominant (strongly relevant), weakly relevant and redundant ones. These criteria are briefly described below.

3.2.1. Data representation

Giving the input data tabulated as Ω samples. A *signature* is a vector of r features x called pattern vector denoted by $x = \{x_i, i = 1, \dots, r\}$. The functional states are

represented by M classes $C = \{c_i, i = 1, \dots, M\}$ in an r -dimensional space. Making a decision consists in assigning an incoming input vector to the appropriate class. This decision consists in recognizing the functional state of the system. Let's associate to a feature x_k the function φ_{ij}^k relative to each pairs of instances $(\omega_i, \omega_j), i \neq j$.

$$\varphi^k(\omega_i, \omega_j) = \begin{cases} (\omega_i, \omega_j) \mapsto \varphi_{ij}^k = \\ 1 \Leftrightarrow x_k(\omega_i) = x_k(\omega_j) & i, j = 1, \dots, n \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The function φ_{ij}^c relative to each pair of instances and their corresponding labels is obtained in the way.

$$\varphi^c(\omega_i, \omega_j) = \begin{cases} (\omega_i, \omega_j) \mapsto \varphi_{ij}^c = \\ 1 \Leftrightarrow C(\omega_i) = C(\omega_j) & i, j = 1, \dots, n \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

3.2.2. Weak relevance measure

The weakly relevance of a set of feature is defined by the number of all pairs of objects who have at least one discriminating variable and different labels or different distributions of labels.

Proposition 1: *The discriminating capacity measure of a feature set $DC(L, \Omega)$:*

$$\text{On } (\Omega \times \Omega) \mapsto DC(L, \Omega) = \sum_{i=1}^n \sum_{j=1}^n \overline{\prod_{k=1}^m \varphi^k} \cdot \overline{\varphi^c} \quad (3)$$

Given a subset of m features $L = (x_1 \dots x_m)$; the subset of feature group relevance is the number of pairs that are discriminate at least with one feature for each class.

3.2.3. Strong relevance to the sample/distribution

To measure the exclusiveness of a feature, the equivalent of a "relevance gain" is defined as the measure related to a feature compared to a subset of features and is termed the Discriminating Capacity Gain (DCG).

First we define the relevance of a feature x_k compared to a relevant pre-selected features subset $L = (x_1 \dots x_m)$ on pairs of instances (ω_i, ω_j) .

The strong relevance (SR) of feature x_k on the data pair ω_i, ω_j is given by:

$$\text{On } (\omega_i, \omega_j) \mapsto SR(x_k, L, \omega_i, \omega_j) = \overline{\varphi^c} \cdot \overline{\varphi_{ij}^k} \cdot \prod_{l=1}^m \varphi^l \quad (4)$$

Proposition 2: *Discriminating capacity gain:* DCG

The aggregation of the Strong Relevance (SR) expression on the whole pairs will define the DCG as:

$$\text{On } (\Omega \times \Omega) \mapsto DCG(x_k, L, \Omega) = \sum_{i=1}^n \sum_{j=1}^n \overline{\varphi^c} \cdot \overline{\varphi_{ij}^k} \cdot \prod_{l=1}^m \varphi^l \quad (5)$$

The DCG of a feature x_k for a set of objects compared to a set of L features is equal to the number of object couples discriminated by only x_k and no other features.

3.2.4. Redundant feature

Let S be the current set of features if

$$DC(S, \Omega) - DC(S - \{x_l\}, \Omega) = 0 \quad (6)$$

Then x_l is a redundant or irrelevant feature compared to the feature subset S on Ω .

3.3. STRASS Algorithm

The criteria are associated with an algorithm related to the greedy type algorithms and noted STRASS (**Appendix A**). STRASS detects the strongly relevant features, the partially redundant features, selects a minimum feature subset and ranks the features' relevance. The algorithm breaks up into three stages depending on its initialisation:

- (1) Selection of strongly relevant features or predominant features which are impossible to exclude because they are the only ones which allow the discrimination of classes.
- (2) Selection of the remaining features or weakly relevant features which have the largest discriminating capacity and when combined with a subset of features, the resulting overall discriminating power is increased. The features having equivalent discriminating capacity are retained as weakly relevant and redundant and are denoted by WRr1 and WRr2.
- (3) Suppression of redundant features. At this stage, backward elimination is employed to detect the features that become redundant compared to the subset of the selected features when adding a new feature.

