

Towards a Sensor Classification Scheme for Robotic Manipulators

Miguel F. M. Lima, J.A. Tenreiro Machado, and Manuel Crisóstomo

Abstract— This paper analyzes the signals captured during impacts and vibrations of a mechanical manipulator. To test the impacts, a flexible beam is clamped to the end-effector of a manipulator that is programmed in a way such that the rod moves against a rigid surface. Several signals are captured and their Fourier Transforms are calculated and approximated by trendlines based on a power law formula. A sensor classification scheme based on the frequency spectrum behavior is presented.

I. INTRODUCTION

In practice the robotic manipulators present some degree of unwanted vibrations. In fact, the advent of lightweight arm manipulators, mainly in the aerospace industry, where weight is an important issue, leads to the problem of intense vibrations. On the other hand, robots interacting with the environment often generate impacts that propagate through the mechanical structure and produce also vibrations.

In order to analyze these phenomena a signal acquisition system was developed. The manipulator motion produces vibrations, either from the structural modes or from end-effector impacts. The instrumentation system acquires signals from several sensors that capture the joint positions, mass accelerations, forces and moments, and electrical currents in the motors. Afterwards, an analysis package, running off-line, reads the data recorded by the acquisition system and extracts the signal characteristics.

Due to the multiplicity of sensors, the data obtained can be redundant because the same type of information could be seen by two or more sensors. Because of the price of the sensors, this aspect can be considered in order to reduce the cost of the system. On the other hand, the placement of the sensors is an important issue in order to obtain the suitable signals of the vibration phenomenon. The study of these issues can help in the design optimization of the acquisition system. In this line of thought a sensor classification scheme is presented.

Several authors have addressed the subject of the sensor classification scheme. White [1] presents a flexible and comprehensive categorizing scheme that is useful for

describing and comparing sensors. The author organizes the sensors according to several aspects: measurands, technological aspects, detection means, conversion phenomena, sensor materials and fields of application. Michahelles and Schiele [2] systematize the use of sensor technology. They identified several dimension of sensing that represent the sensing goals for physical interaction. A conceptual framework is introduced that allows categorizing existing sensors and evaluates their utility in various applications. This framework not only guides application designers for choosing meaningful sensor subsets, but also can inspire new systems and leads to the evaluation of existing applications.

Today's technology offers a wide variety of sensors. In order to use all the data from the diversity of sensors a framework of integration is needed. Sensor fusion, fuzzy logic, and neural networks are often mentioned when dealing with problem of combing information from several sensors to get a more general picture of a given situation. The study of data fusion has been receiving considerable attention [3][4]. A survey of the state of the art in sensor fusion for robotics can be found in [5].

This paper is a first step towards the development of a sensor classification scheme based on the frequency spectrum of the signals.

Bearing these ideas in mind, this paper is organized as follows. Section 2 describes briefly the robotic system enhanced with the instrumentation setup. Section 3 presents the experimental results. Finally, section 4 draws the main conclusions and points out future work.

II. EXPERIMENTAL PLATFORM

The developed experimental platform has two main parts: the hardware and the software components [6]. The hardware architecture is shown in Fig. 1. Essentially it is made up of a robot manipulator, a personal computer (PC), and an interface electronic system.

The interface box is inserted between the robot arm and the robot controller, in order to acquire the internal robot signals; nevertheless, the interface captures also external signals, such as those arising from accelerometers and force/torque sensors. The modules are made up of electronic cards specifically designed for this work. The function of the modules is to adapt the signals and to isolate galvanically the robot's electronic equipment from the rest of the hardware required by the experiments.

The software package runs in a Pentium 4, 3.0 GHz PC and, from the user's point of view, consists of two

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TABLE 1 PHYSICAL PROPERTIES OF THE FLEXIBLE BEAMS.

