Signal Processing and Recognition Group

Fault analysis in rotating machines by using differential directional operators on thermal images

Hermes Alexander Fandiño Toro
Julio César García Álvarez
Germán Castellanos Domínguez

March 13, 2012

Contents

Signal Processing and Recognition Group

Contents

Signal Processing and Recognition Group

Introduction

Signal Processing and Recognition Group

Advantages of thermal imaging for machine inspection

- Analysis of thermal images allows machine to be evaluated under different operation conditions without the need for physical contact.
- Thermal distribution alterations on some regions of image can predict the presence of a different type of failures.

Contents

State of the art

Current approaches on rotative machine inspection

- Motor operation estimation by using data and signal-based models [Bellini *et* al. 2004]. However, model-based approaches become very complex, due to the variability of the different materials being inspected.
- Fault detection by acoustic and vibration measurement and signal analysis [Tse *et* al., 2004], [Peng *et* al., 2005]. Nonetheless, measurement is partially–invasive and would implicate the usage of additional measurement equipment on the inspected machine.

State of the art

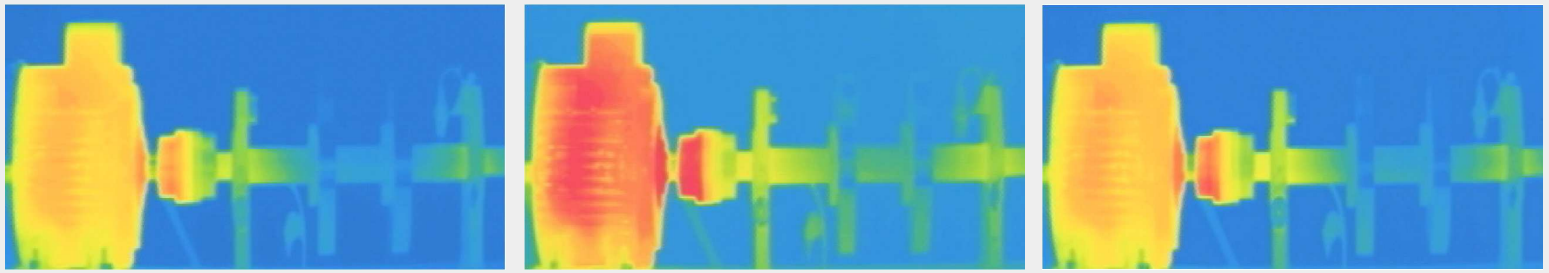
Thermal image representation [Younus and Yang, 2010]

- Image is mapped into a multi–resolution scheme using Discrete Wavelet Transform.
- Different types of faults can be identified by value variation of some statistical measure accomplished on approximation wavelet coefficients.
- An especial kind of statistical measures –the shape measures–, are used considering that data distribution follows a unimodal probability function.
- Just one *Region of Interest* (ROI) is considered for the analyzed conditions $\rightarrow$ the localization of identified fault is not possible.

Proposal

Signal Processing and Recognition Group

Motor operating conditions



(a) Normal operation (b) First wheel unbalance (FWU) (c) Second wheel unbalance (SWU)

Figure 1: Test bench image acquired at the same time point (7200s) under 3 different operating conditions.

Proposal

Signal Processing and Recognition Group

Hypothesis

- A fault alters not only the temperature distribution but the heat propagation direction.
- Temperature alterations propagate within the boundaries of inspected parts.
- ROI can be segmented by identifying hot spots on inspected parts.

Proposal

Signal Processing and Recognition Group

Objectives

- Fault identification by using directional operators instead statistical measures.
- An automatic ROI segmentation method leads to improve the identification of hot spots inside inspected parts.
- Fault localization can be implemented on this proposed methodology.

Contents

Signal Processing and Recognition Group

Outline

Signal Processing and Recognition Group

Fault identification by differential directional operator analysis on thermal images

- Test bench,
- Thermal image preprocessing,
- Feature extraction,
- Relevance analysis,
- Performance evaluation.