STRASS, presented in our previous study [22], has proved to be more efficient when compared to five (5) representative algorithms on artificial benchmarks well known for their features interactions and satisfactory performance for the selection of a minimal set of relevant features and handling the k-way features interaction [11]. Reference list entries should be alphabetized by the last name of the first author of each work.

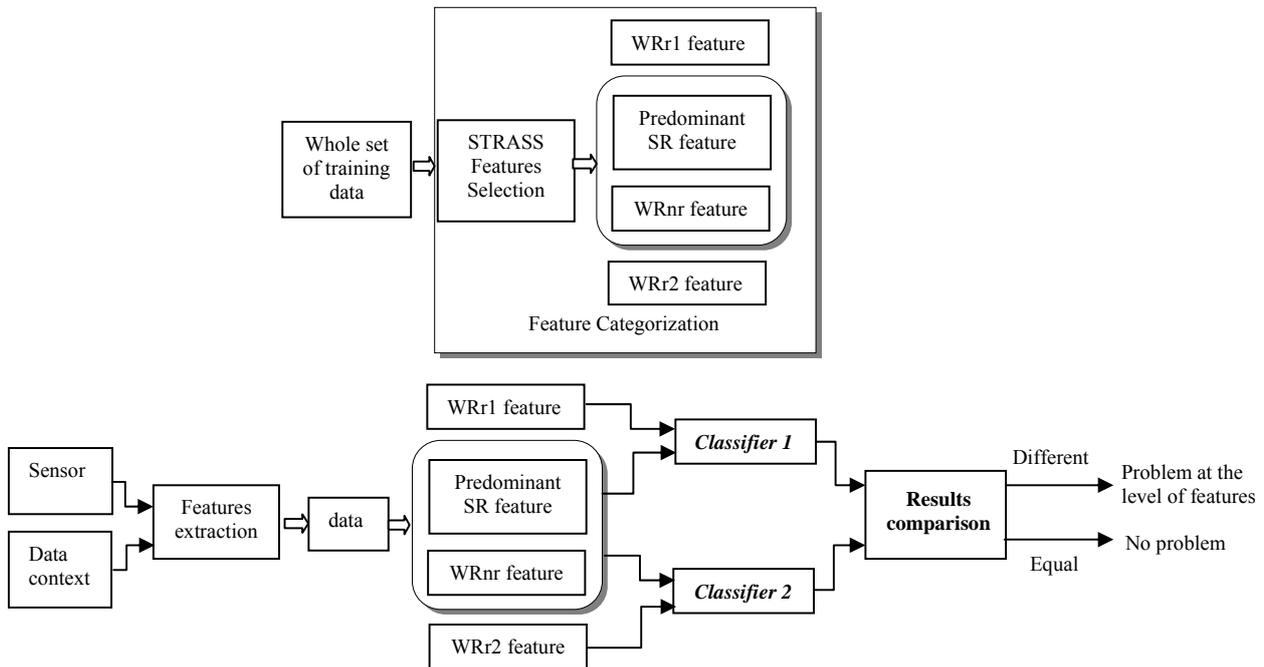


Figure. 2 The proposed fault detection system

4. FEATURES CATEGORIZATION TO CONSTRUCT A RELIABLE FAULT DETECTION SYSTEM

Reliability requires the minimization of undetectability and false alarm probability due to sensor readings or fault propagation. In this study the feature categorization will be used to design reliable fault detection system. Due to their natural discriminating characteristics the selected features can be practical to develop a measure of confidence for the fault detection system show in Fig. 2.

