Effect of Sensor Type and Positioning on Features for Condition Monitoring of a Mechatronic System

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Abstract. In this paper, a methodology is described able to give general suggestions and guide lines in choosing the most suitable parameter, measuring strategy and the feature set for possible use in a condition monitoring procedure. The tests have been carried out on a mechatronic system in real scale, realizing a sinusoidal motion of its end effector. Internal sensors to the controller have been used (encoder and current sensors) and external to it (laser Doppler vibrometer and three-axis accelerometer). A kinematic and dynamic model of the mechanical linkage of the automated system allows the user to correlate the measurements and to compute the other quantities, even though of different type and/or measured in other point of the device. The most suitable quantities and features have been recognized with respect to the capability of identifying different operating statuses of the device, often independently on the measuring point, if the simulation model is used.

1. Introduction

Condition Monitoring (CM) of a mechatronic system operating in a modern industrial scenario, like the so-called Industry 4.0, is a practice having a larger and larger role with reference to the management of the system itself. In fact, CM allows a reliable knowledge of the actual status of the device, in order to optimize its working conditions, at both the set up and during the operating time, preventing the occurrence of critical faults and guaranteeing a reliable operation, by means of a suitable maintenance strategy [1].

The availability of many sensors, also of low-cost type, the possibility of interconnecting them, the capability of post-processing their data also by means of advanced algorithms like Artificial Neural Networks (ANN) make possible very effective strategies of CM, as for sensitivity of detection of each defect and selectivity with respect to different fault conditions.

Optimization of a CM approach, even though many examples can be found with reference to various industrial applications, is a task difficult to frame into a unique solution of general validity, being many the elements to be considered.

In fact, many measurement systems can be used [2], different features, available in both the time and frequency domains [3], [4], [5], can assess the condition of interest and also many criteria of combining and processing features exist. Furthermore, the position of installation of sensors is a very crucial aspect to be considered for a reliable and effective CM strategy; finally, the evaluation of the CM capability of
a monitoring system based on internal sensors to the controller with respect to the use of external sensors is one other topic of diffused interest.

Different examples of criteria of improving the CM frame of a mechatronic system are available in literature. In [6] unsupervised Neural Networks are used to realize a sensor based feature evaluation and selection and spatial statistics for a quantitative measurement of the feature’s suitability. In [7] a cross validation method among features and parameters is proposed, able to individuate a limited set of them non-redundant between each other for efficient quality control of production lines. In [8] the feature’s selection is carried on a step by step basis, in conjunction with an automated signal preprocessing tool, in order to define the features set and to maximize the performance of the predictive maintenance tool. In [9] non-binary decision trees select features in a multi-sensor process monitoring, while a sensor network is proposed in [10], able to improve defect detectability by measuring contemporaneously interconnected phenomena. A very practical tool is described in [11], ranking techniques for fault diagnosis; system observability is of concern and its implications on features and on the choice of the sensor position are discussed.

All these examples are interesting, even though they are mostly based on external sensors to the motion controller and to the automation system, which is an approach more suitable in most cases for research applications than the industrial ones; furthermore, a more general validity of these proposal should be better demonstrated.

Nevertheless, many examples of actions based on diagnosis and diagnostics of machine subsystems, each consisting of a servomotor driving different parts of a machine, can be found, which use current of the motor and the tracking deviation with respect to the nominal motion law, as the main features [12], [13]. They are mainly data driven, having many pros and cons [14].

In this paper, the Authors aim at facing the above problems by a parallel use of measurements, data processing and merging of the experimental information with simple modelling of the main subsystems of a mechatronic device. This approach, which has been extensively described in [15], allows the user to obtain the feature of interest directly by measurement or by means of the value of another quantity, measured in a different point; the theoretical model correlates measurements of different quantities and in different positions; in this way, the physical meaning of the transposition is strongly emphasized.