Test bench

Signal Processing and Recognition Group

Test bench

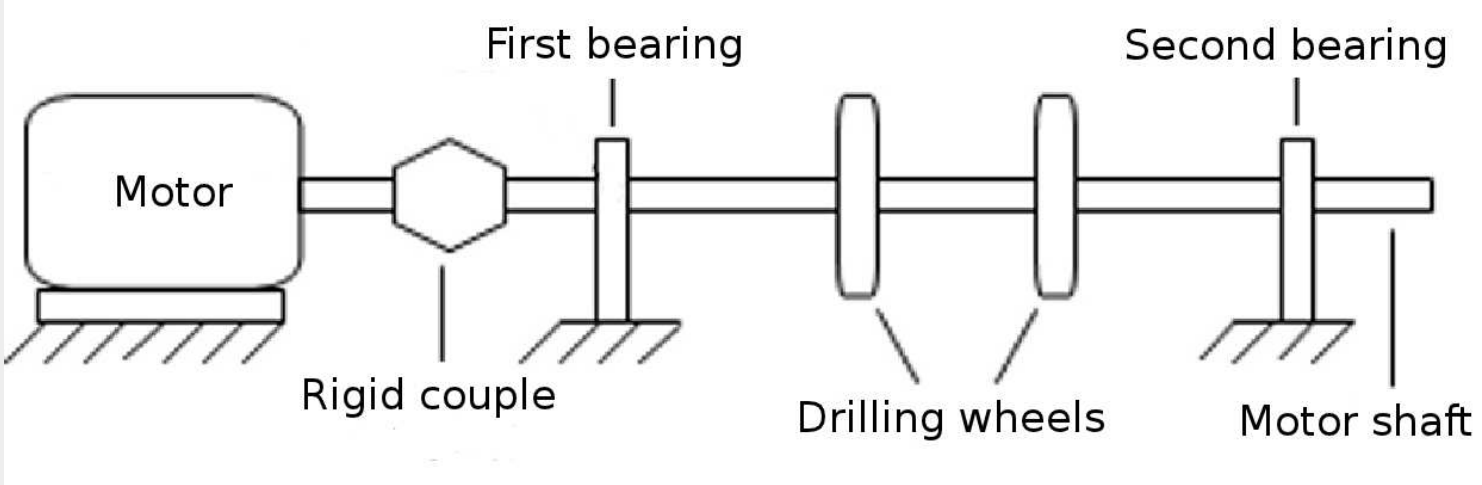


Figure 1: By attaching 5g-weighted masses inside the drilling wheels, two types of unbalance are induced, whose labels are described according to its nearest bearing.

Test bench

Signal Processing and Recognition Group

Thermal camera set–up

(FLIR A320 camera)	Emissivity	0.82
	Reflected temperature	20°C
	Distance to test bench	1.5m
	Relative humidity	50%
	Ambient temperature	20°C
	Thermal scale	$10 - 50$°C
Video settings	Image size	640×480 pixels
	Frame rate	1 fps
	Image format	MPEG-2

Table 1: Camera settings

Test bench

Signal Processing and Recognition Group

Image acquisition and database

- 2–hour (3600s) recordings per three operating condition types: Normal condition *to* **normal**, First Wheel Unbalance *to* **fwu** and Second Wheel Unbalance $\rightarrow$ **swu**.
- Framing by 1 frame per second.
- Acquired frames are down–sampled to one frame each 60s.
- A total of 53 images for each condition are accomplished.
- `RGB` and `YCbCr` color spaces are either considered.

Thermal image preprocessing

Signal Processing and Recognition Group

Background remotion - Multilevel thresholding

1. Define range $\mathbf{R} = [a, b]$ where $a = min(I)$ and $b = max(I)$.
2. Define subrange limit $T_1 = \mu - k_1\sigma$ and $T_2 = \mu + k_1\sigma$, where μ and σ are calculated for R.
3. Pixels in intervals $[a, T_1]$ and $[T_2, b]$ are quantized to its weighted means.
4. For next iteration: $a = T_1 + 1$, y $b = T_2 - 1$. Do the same while difference between T_2 and T_1 is greater than 1.