Characteristics	Thin rod	Gross rod
Material	Steel	Steel
Density [kg m^{-3}]	4.34×10^3	4.19×10^3
Mass [kg]	0.107	0.195
Length [m]	0.475	0.475
Diameter [m]	5.75×10^{-3}	7.9×10^{-3}

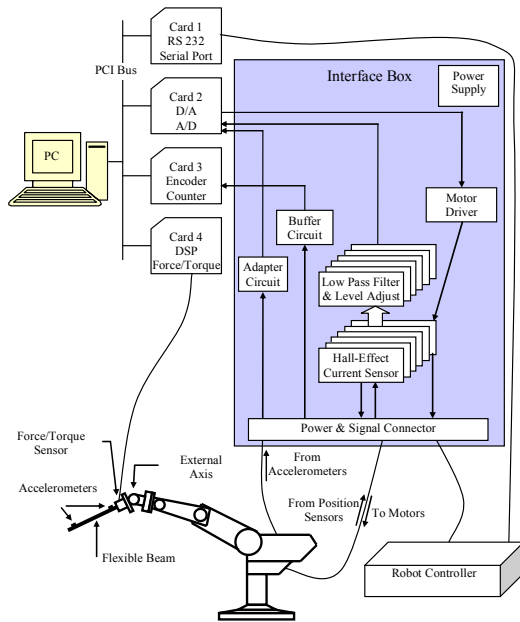


Figure 1 Block diagram of the hardware architecture.

applications: the acquisition application and the analysis package. The acquisition application is a real time program for acquiring and recording the robot signals.

After the real time acquisition, the analysis package processes the data off-line in two phases, namely, pre-processing and processing. The pre-processing phase consists of the signal selection in time, and their synchronization and truncation. The processing stage implements several algorithms for signal processing such as the auto and cross correlation, Fourier transform (FT), and window Fourier transform.

III. EXPERIMENTAL RESULTS

In the experiments a flexible link is used that consists of a long and round flexible steel rod clamped to the end-effector of the manipulator. In order to analyze the impact phenomena in different situations two types of beams are used. Their physical properties are shown in Table 1. The robot motion is programmed in a way such that the rods move against a rigid surface. Figure 2 depicts the robot with



Figure 2 Steel rod impact against a rigid surface.

the flexible link and the impact surface.

During the motion of the manipulator the clamped rod is moved by the robot against a rigid surface. An impact occurs and several signals are recorded with a sampling frequency of $f_s = 500$ Hz. The signals come from several sensors, such as accelerometers, force and torque sensor, position encoders, and current sensors.

In order to have a wide set of signals captured during the impact of the rods against the vertical screen thirteen trajectories were defined. Those trajectories are based on several points selected systematically in the workspace of the robot, located on a virtual Cartesian coordinate system (see Fig. 3). This coordinate system is completely independent from that used on the measurement system. For each trajectory the motion of the robot begins in one of these points, moves against the surface and returns to the initial point. A paraboloid profile was used for the trajectories.

A. Time domain

Figures 4 to 7 depict some of the signals corresponding to the cases: (i) without impact, (ii) the impact of the rod on a gross screen and (iii) the impact of the rod on a thin screen using either the thin or the gross rod.