Preliminary results reached in [15] encouraged to pursuit this action, with reference to the analysis of many more features, in both the time and frequency domain, obtained with reference to both internal quantities to the controller and to data measured by external contact and non-contact transducers, positioned in different points of the mechatronic system.

This work is expected to give more general suggestions and guide lines in choosing the most suitable parameter and measuring strategy, measuring points and, finally, the features set for possible use in CM procedure, which is based also on ANN.

In section 2, the test bench is described based on a mechatronic system in real scale, together with the basics of the set methodology, which is more completely described in [15]. Section 3 shows the main results with reference to operating conditions different as for the setting of the controlling parameters. Results will also show the effect on the features of interest of using different output of the simulation model, which are modified, being different the experimental input of the model itself, as for sensor and/or measuring point. Different features will be taken into account in both the time and frequency domain. Conclusion and future work will end the paper.

2. Materials and methods

A mechatronic system in real scale has been used to implement the methodology (figure 1(a)).

The test bench is based on a kinematic chain, having one ball screw, two nuts and a spline shaft; driven by two synchronous servomotors, it is able to realize an alternate linear motion along a vertical axis, together with a rotation (figure 1(b)). The Motor 1 is motionless in this first analysis, so the motion of the shaft is a pure translation.

The system is monitored using different data sources:
Figure 1. (a) Picture of the test bench. (b) Scheme of the motion system and reference system.

1. Signals from internal sensors of the servomotors (encoder and current sensors)
2. Signals from external transducers to the controller:
   - a capacitive three-axis accelerometer, installed on the ball screw shaft (figure 2(a))
   - a laser Doppler vibrometer, (LDV) whose laser beam is sent, through a 45° prism, to the end surface of the ball screw shaft (figure 2(a) and (b)).

Figure 2. (a) Scheme of the external sensors system. (b) Picture of the LDV measurement set-up.
A trigger signal from the PLC enables to synchronize external data acquisition and the PLC acquisition system. It is to be noticed that only external sensors can be calibrated: the calibration of the accelerometer is carried out according the procedure in [16].

The methodology is based on the following main steps:

- Realization of a kinematic and dynamic model of the system under examination, whose outputs are: angular position at motor 1, angular velocity at motor 1, linear acceleration at ball screw shaft and current at the motor 1.
- Realization of experiments, corresponding to different settings or different operating conditions. In this work, tests for different $j_{\text{load}}$ parameter have been carried out, that means changing the motor response to the inertia of the whole system: an incorrect setting affects the accuracy of the motion.
- Multiple runs of the model, considering as the input one quantity among the measured ones:
  - Angular position from the encoder, $M_{\text{pos}}$
  - Angular velocity from the motor controller, $M_{\text{vel}}$
  - Electric current at the driving servomotor, $M_{\text{cur}}$
  - Linear acceleration from the accelerometer, $M_{\text{acc}}$
  - Linear velocity from the LDV, $M_{\text{vel}}$

Changing the measured quantity which is used as the input of the model, the outputs are measured quantities or calculated, depending on the measured ones. Table 1 shows this correspondence. For instance, $S_{\text{acc}}(M_{\text{vel}})$ means the simulated linear acceleration of the model when the experimental input is $M_{\text{vel}}$.

- Comparison between the outputs of the model and the experimental data
- Calculation and selection of the most suitable features for the $j_{\text{load}}$ identification.

The kinematic and dynamic model has been realized by Simulink. Due to the heterogeneity of the signals from different sources, to the need of guaranteeing the flexibility in the data post-processing and the integration of all data available, a set of algorithms has been developed in Matlab. Figure 3 shows the whole data processing flow.