Thermal image preprocessing

Signal Processing and Recognition Group

A–priori ROIs

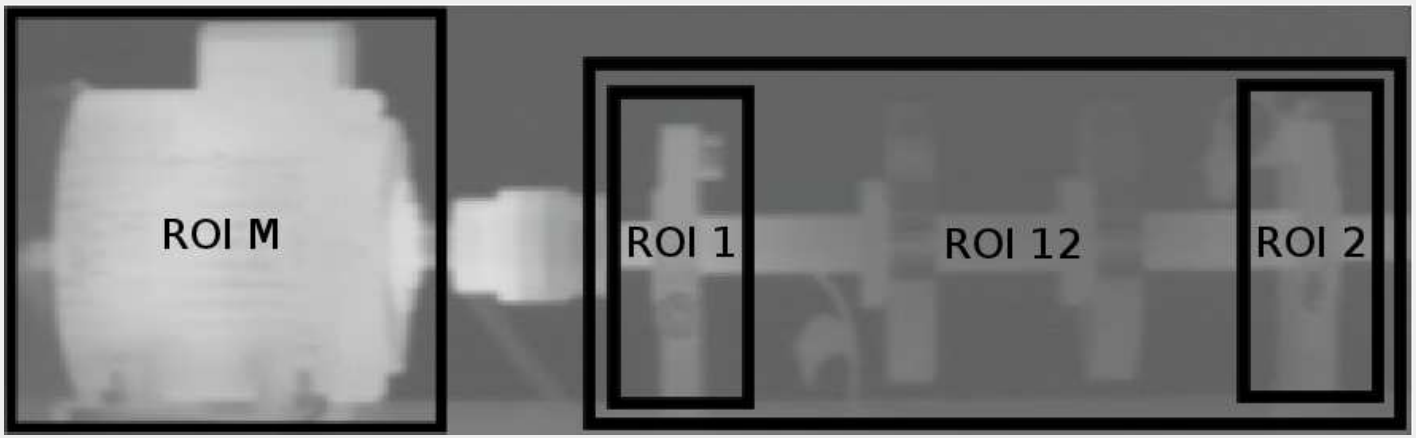


Figure 1: A–priori arbitrary–selected ROIs

Thermal image preprocessing

Signal Processing and Recognition Group

Color spaces

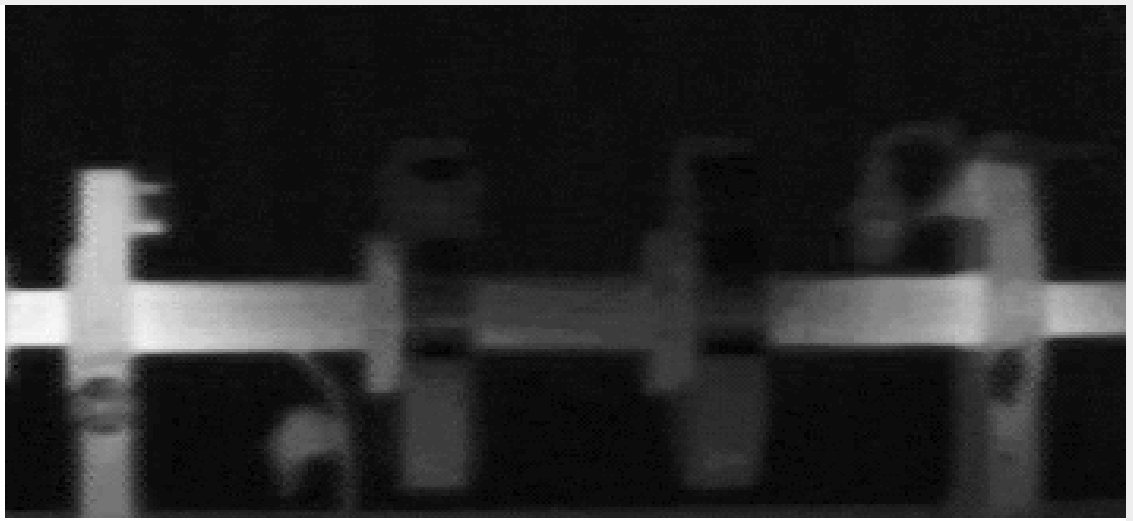


Figure 1: Infrared image - Luminance layer in YCbCr color space.

Thermal image preprocessing

Signal Processing and Recognition Group

Color spaces

- Thermal images are conventionally provided by three color planes. Nonetheless, just one color plane should be used for the feature extraction process.
- In our case, a thermal gray–scale image is projected into a `RGB` space, providing three color planes with approximately the same thermal value (even for γ–corrected images). Therefore, any of those three planes can be used.
- However, projection of thermal values on color planes is non–linear. Therefore, a chroma-intensity transformation is more convenient for carrying information of color planes into a single plane. So, the intensity plane Y of the `YCbCr` space is suggested for usage at the feature extraction process.

Thermal image preprocessing

Signal Processing and Recognition Group

Image quantization and segmentation

After multilevel thresholding is used, the image is quantized into pixel value intervals. High–valued intervals are selected to segment the image.

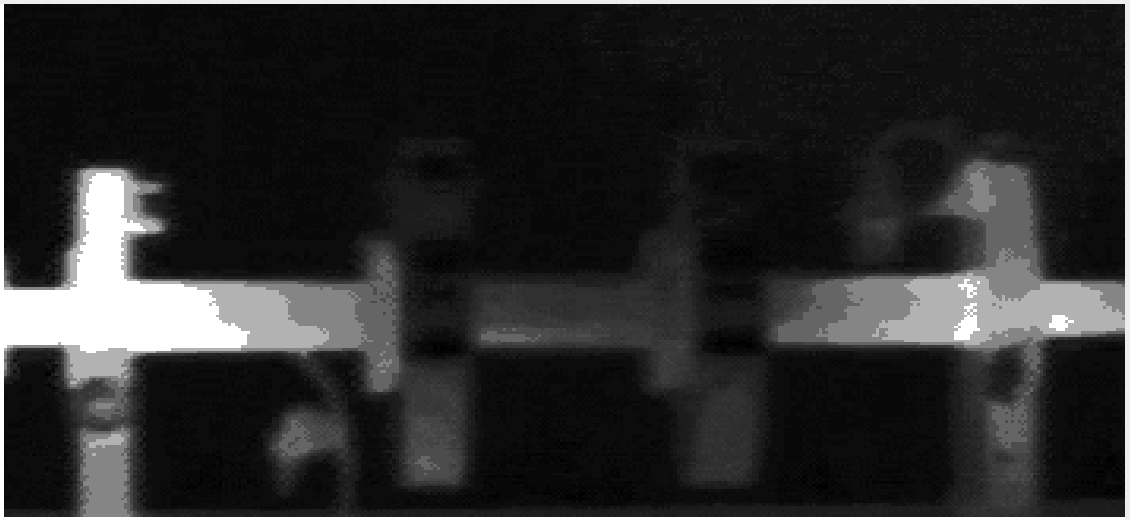


Figure 1: Quantized image.