With reference to Fig. 2:

1. Firstly, a fault detection classifier is built using all predominant features (SR), weakly relevant but non-redundant features (WRnr) and weakly relevant features (WRr1).
2. Secondly, redundant features can be used with the predominant and the WRnr ones to build another classifier.
3. In the case of similar results, the second classifier confirms the result obtained with the first one. When the results obtained are different, it is an indication that there is a problem in the acquisition platform (a sensor is defiling) or in the data collection (a parameter is erroneous). The identification of the features is determined by a close examination of the redundant feature, or acquisition of another data.

We should therefore allow for some redundancy in sensors for the predominant measure in case of failures, and the examination of the redundant feature to relay the information. Therefore, missed alarms and false alarms can be detected.

5. EXPERIMENTS AND RESULTS

Our algorithm was implemented in MATLAB 7.5 environment. For the filtering algorithms and classifiers existing tools in WEKA machine learning platform [24] have been used. The experiments were run using WEKA with its default values.

5.1. Feature Selection and Categorization Results

The proposed algorithm has been evaluated on datasets from the UCI Machine Learning Repository [39]. Their characteristics are shown in Table 1.

Datasets	Instances	Features	Classes
Heart	270	14	2
Lung cancer	32	57	2
Hepatitis	20	20	2
Machine	12829	22	22
RFM	3519	72	22

Table 1. Summary of dataset

For the fault detection task Machine, RFM datasets (**Appendix B**) have been used. This data was originally taken at Texas Instruments as part of the SEMATECH J-88 project. For more information about this data set, please see [2][3].

Most existing feature selection algorithms are adapted for discretized (qualitative) data. Therefore for data sets with continuous features, the authors propose to use the MDL (Multi-interval discretization of continuous attributes) discretization algorithm proposed by Fayyad et al [8] also implemented in WEKA environment [24]. Table 2 presents the number of features selected by each features selection algorithm. The proposed algorithm has substantially reduced the number of features necessary to construct a classifier (18% in average in feature space). Table 3 gives STRASS selected features and their categorization. Heart and

Hepatitis have dominant features and redundant ones, thus make it possible to construct a second classifier to detect the same diagnosis and compare the results. For lung cancer and RFM datasets, the selected features are all predominant.

Datasets	ALL	STRASS	CFS	FCBF	ACP
Heart	13	8	6	5	12
Lcancer	56	3	8	6	25
Hepatitis	19	9	9	6	16
Machine	21	5	10	8	17
RFM	71	8	18	11	12
Average	36	6.6	10.2	7.2	16.4

Table 2. Number of features selected by each features selection algorithm

Data sets	STRASS Selected feature	SRp	WRnr	WRr1=WRr2
Heart	8 {3,7,8,1,2,12,9,13}	{3,7,8,1,2,12,13}		4=5=6=9 11=13
L cancer	3 {9,43,34}	{9,43,34}		3=7; 8=9
Hepatitis	9 {11,18,17,6,14,8,12,3,2}	{11,18}	{17,6,14,8,12,2}	3=7=10
Machine	5 {1,3,7,17,13}	{3,17,13}	{1}	{7=11,12,14,16}
RFM	8 {35,26,22,14,44,66,9,4}	{35,26,22,14,44,66,9,4}		

Table 3. STRASS feature categorization

5.2 Detection Results

For the classification task, three different classifiers have been used decision tree (C4.5), K-nearest-neighbor (IB_k), Support Vector Machines (SVM) and multilayer perceptron (MLP). In our experiments, k is set as 1. The classification results are obtained with 10-fold cross-validation. These results are compared with two Correlation-Based Feature Selection algorithms: CFS¹ [10] and FCBF² [25] and the Principal Component Analysis (PCA). TABLES 4-6 show results in both accuracy and kappa obtained with a two tailed test. The symbols “+” and “-” respectively identify significant improvement if an algorithm wins over or loses to the learning algorithm with the whole dataset.