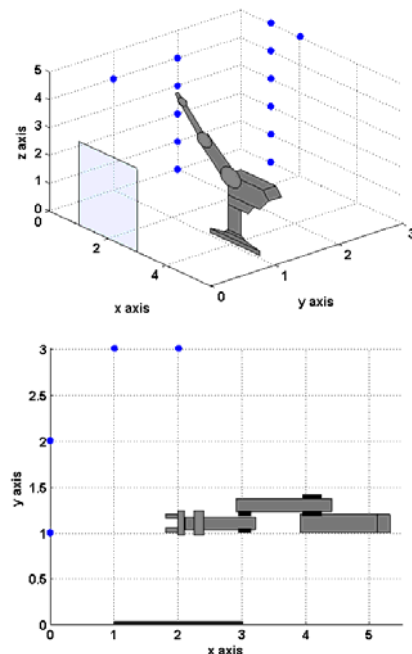
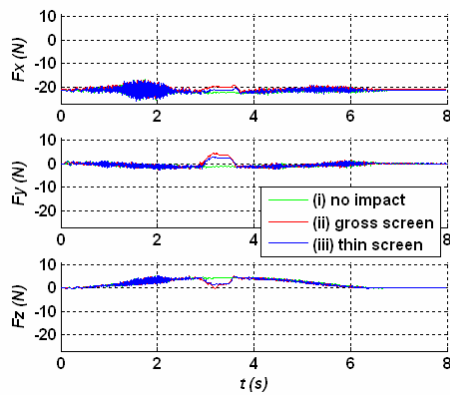
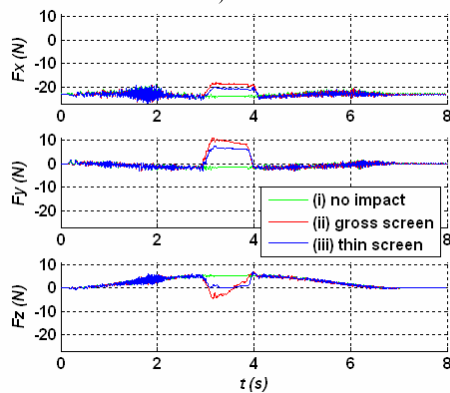


Figure 3 Schematic representation {3D, 2D} of the robot and the impact surface on the virtual cartesian coordinate system.

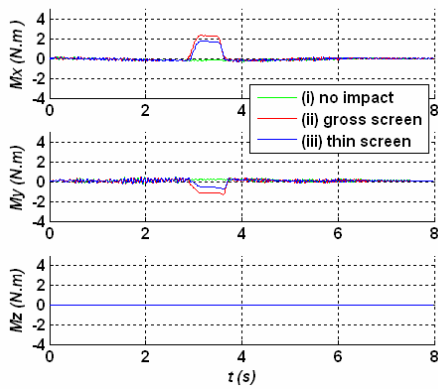


a) thin rod

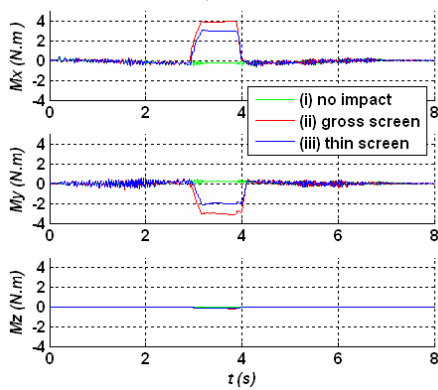


b) gross rod

Figure 4 Forces at the gripper sensor.