Thermal image preprocessing

Signal Processing and Recognition Group

ROI masking

After segmentation, ROI masks are carried out, whose pixel locations are saved to further analysis.

Figure 1: ROI masks (in white).

Thermal image preprocessing

Signal Processing and Recognition Group

Automatically detected ROIs

Figure 1: Detected ROIs

Feature extraction

Sobel edge detection operator

Discrete differentiation operators computing a gradient approximation of the image intensity function [Jin-Yu *et* al. 2009].

$$T_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \qquad T_x = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix}$$

Feature extraction

Signal Processing and Recognition Group

Prewitt edge detection operator

Discrete differentiation operators computing a gradient approximation of the image intensity function [Gonzalez & Woods, 2002].

$$T_x = \begin{bmatrix} -1 & 0 & +1 \\ -1 & 0 & +1 \\ -1 & 0 & +1 \end{bmatrix} \qquad T_x = \begin{bmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ +1 & +1 & +1 \end{bmatrix}$$

Feature extraction

Signal Processing and Recognition Group

Convolution with filtering masks

Gradient operator is implemented on a linear filter of size $m \times n$, carried out on image f of size $M \times N$ [Gonzalez & Woods, 2002]:

$$g(x,y) = \sum_{i=-a}^{a} \sum_{i=-b}^{b} w(s,t) f(x+s, y+t) \tag{1}$$

Feature extraction

Direction angle of gradient vector

Approximation to the second derivative:

$$\alpha(x, y) = tan^{-1} \frac{G_y}{G_x} \tag{1}$$

$$G_x = T_x * f; \tag{2}$$

$$G_y = T_y * f; \tag{3}$$

Relevance analysis

Signal Processing and Recognition Group

Finding of relevant angles

After convolution between image and gradient operators, a histogram of angle direction is obtanied in order to search for relevant angles (features).

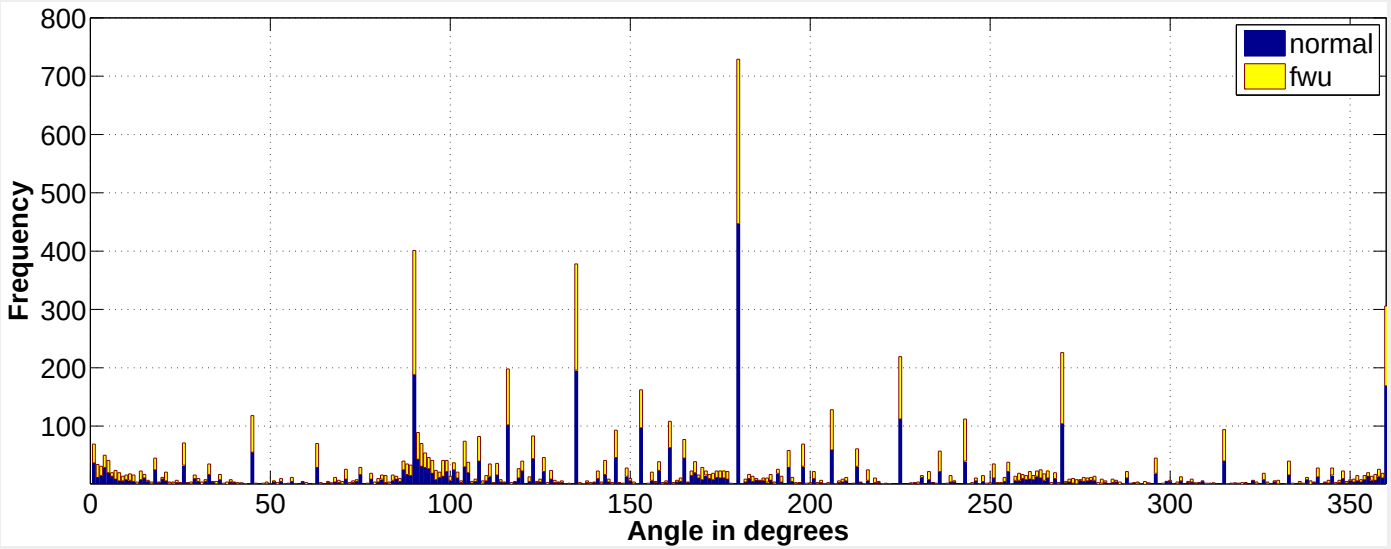


Figure 2: Stacked histogram for 2 frames of the test bench under different operation condition, at same time.