Datasets	C4.5	C4.5+ STRASS	C4.5+ CFS	C4.5+ FCBF	C4.5+ ACP
heart	83.7	85.18+	83.3-	84.4 +	81.67-
L cancer	78.12	84.35 +	78.21	85.5+	57.92-
hepatitis	81.3	81.3	81.91+	80.6 -	79.75-
machine	94.58	94.72+	94.81+	94.70+	93.22-
RFM	94.38	95.34+	94.07-	94.13-	86.79-
Average	86.41	88.17+	86.4	87.86+	79.87-
Win/Loss		4+/0-	2+/2-	3+/2-	5-/0+

Table 4. C4.5 Classifier precision with and without filtering

¹ CFS with best first search

² FCBF with the relevance threshold SU set to 0.

Datasets	IBk	IBk+ STRASS	IBk+ CFS	IBk+ FCBF	IBk+ ACP
Heart	83.2	82.5 -	82.5-	81.9 -	80.74-
L cancer	75	78.5 +	71.3-	71.8-	65.42-
Hepatitis	83.8	85.8+	77.38-	84.5+	83.96+
Machine	95.80	95.97+	93.3-	94.95-	95.3-
RFM	94.65	96.06+	95.84+	94.67	93.91-
Average	86.49	87.76+	84.06-	85.56-	83.86-
Win/Loss		4+/1-	1+/4-	1+/3-	1+/4-

Table 5. IBk Classifier precision with and without filtering

Datasets	SVM	SVM+ STRASS	SVM+ CFS	SVM+ FCBF	SVM+ ACP
heart	84	84.3+	84.44+	85.18+	84.26+
L cancer	65.62	81.25+	81.25+	87.5+	70.00+
Hepatitis	86.45	87.74+	85.16-	85.80-	83.25-
Machine	88.98	61.12-	73.40-	72.60-	78.12-
RFM	90.12	94.32+	89.78-	88.92-	87.45-
Average	83.03	81.74-	82.8-	84+	80.61-
Win/Loss		4+/1-	2+/3-	2+/3-	2+/3-

Table 6. SVM Classifier precision with and without filtering

Datasets	MLP	STRASS	CFS	FCBF	ACP
heart	80.43	83.12+	82.61+	79.35-	80.93+
L cancer	67.9	86.67+	85.42+	79.58+	59.17-
hepatitis	84.23	85.21+	84.46+	85.24+	82.23-
machine	79.28	59.87-	50.74-	58.90-	64.66-
RFM	90.51	90.5	89.87-	89.61-	89.16-
Average	80.47	81.07+	78.62-	78.53-	75.23-
Win/Loss		3+/1-	3+/2-	2+/3-	1+/4-

Table 7. MLP Classifier precision with and without filtering

From these results it can be concluded that STRASS leads to a better performance than CFS, FCBF and ACP classifiers. The combination of C4.5 and STRASS produced the best results. For both classifiers, the reduction of features by STRASS gives results comparable or even superior when using all features: average accuracy 88.17% (STRASS) vs. 86.41% (Full Set) for C4.5, 87.76% (STRASS) vs. 86.49% (Full Set) for IBk and 81.07% (STRASS) vs. 80.47% (Full Set) for MLP. The application on Machine and RFM process demonstrates that this method is very effective for feature selection and classification.

6. CONCLUSION AND FUTURE WORK

In this paper we proposed to use STRASS, a contextual-based feature selection algorithm for fault detection to categorize measures and to determine the interaction between features. This enabled us to detect the redundancy among measures. STRASS was initially evaluated in datasets related to medical diagnosis. The proposed feature selection algorithm was then applied to two well known fault detection benchmarks. STRASS has demonstrated its efficiency and effectiveness in reducing the dimensionality of datasets while maintaining or improving the performances of learning algorithms. The application of this feature categorization on Machine and RFM datasets has demonstrated that this method is very effective for fault detection.