a) thin rod

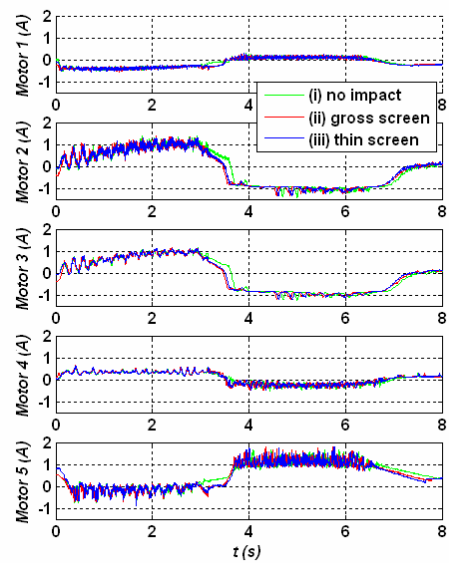


b) gross rod

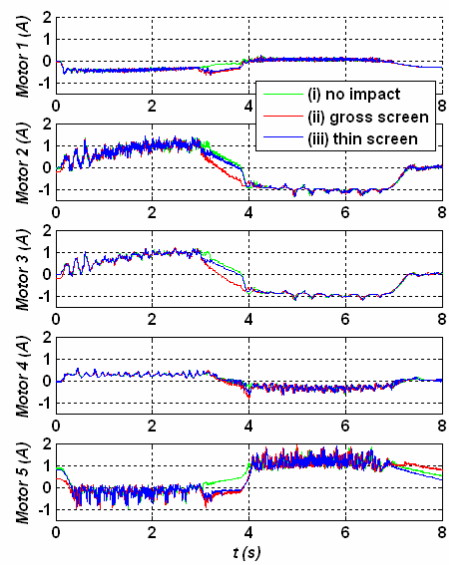
Figure 5 Moments at the gripper sensor.

Due to space limitations only the most relevant signals are depicted. In this example, the signals present clearly a strong variation at the instant of the impact that occurs, approximately, at $t = 3$ s. Consequently, the effect of the impact forces (Fig. 4) and moments (Fig. 5) is reflected in the current required by the robot motors (Fig. 6). Moreover, as would be expected, the amplitudes of forces due to the gross screen (case *ii*) are higher than those corresponding to the thin screen (case *iii*). On the other hand, the forces with the gross rod (Fig. 4 *b*) are higher than those that occur with the thin rod (Fig. 4 *a*). The torques present also an identical behavior in terms of its amplitude variation for the tested conditions (see Fig. 5).

Figure 7 presents the accelerations at the rod free-end



a) thin rod



b) gross rod

Figure 6 Electrical currents of the robot's axes motors.

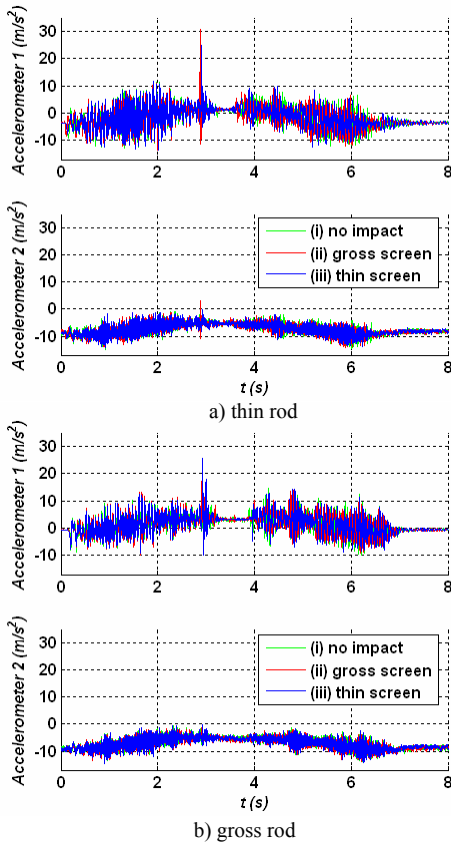


Figure 7 Rod accelerations.

(accelerometer 1), where the impact occurs, and at the rod clamped-end (accelerometer 2). The amplitudes of the accelerometers signals are higher near the rod impact side. Furthermore, the values of the accelerations obtained for the thin rod (Fig 7 a) are higher than those for the gross rod (Fig 7 b), because the thin rod is more flexible.

B. Frequency domain

Figures 8 and 9 show, as examples, the amplitude of the Fast Fourier Transform (FFT), of two signals captured during the same impact trajectory. These figures illustrate the different behaviors of the spectrum, depending on the signal in study. All the signals of the trajectories set referred previously were studied, but due to space limitations only the most relevant are depicted.

In order to examine the behavior of the FT signal, in a systematic way, a trendline was superimposed over the spectrum over, at least, one decade. The trendline is based on the power law approximation [7]

$$|\mathcal{F}\{f(t)\}| \approx c\omega^m \quad (1)$$

where \mathcal{F} is the FT of the signal, $c \in \mathfrak{R}$ is a constant that depends on the amplitude, ω is the frequency, and $m \in \mathfrak{R}$ is the slope.