Relevance analysis

Signal Processing and Recognition Group

Principal Component Analysis (PCA)

Relevant angles are found by the vector P of Q number of features:

$$P^T P = U\sqrt{(\lambda)}V^T \in Q \times Q \tag{4}$$

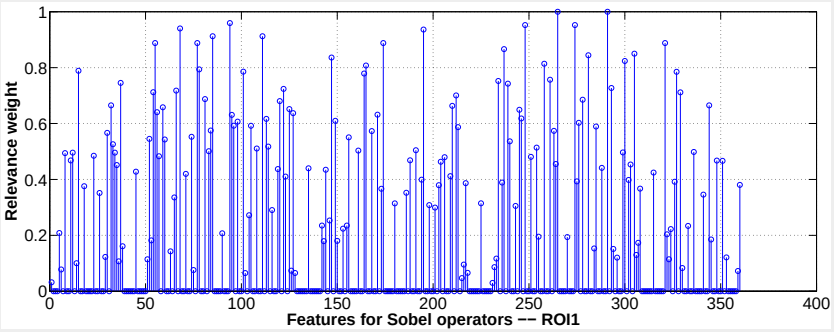
where:

- U: Eigenvalues matrix;
- λ: Eigenvector.

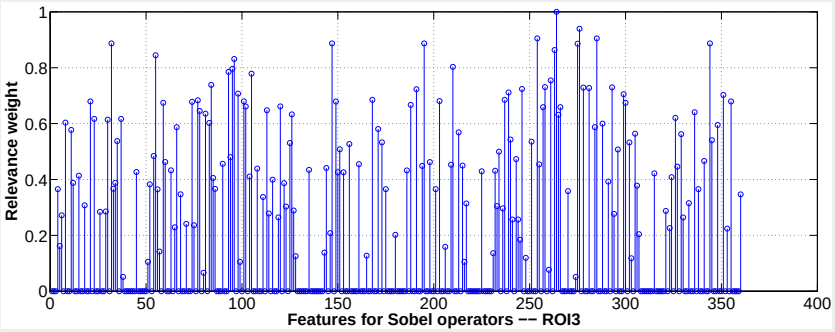
Relevance analysis

Signal Processing and Recognition Group

Results using Sobel operator



(a) RGB colorspace



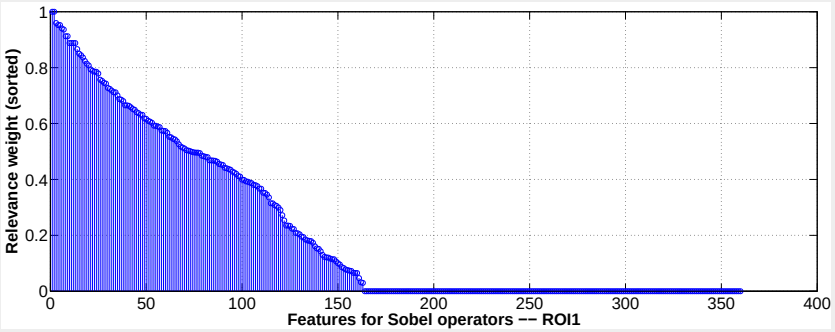
(b) YCbCR colorspace

Figure 2: Relevance analysis for features inside ROI1 and ROI3.

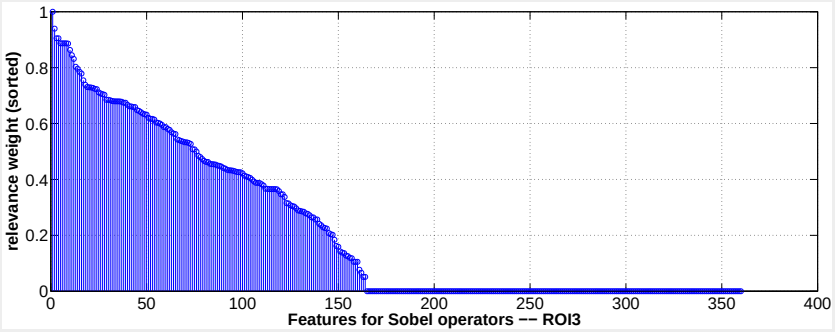
Relevance analysis

Signal Processing and Recognition Group

Results using Sobel operator



(a) RGB colorspace



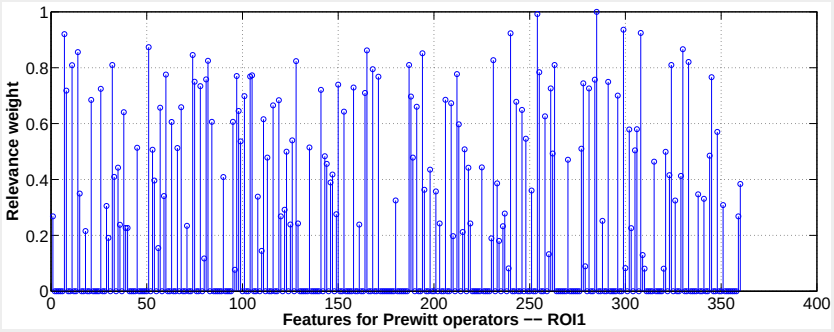
(b) YCbCR colorspace

Figure 2: Relevance analysis for features inside ROI1 and ROI3.

