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Compressive Sensing Based Reflectometer for Sparse-Faults Detection in Elevator Belts

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***Abstract*— This paper presents a design approach to early detection of elevator belt failures. The proposed system is based on Time Domain Reflectometer (TDR) techniques with the objective to detect the presence and the location of faults along the cables. The proposed detection circuit, which measures the cable impedance variations, presents the spatial location of the fault as the main technical challenge due to the very high time-resolution required. In order to reduce the electronics costs of each individual node installed in a monitoring distributed system, this paper proposes to improve the location capabilities by implementing a Compressive Sensing (CS) based receiver. Using CS allows us to reduce the number of samples to be sent to a central processor to implement the recovery process of the time-domain sparse signal, and still using a low cost data acquisition system connected to each monitored elevator.**

***Index Terms*— Compressive Sensing, Fault Inspection, Monitoring Systems, Time Domain Reflectometry**

I. Introduction

Nowadays there is a trend to continuously improve safety, efficiency and autonomy of any industrial equipment, focusing these researches on the design of low-cost and low-energy monitoring systems with real-time and non-destructive failure detection capabilities, predictive maintenance tasks, remote sensor processes and adaptive control [1]-[2]. Specifically, the monitoring instrumentation presented in this paper is orientated to the inspection of elevators belts and based on reflectometry techniques, with the final objective of placing a low power and low cost sensor node at each elevator, allowing the deployment of a distributed network.

Reflectometry techniques have been widely used for inspection of cables in the literature, including several alternatives for different domains such as time (TDR) [3]-[6], frequency (FDR), time-frequency (TFDR) [7], noise (NDR) [8], spread spectrum-time (SSTDR) [9] and Impedance Spectroscopy (IS) [10]. For this application, where multiple nodes will be installed, a TDR based method was selected in order to minimize the equipment complexity and costs comparing with the other alternatives. However, the accuracy of the TDR based systems is strongly dependent on the ADC sampling rate. In this paper we propose to increase the location accuracy (in the order of cm) implementing Compressive Sensing (CS) techniques by using a low cost 12-b 1MSps ADC embedded in the microcontroller (MCU).

CS technique, introduced in [11], allows to acquire a dimensionally reduced representation of the reflected signal by exploiting its time-sparsity property (i.e., only a few of samples contain information), at the expense of increasing the computational burden to recover the original signal. In the proposed system, this recovery process is remotely implemented by a central processor, providing a higher accuracy fault location still exploiting the benefits of TDR.

The paper is organized as follow. Section II details the design of the proposed reflectometer. Section III describes the experimental results regarding detection capabilities. In Section IV, a CS based system is detailed and experimentally validated. The conclusions are drawn in Section V.

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II. Reflectometer Based System Design

TDR systems work by transmitting a rectangular voltage pulse through the pair of cables under test. The wave will be reflected when an impedance discontinuity appears, which is defined by using the reflection coefficient ρ [10]:

$$\rho = \left({Z_L - Z_0}\big/{Z_L + Z_0} \right) \tag{1}$$

where Z_0 is the characteristic impedance of the transmission medium and Z_L is the load impedance of the cable discontinuity. Z_0 is given by [6]:

$$Z_0 = \left(\eta_0 / \pi \sqrt{\varepsilon_r} \right) \cosh^{-1}(D/d) \tag{2}$$

where η_0 is the characteristic impedance of free space (377 Ω), ε_r is the relative permittivity of the surrounding dielectric, D is the center distance between the cables and d is their diameter. Additionally, the distance between the fault and the injection point is calculated as $l=t\cdot v/2$, with t the time interval between the incident and the reflected signals and $v=c/\sqrt{\varepsilon r}$ is propagation velocity, with c the speed of light.

The proposed TDR system has been designed to be connected to the wires of a coated steel belt (CSB) structure, which is the most common technology in elevator belts today, having several steel ropes (10-cores in the tested case) encapsulated by materials as polyurethane, polyamide, nylon or a mixture of them. Each tested union of 4 wires is modeled by a transmission line as illustrated in Fig.1a, where 2 pairs are connected at one extreme of the belt, so that both the pulse insertion and the load termination are placed in the designed data acquisition system side (Fig.1b,). The load termination has been implemented using a programmable resistors R_L with the purpose of adapting the impedances as a first step of the inspection process. Moreover, a programmable input resistor R_{in} implements a source impedance to set a minimum impedance at the AD8011 buffer output in order to avoid possible damages if there is a short circuit at the line. Both variable resistors are implemented using digitally controlled potentiometers (MAX5481). The reflected signal is compared with a reference voltage, previously adjusted during the calibration process to the expected value without fault, and amplified by an instrumentation amplifier (INA321). The amplifier output is converted to digital by the 12-b 1MSps ADC embedded in a low-cost ARM based MCU STM32F103RB. Finally, the board was designed by using 2 metal layers and a FR-4 dielectric, with a 13.9x12.2 cm^2 dimension, suitable for its installation in the elevator box.