2.1 Modeling of the system under analysis
The modeling of the system under analysis has been described in detail in [15]. The final equation describing the behavior of the system is:

$$C_m = C'_r + I'\dot{\theta}_1$$

where:
- $C_m$ [N ∙ m]: motor torque
- $C'_r$ [N ∙ m]: friction torque felt at the motor axis
- $I'$ [kg ∙ m$^2$]: moment of inertia at the motor axis
- $\theta_1(t)$ [rad]: angular position of the driving pulley

\[1\]
Table 1. Inputs and outputs of the Simulink model.

| INPUT  | S-pos_a | S-vel_a | S-acc_l | S-cur  |
|--------|---------|---------|---------|--------|
| M-pos_a| M-pos_a = S-pos_a | S-vel(M-pos_a) | S-acc(M-pos_a) | S-cur (M-pos_a) |
| M-vel_a| M-pos_a | M-vel_a = S-vel_a | S-acc(M-vel_a) | S-cur (M-vel_a) |
| M-vel_l| M-pos_a | S-vel_l (M-vel_l) | S-acc(M-vel_l) | S-cur (M-vel_l) |
| M-acc_l| M-pos_a | M-vel_a | M-acc_l = S-acc_l | S-cur (M-acc_l) |
| M-cur  | M-pos_a | M-vel_a | S-acc(M-cur) | M-cur = S-cur |

Figure 3. Flow of the data processing.
3. Results
The experimental results refer to tests, which have been carried on the mechatronic device described in figure 1, able to realize a sinusoidal motion of the end effector, suitable for packaging applications. The motion frequency is 3 Hz and the set-up of the controller is modified during the tests, by changing the $J_{\text{load}}$ parameter. The acquisition data rate is 1 kHz, for all the measured quantities.

The motion repeatability of the end effector, in terms of variability of the motion law among cycles in repeated test at same working conditions, is less than 0.5% of the stroke of the end effector.

Figure 4 and figure 5 show some examples of the methodology. In particular, Figure 4 compares the acceleration data related to the linear motion of the end effector, being directly measured by the linear accelerometer and using current and encoder data, which are both available at the controller; figure 5 presents the frequency spectra of the servomotor current, being directly measured at the controller and using accelerometer and LDV data.

Some interesting preliminary considerations can be made.

In figure 4 it is evident the working behaviour of the kinematic linkage: if the acceleration law is based on current data, amplitude values of it are quite correct, but timing is managed by the inertial effects of the kinematic chain.

![Figure 4](image.png)

**Figure 4.** Comparison of the linear acceleration of the end effector, based on the accelerometer itself or starting from current and encoder signals ($J_{\text{load}}=6.4 \text{ kg/cm}^2$).

![Figure 5](image.png)

**Figure 5.** FFT spectrum of the current signal, as measured in the controller, M-cur, or obtained by means of the accelerometer data, S-cur (M-acc), and of the LDV S-cur (M-vel).
In figure 5, beyond approximately 100 Hz, the floor level of the spectra of simulated current, with respect to the measured one, are higher, both due to local mechanical vibrations, $S$-cur (M-acc), and to noise introduced by signal derivative, LDV $S$-cur (M-vel). For this reason, frequency analyses have been limited to a bandwidth of 0-100 Hz.

Figure 6 and 7 show the FFT spectra of the current signal, as measured in the controller or obtained by means of the accelerometer data and from the LDV, in the frequency ranges 0-50 Hz and 50-100 Hz, respectively. The fundamental and higher harmonics are clearly visible.

**Figure 6.** FFT spectra of the current signal, as measured in the controller or obtained by means of the accelerometer, $S$-cur (M-acc), and of the LDV $S$-cur (M-vel), in the frequency range 0-50 Hz.

**Figure 7.** FFT spectra of the current signal, as measured in the controller or obtained by means of the accelerometer, $S$-cur (M-acc), and of the LDV $S$-cur (M-vel), in the frequency range 50-100 Hz.

On the basis of a preliminary selection, the features, which are considered for this analysis are the following ones. These have been evaluated for each input of Table 1.