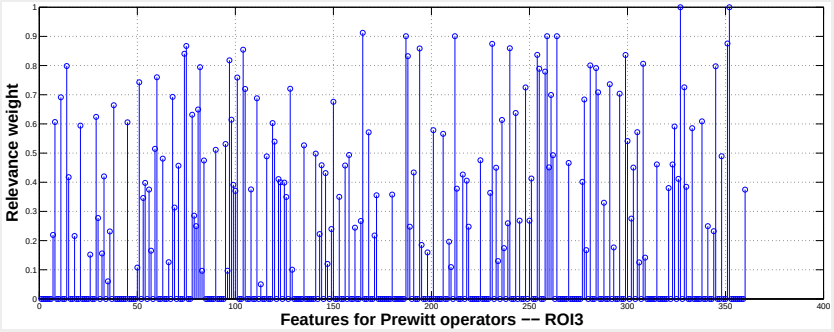
Relevance analysis

Signal Processing and Recognition Group

Results using Prewitt operator



(a) RGB colorspace



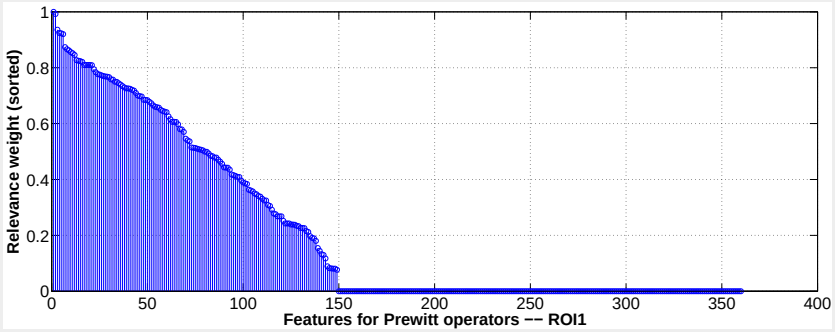
(b) YCbCR colorspace

Figure 2: Relevance analysis for features inside ROI1 and ROI3.

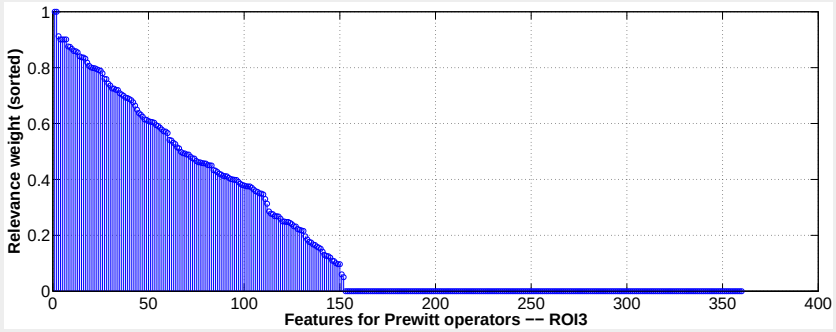
Relevance analysis

Signal Processing and Recognition Group

Results using Prewitt operator



(a) RGB colorspace



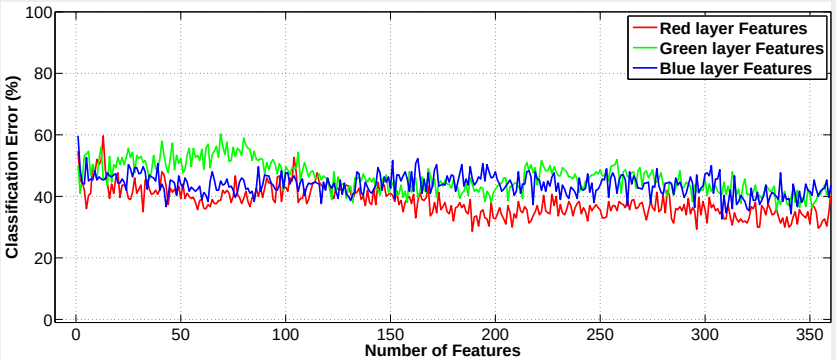
(b) YCbCR colorspace

Figure 2: Relevance analysis for features inside ROI1 and ROI3.