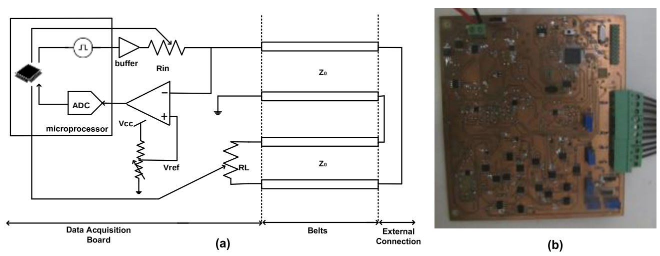

Fig. 1. 4-wire channel description (a) and designed data acquisition board (b)

III. Experimental Validation: Detection Capabilities

In order to characterize the belt as a transmission medium and to evaluate the sensitivity of the TDR, preliminary measurements were performed employing different belt lengths and using R_L to emulate the fault at the end of the line. Its minimal resistance variation (10 Ω), was detected, and the propagation time *t* of the reflected signal was measured for different known locations *l* (i.e., different belt lengths), leading to set the velocity *v* at $1.45 \cdot 10^8$m/s and ε_r at 4.28. Thus, for the dimensions of the 2-wire line (*D*=2mm and *d*=1mm), the characteristic impedance Z_0 results 76.39 Ω.

The system was tested in a real elevator, with a 160-meter length belt, installed in the factory of *MP Lifts*. After calibrating R_{in} and R_L with respect to the line impedance, damage was induced on the belt, cutting progresively the external dielectric and the first conductor core. This induced fault started to be detected for a minimum voltage variation of 32mV at the instrumentation amplifier output (with gain *G*=5). This voltage variation, which is limited by the amplifier input noise, theoretically corresponds with an impedance variation of 0.6 Ω over the characteristic impedance, for a 3.3V input voltage. However, this impedance variation was achieved when the wire section was cut around a 90%, i.e., soft faults have almost no influence over the tested 320-m line. Even with this limitation, it is possible to detect the fault before one cable of the 10-cores belt is totally broken, providing predictive maintenance capabilities by real time inspections.

To reduce costs, the ADC embedded in the MCU has been used; whose sampling speed severely limits the accuracy of the fault location. As an example, for a pulse train generated with a width of 20 ns and a period of 10 µs, Fig.2 shows the experimental measurement of the effect of causing an open circuit at a distance *l*=4m, which leads to a reflected pulse at 55 ns from the original pulse. As the propagation speed is know, it is possible to theoretically locate the fault by $l=t \cdot v/2$, resulting in *l*=3.9875m by using a high accuracy oscilloscope. However, the proposed low-cost TDR system is limited by a sampling time of 1µs, which leads to a very low spatial resolution. In order to improve the location capabilities, and still using low-cost electronics, a CS based extension is proposed as novelty in Section IV.

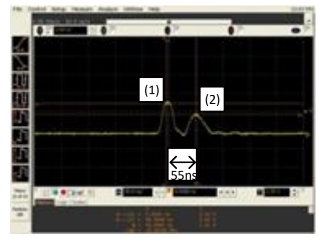

Fig. 2. Generated (1) and reflected (2) pulses with a fault located at 4 m.

IV. Compressive Sensing for Location Purposes

CS is a well-known technique based on reconstructing a sparse *N*-dimensional signal vector *x* from an *M*-dimensional representation $y=\Phi x$ ($K<M<<N$) in an orthonormal basis, where *K* is the number of non-zero components of *x* and Φ is the *MxN* observation matrix [11]. The main advantage of CS is to recover the received signal from a fewer number samples than required by the Shannon-Nyquist sampling theorem by exploiting the sparsity property of the input signal.

There is a wide literature regarding solving the CS recovery algorithms. The proposed system employs a *l1*-minimization algorithm as it is one of the most employed decoding models, which can be easily implemented in an external PC. For this application, the TDR signal can be considered sparse in time domain, with the original and reflected pulses as the only non-zero components. Therefore, the convenience of reducing the width of the generated pulses, in order to increase the sparsity level, leads to set it at 20 ns, which meets the MCU GPIO specifications. In summary, the main steps to implement the proposed CS technique are listed below:

1) The reflected pulse train is sampled by the ADC, taking *N* samples per period.