For each type of signal, the frequency interval was defined approximately in the middle range of the frequency content of the signal.

Figure 8 shows the FFT amplitude of the electrical current of the axis 3 motor that occurs in the case of impact with the thin rod. A trendline was calculated, and superimposed to the signal (case ii), with slope $m = -1.31$. The others current signals were studied, revealing also an identical behavior in terms of its spectrum spread, both under impact and no impact conditions, either for the thin rod or the gross rod. The spectrum was approximated by trendlines in a frequency range larger than one decade.

According to the robot manufacturer specifications [8] the loop control of the robot has a cycle time of $t_c = 10$ ms. This fact is observed approximately at the fundamental ($f_c = 100$ Hz) and multiple harmonics in all spectra of motor currents.

The FFT amplitudes of the axes positions signals were studied [9], revealing also a behavior similar to the electrical current in terms of the spectrum spread for the tested conditions (impact, no impact, thin rod and gross rod).

Figure 9 shows the FFT amplitude of the F_z force (case i) due to the impact with the thin rod. This spectrum is not so well defined in a large frequency range. Nevertheless, the spectrum was approximated by a trendline in a frequency range of approximately one decade in order to get a systematic method of comparison. The trendline has a slope of $m = -0.13$.

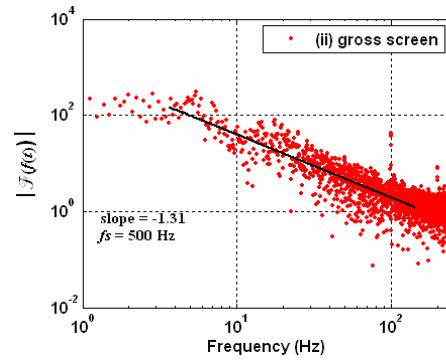
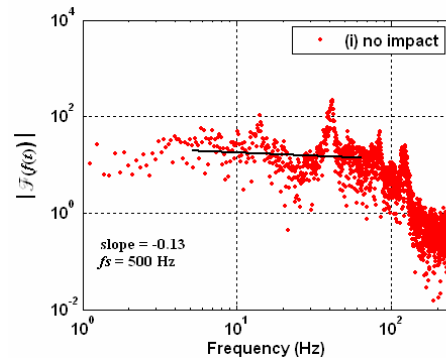


Figure 8 Spectrum of the axis 3 motor current for the thin rod.

Figure 9 F_z force spectrum for the thin rod.

The torques and accelerations signals were studied also for the distinct test conditions, namely: impact, no impact, thin rod and gross rod. Their FFT amplitudes revealed also an identical behavior in terms of its spectrum spread for the tested conditions.

Whereas the trendlines used for the electrical currents and position signals FT seem appropriate, the same technique used for the forces/moments and acceleration signals is questionable. However, in spite of this, trendlines were used for all FT signals in order to obtain comparable units. In fact, the purpose of this research is to establish a relationship between signals of the same system based on the spectrum behavior. There are others approaches as, for example, the correlation between the signals that is currently under development.

C. Spectrum trendlines slopes analysis

Based on the several values of the spectrum trendlines slopes some statistics can be performed. During each trajectory of the robot eighteen signals were captured. For each trajectory there are three cases: (i) without impact, (ii) the impact of the rod on a gross screen, and (iii) the impact of the rod on a thin screen. As referred before, thirteen trajectories were defined. Additionally, the same trajectories were executed with the thin rod and with the gross rod. These samples lead to a population of 1404 slope values.