STRASS is based on two criteria of relevance that permit to obtain a useful feature categorization. In fact the algorithm detects the strongly relevant features, the weakly relevant and their corresponding partially redundant feature and selects a minimum feature subset. Moreover the proposed criterion in this study provides a useful ranking incorporating the context of others features and detects the equivalent measures (partially redundant features). Future work will focus on exploiting this features categorization to construct a reliable fault detection system by adding redundant measures for the predominant ones and use the redundant information from the redundant measures to construct an equivalent classifier to relay the information (in the case of same result for both classifier) or to point out a problem in the acquisition platform or in the data collection (in the case classifiers give different results).

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Appendix A: Algorithm STRASS

E	The whole set of data pairs $\Omega \times \Omega$.
$L = \{x_1, x_2 \dots x_m\}$	A set of features to be treated
$S = \emptyset$	Selected features
$SR_p = \emptyset$	Strongly relevant predominant features
$DC_{Tot} = DC(L)$	
$DC_{max} = 0$	
$WRnr = \emptyset$	Weakly relevant and not redundant features
$WRr1 = \emptyset$	Weakly relevant and redundant features
$WRr2 = \emptyset$	Weakly relevant and redundant features

Table A1 STRASS algorithm pseudo-code

```

1. Selection of predominant features
   for each feature  $x_k$  of  $L$  do
       scan the examples space  $E$ 

           if  $DCG(x_k, L-x_k) \neq 0$ 
                $S = S + x_k$ ;  $L = L - x_k$ ;
                $SR_p = S$ ;
                $E = E - \{\text{discriminated pairs}\}$ 

2. Selection of weak relevant features
   while  $DC(S) < DC_{tot}$  do
       for each feature  $x_k$  of  $L$  do
           scan the examples space  $E$ 

               if  $DC(x_k + S) > DC_{max}$ 

                    $DC_{max} = DC(\{x_k\} + S)$ 
                    $x_{k\_max} = x_k$ ;  $S = S + \{x_{k\_max}\}$ ;
                    $L = L - \{x_{k\_max}\}$ 
                    $WRnr = WRnr + \{x_{k\_max}\}$ 

               if  $DC(x_k + S) = DC_{max}$ 

                    $WRr1 = WRr1 + \{x_{k\_max}\}$ 
                    $WRr2 = WRr2 + \{x_k\}$  // detection of redundant features
                    $E = E - \{\text{discriminated pairs}\}$ 

3. Detection of the partially redundant features
   for each feature  $x_k$  of  $S$  do
       if  $DC(x_k, S - \{x_k\}) = 0$ 
            $S = S - \{x_k\}$ ; // suppression of the redundant features
            $WRr2 = WRr2 + \{x_k\}$ ; // detection of redundant features

return  $S, SR_p, WRnr, WRr1, WRr2$ 

```

Appendix B: Machine and RFM Datasets

Machine and RFM datasets are elaborated for fault detection and diagnosis in semiconductor etch [2]. The data comes from the metal etch step in semiconductor processing, specifically the Al-stack etch process. Data was collected on the commercially available Lam 9600 plasma etch tool [3]. The metal etcher was equipped with the machine state sensors, built into the processing tool; it collects machine data during wafer processing. The machine data consists of measured and controlled variables sampled at 1 second intervals during the etch. These are engineering variables, such as gas flow rates, chamber pressure and RF power. These variables are listed in Table B1. The RFM sensors measure the voltage, current and phase relationships at the fundamental frequency of 13.56 MHz and the next four harmonics at four locations in the RF control system. The resulting 70 values are sampled every 3 seconds.

Table B1 Machine state variables used for process monitoring.

x1 : Time	x12 : Phase Error
x2 : Step Number	x13 : RF Power
x3 : BCl3 Flow	x14 : RF Impedance
x4 : Cl2 Flow	x15 : TCP Tuner
x5 : RF Bottom Power	x16 : TCP Phase Error
x6 : RFB Reflected Power	x17 : TCP Impedance
x7 : Endpoint A Detector	x18 : TCP Top Power
x8 : Helium Pressure	x19 : TCP Reflected Power
x9 : Chamber Pressure	X20 : TCP Load
x10 : RF Tuner	X21 : Vat Valve
x11 : RF Load	

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