2) A *M*x*N* observation matrix Φ, conformed by normally distributed random numbers, is multiplied by the original *N*-dimensional vector *x* in order to obtain the compressed *M*-dimensional vector *y*.

3) The vector *y* is sent to the central processor, where the recovery algorithms, encoded in a Matlab script, are implemented in order to find the minimum *l1*-norm solution to the underdetermined linear system $y=\Phi x$ [11].

4) Once the vector *x* is recovered, the fault can be easily located, by using $l=t \cdot v/2$, where *t* is function of the number of samples between both received pulses and the sampling time.

In order to determine the minimum number of samples (*M*) needed (to send to the external PC) to achieve the required spatial resolution (Δ) in the detection of the fault, a set of measurements was performed using the embedded 1MSps ADC of the ARM MCU. Fig.3 shows the probability of a

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complete detection for different values of M and Δ using the same experiment of Fig.2. From this experiment, it is possible to know that, during a signal period T=10 µs, each 1m-section is equivalent to 55/4=13.75 ns, so the time resolution will be T/N and the spatial resolution will be $\Delta=(T[ns]/N)/13.75$ m.

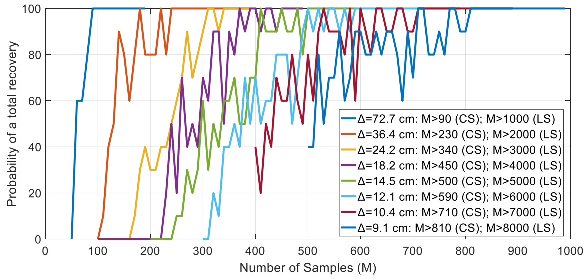

Fig. 3. Number of necessary M samples for different Δ spatial resolutions

TABLE I
EXPERIMENTAL LOCATION FOR DIFFERENT FAULTS

Theoretical Location	Experimental Location for N=1000	Experimental Location for N=8000
4 m	4.750	4.078
8 m	7.651	8.037
12m	12.708	11.932

TABLE II
COMPARISON BETWEEN DIFFERENT RELATED WORKS

Publication	Technology	Location Resolution [cm]
[3]	TDR	40
[4]	TDR	10
[5]	TDR	14.4
[6]	TDR	30
[7]	TFDR	9-26
[8]	NDR	6.4-8.8
[9]	SSTDR	6
[10]	IS	40
This work	CS-TDR	9.1

It is possible to observe how the benefits of the proposed method increase with the required resolution, regarding the number of samples necessary for a conventional Linear Sampling (LS) process. Once the signal is recovered with a proper value of M, the fault is located with a spatial resolution that directly depends on N. Table I shows the locations obtained for different faults, which are into the expected accuracy ranges for N=1000 and N=8000, i.e., 72.7 cm and 9.1 cm respectively. Since the spatial location of the fault is calculated from $l=t{\cdot}v/2$, the main uncertainty source will be given by $\Delta_t+\Delta_v$, where Δ_t=9.1cm is the accuracy obtained by using the proposed CS based method and Δ_v is the accuracy of the speed estimation, which was performed by using a 1 GSps oscilloscope, i.e., with Δ_v=7.2cm in this case. However, Δ_v strictly depends on the sampling rate of the equipment employed during the calibration process and it is independent of the proposed solution.

Additionally, note that the limit was fixed at N=8000 in order to have enough capacity to store the 810x8000 observation matrix by using a 32MB external memory. Moreover, only one possible fault is assumed for each measurement. Thus, for the case of multiple faults the sparsity level would be lower (higher K), so it would be necessary a higher M in order to keep the spatial resolution given by N.

Finally, a comparison regarding spatial resolution with other previously published cable inspection systems is showed in Table II. It is possible to observe how the results are satisfactory, in the same order of the higher resolution systems, and still avoiding the GHz-sampling generation used in other TDR based systems [4]-[5] and the high-cost equipment employed for other technologies [8]-[10].

V. CONCLUSION

In this paper, we have proposed a reliable and accurate measurement method for a cost-effective and high performance TDR based system for testing and monitoring of elevators belts purposes. A low cost electronics data acquisition system, based on the measurement of impedance variations, has been designed and experimentally validated in a real scenario. As main contribution, the fault location functionalities are implemented by using CS techniques, with the objective to increase the measurement accuracy, without increasing the hardware requirements for the multiple installed nodes, and reducing the amount of transferred data to the central processor. The proposed system is able to recover the reflected signal with a spatial resolution of 9.1 cm by using a sampling frequency (1MSps) much lower than those employed in the previous works based on linear sampling, and allowing, as a future research stage, its implementation in a distributed wireless sensor network with multiple installed low cost sensor nodes.

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