A box plot provides a visual summary of many important aspects of a data distribution. It indicates the median, upper and lower quartile, upper and lower adjacent values (whiskers), and the outlier individual points. Figure 10 shows a box plot of the spectrum trendlines slopes for the three cases of the thin rod impact, namely: (i) without impact, (ii) the impact of the rod on a gross screen, and (iii) the impact of the rod on a thin screen. Moreover, Fig. 11 depicts the respective interquartile range (IQR) versus the median. The IQR is obtained by subtracting the lower (first) quartile value from the upper (third) quartile value.

The IQR is a robust way of describing the dispersion of

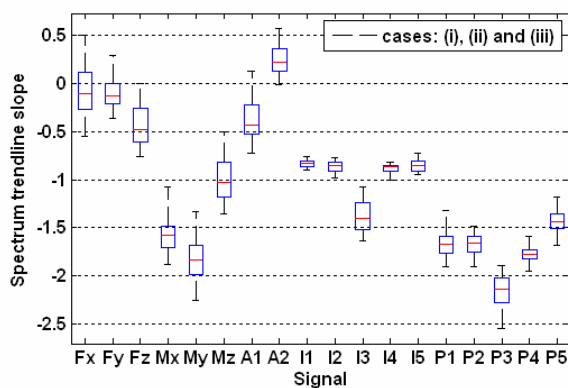


Figure 10 Statistics of spectrum trendlines slopes for all the cases (i, ii, iii) using the thin rod.

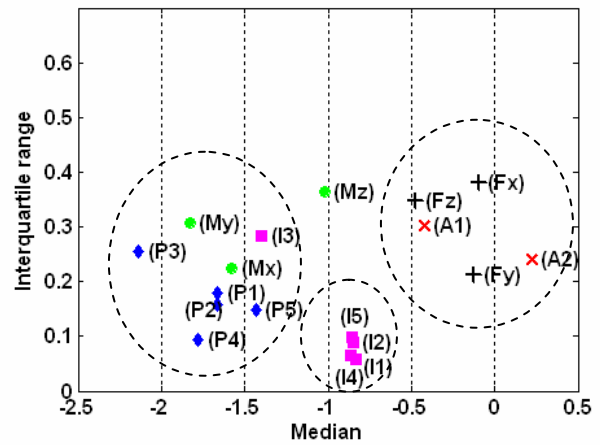


Figure 11 IQR versus median for all the cases (i, ii, iii) using the thin rod.

the data. From Fig. 11 three groups of signals can be defined. The ellipses depicted in the chart represent these groups. The forces $\{F_x, F_y, F_z\}$ and the accelerations $\{A_1, A_2\}$ signals are located close to each other. Positions $\{P_1, P_2, P_3, P_4, P_5\}$, moments $\{M_x, M_y\}$, and I_3 signals are located on the left side of the Fig. 11. Finally, electrical currents $\{I_1, I_2, I_4, I_5\}$ are situated in the middle of the chart and near each other. It rests the M_z signal that apparently is alone.

Figures 12 and 13 show the same statistic analysis described previously, but now for the gross rod. In Fig. 13 again three groups of signals can be defined. One groups the $\{F_x, F_y, F_z, A_1, A_2\}$ signals, and the second is formed of the $\{I_1, I_2, I_4, I_5\}$ signals. The third group consists of the $\{P_1, P_2, P_3, P_4, P_5, M_x, M_y, M_z, I_3\}$ signals. Comparing with the thin rod case, it can be seen that now the M_z signal joined the group of “torques and positions”.

Finally, figures 14 to 15 depict the statistics of the overall spectrum trendlines slopes, considering the data for the thin and gross rods. Three groups are observed again: the group

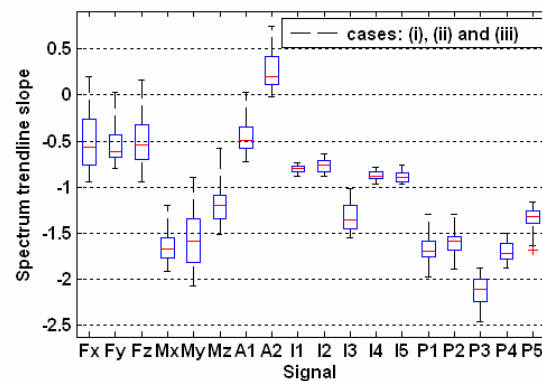


Figure 12 Statistics of spectrum trendlines slopes for all the cases (i, ii, iii) using the gross rod.