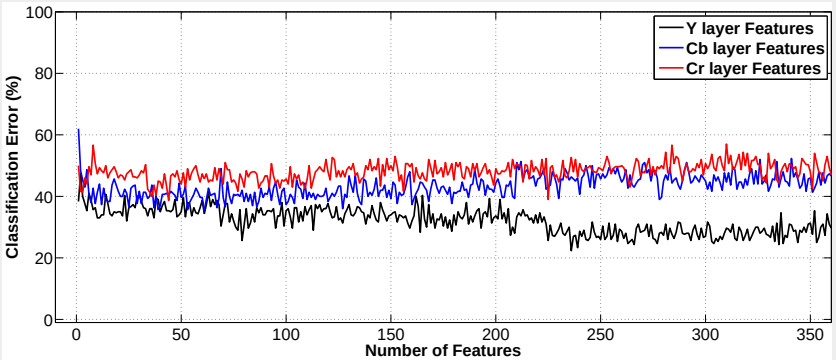
Performance evaluation

Signal Processing and Recognition Group

Classification error – Sobel operator, ROI 1



(a) RGB colorspace



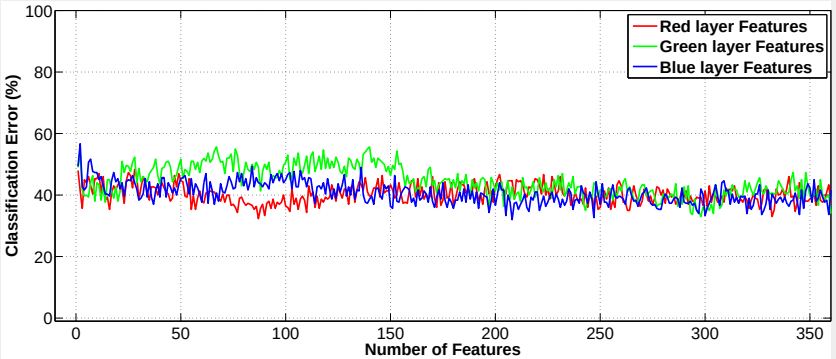
(b) YCbCR colorspace

Figure 3: Clasification error for ROI1 (first wheel) using Sobel operator.

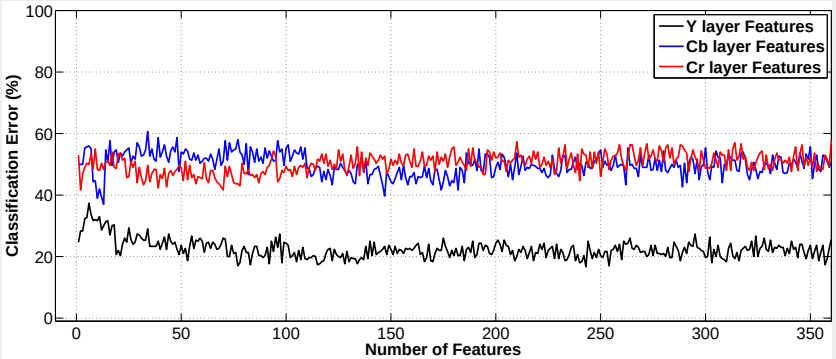
Performance evaluation

Signal Processing and Recognition Group

Classification error – Sobel kernel, ROI 1



(a) RGB colorspace



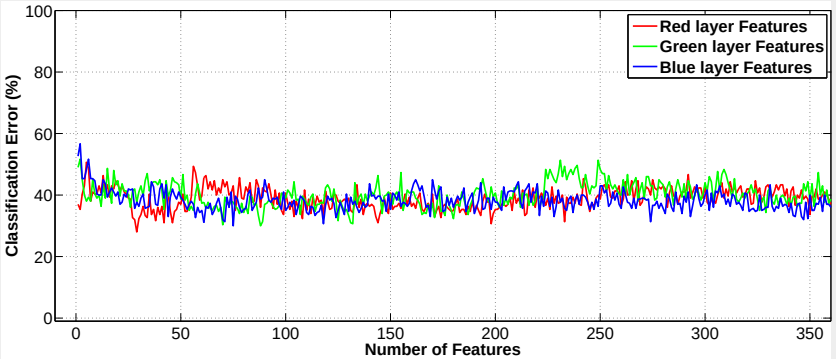
(b) YCbCr colorspace

Figure 3: Clasification error for ROI3 (second wheel) using Sobel operator.