Features in the time domain:
- RMS of the time difference between linear acceleration model output and the measured acceleration (RMS_ACC),
- RMS of the current signals (RMS_CUR),
- RMS of the angular velocity signals (RMS_VEL),
- Kurtosis of the current signals (KURT_CUR),
- Mean of the maximum difference between current model output and the measured current (RMS_CUR_diff).
Frequency domain:
- Power content of acceleration in correspondence to the fundamental and higher harmonics, the band 0 – 50 Hz (pkACC[0-50]Hz),
- Power content of acceleration in correspondence to the fundamental and higher harmonics, the band 50 – 100 Hz (pkACC[50-100]Hz),
- Power content of current signal in correspondence to the fundamental and higher harmonics, the band 0 – 50 Hz (pkCUR[0-50]Hz),
- Power content of current signal in correspondence to the fundamental and higher harmonics, the band 50 – 100 Hz (pkCUR[50-100]Hz),
- Power content of current signal in correspondence to the fundamental and higher harmonics, the band 10 – 50 Hz (pkCUR[10-50]Hz),
- Power content of the experimental tracking deviation, in correspondence to the fundamental and higher harmonics, the band 0 – 50 Hz (pkTD[0-50]Hz),
- Power content of the experimental tracking deviation, in correspondence to the fundamental and higher harmonics, the band 50 – 100 Hz (pkTD[50-100]Hz).
- Power content of the linear velocity by the LDV, in correspondence to the fundamental and higher harmonics, the band 0 – 50 Hz (pkVIB[0-50]Hz),
- Power content of the linear velocity by the LDV, in correspondence to the fundamental and higher harmonics, the band 50 – 100 Hz (pkVIB[50-100]Hz).

The main results are as in the following (figures 8-9) and Table 2.

**Figure 8.** Features in the time domain, changing the input measured quantity used as an input of the model.
As for time domain, the features mostly able to acknowledge the differences between settings of the mechatronic systems are the ones related to the quantity current and acceleration: in fact, differences are remarkable when the RMS of both the M-cur and S-acc1 (M-cur) signals is taken into account. Current experimental data M-cur are able to discriminate also when they are used for predicting linear acceleration S-acc1 (M-cur). Differences about kurtosis are negligible with respect to its repeatability.

![Figure 9](image)

**Figure 9.** Features in the frequency domain, changing the input measured quantity used as an input of the model.

Similar results are found in the frequency domain: the quantities able to discriminate the change of settings are mainly motor current and linear acceleration; even though with little differences between
each other; the acceleration indication is more clear in the frequency range 50-100 Hz, the current in the lower one: this effect is probably due to the mechanical inertia of the system and to random vibration along the linkage (not corresponding to harmonics), which make less representative the current signal.

In Table 2, the features related to tracking deviation and linear velocity do not show significant differences, if their repeatability is taken into account.

| Feature          | Mean (j_{load 1}) | Mean (j_{load 2}) | Repeatability |
|------------------|-------------------|-------------------|---------------|
| pkTD[0-50]Hz     | -5.00             | -3.35             | 1.0           |
| pkTD[50-100]Hz   | -41.0             | -41.9             | 0.89          |
| pkVIB[0-50]Hz    | -33.0             | -33.0             | 0.073         |
| pkVIB[50-100]Hz  | -65.7             | -70.3             | 5.9           |

4. Conclusions

In this paper, a methodology has been applied for condition monitoring of a real scale mechatronic system. The approach is based on experimental data and on a kinematic and dynamic model of the device, in order to realize physical correlation between quantities, different between each other and measured in different points of the device. This approach is realized in order to identify the most suitable quantities, measuring positions in the structure and the most selective features in both time and frequency domains. In this preliminary analysis, traditional features have been taken into account, like RMS, kurtosis, and frequency content at specified frequency bands.

Even though preliminary, the results seem interesting: in fact, the most selective quantities have been identified to detect the change of j_{load} setting at the controller, being motor current and linear acceleration of the end effector. The choosing of the quantity seems, at this moment, more important than the selection of the measuring position, if a simple model to correlate quantities is used throughout the kinematic link.

Based on these encouraging results, more quantities will be considered and features, in order to make more reliable, selective and reproducible the approach, in order to set a complete condition monitoring approach.

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