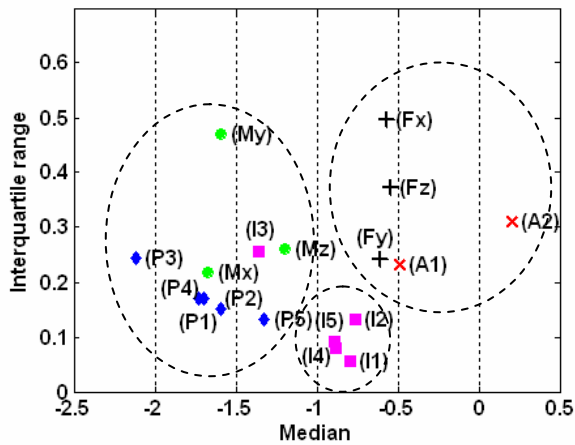


Figure 13 IQR versus median for all the cases (*i, ii, iii*) using the gross rod.

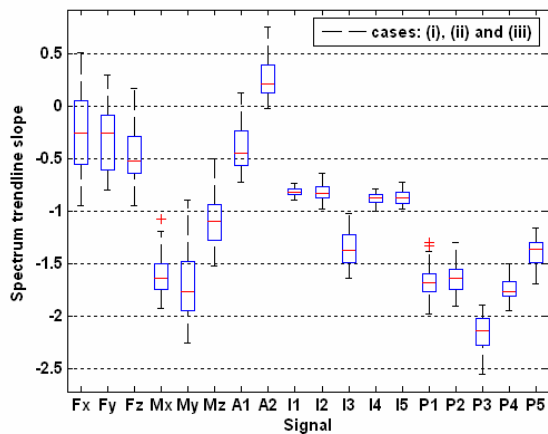


Figure 14 Statistics of spectrum trendline slopes for all the cases (*i, ii, iii*) using the thin and gross rods.

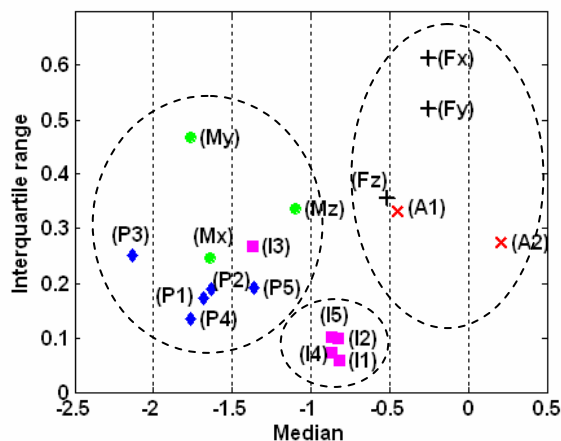


Figure 15 IQR versus median for all the cases (*i, ii, iii*) using the thin and gross rods.

of “positions and torques”, the group of “currents” and the group of “forces and accelerations”. As can be seen the I_3 signal continues to remain in the same group of “positions and torques”. A deeper insight into the nature of this feature must be envisaged to understand the behavior of the I_3 signal.

IV. CONCLUSION

In this paper an experimental study was conducted to investigate several robot signals. A new sensor classification scheme was proposed. The adopted methodology leads to arrange the robotic signals in terms of identical spectrum behavior, obtaining three groups of signals. This observation merits a deeper investigation as it gives rise to new valuable results to instrument control applications.

In future work, we plan to pursue several research directions to help us further understand the behavior of the signals. These include others techniques to measure the similarities of the signals, such as the correlation between the signals.

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