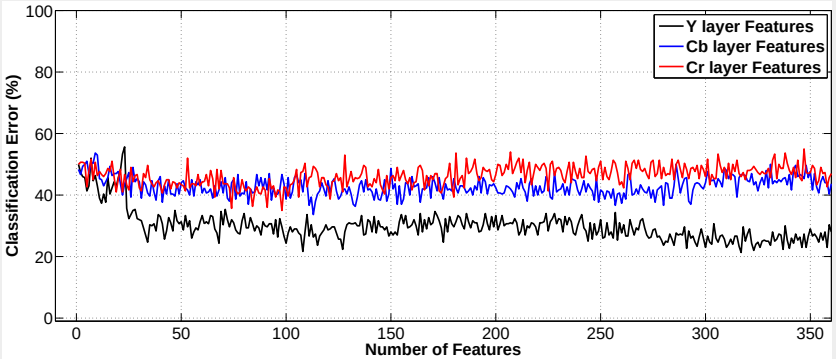
Performance evaluation

Signal Processing and Recognition Group

Classification error – Sobel kernel, ROI 1



(a) RGB colorspace



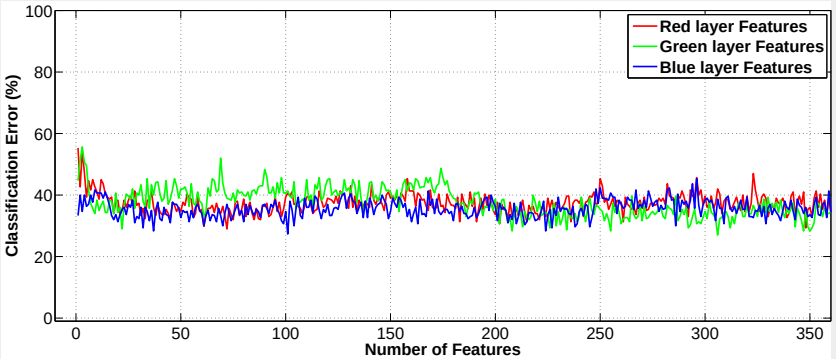
(b) YCbCR colorspace

Figure 3: Clasification error for ROI1 (first wheel) using Prewitt operator.

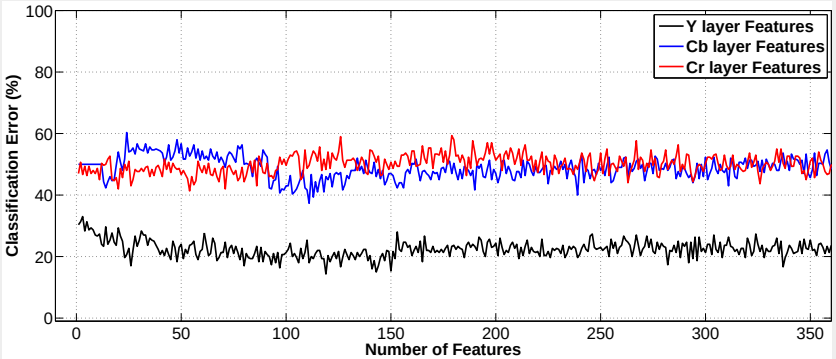
Performance evaluation

Signal Processing and Recognition Group

Classification error – Sobel kernel, ROI 1



(a) RGB colorspace



(b) YCbCr colorspace

Figure 3: Clasification error for ROI3 (second wheel) using Prewitt operator.

Contents

Signal Processing and Recognition Group

Conclusions

Signal Processing and Recognition Group

Conclusions and Future Works

- The high contrast of thermal values between pixels located within hot–spots and background is the key aspect for the improvement of the proposed segmentation method.
- The relevant angles fit with the directions where the hot–spot propagation is detected, meaning an improvement for the fault interpretation. In this context, an increase of the number of relevant angles suspects that a fault occurs.
- Assuming the correspondence between relevant angles and heat propagation directions, directional patterns will be used as texture operators for a closer characterization of hot spots related with faults.

[1] [Bellini *et* al, 2008] A. Bellini, F. Filippetti, C. Tassoni, and G. Capolino, "*Advances in diagnostic techniques for induction machines*," in IEEE Transactions on Industrial Electronics, vol. 55, no. 12, pp. 4109-4126, 2008.

[2] P. Tse, W. Yang, and H. Tam, "*Machine fault diagnosis through an effective exact wavelet analysis*," in Journal of Sound and Vibration, vol. 277, no. 4-5, pp. 1005-1024, 2004.

[3] A. Younus and B. Yang, "*Wavelet co-eficient of thermal image analysis for machine fault diagnosis*," in Proceedings of the International Conference on Mechanical Engineering, ICME09., 2009, pp. 1-6.

[4] Z. Peng, P. Tse, and F. Chu, "*An improved hilbert-huang transform and its application in vibration signal analysis*," Journal of Sound and Vibration, vol. 286, no. 1-2, pp. 187-205, 2005.

[5] Z. Jin-Yu, C. Yan, and H. Xiang-Xiang, "*Edge Detection of Images Based on Improved Sobel Operator and Gradient and Genetic Algorithms*," in International conference on Image Analysis and Signal Processing. IASP 2009, pp. 31-35, 2009.

[6] [Gonzalez & Woods, 2002] R. Gonzalez, and R. Woods, "*Digital Image Processing 2nd Edition*," Prentice Hall, 2002.