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Artículos científicos

Sistema para la medición y evaluación del desplazamiento relativo de entrepiso mediante control con FPGA y programación en VHDL

System for the Measurement and Evaluation of the Relative Displacement of the Mezzanine Through Control with FPGA and Programming in VHDL

Sistema para medição e avaliação do deslocamento relativo da história por meio de controle com FPGA e programação em VHDL

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Resumen

El objetivo de este trabajo fue desarrollar un sistema basado en reglas que determinara y evaluara la variable de desplazamiento relativo del entrepiso. Se utilizan técnicas de descripción de *hardware* con lógica programable mediante la integración de entidades y el diseño jerárquico con programación VHDL. Para su control, el sistema se integra en un arreglo de compuerta programable en campo (FPGA). Mediante un algoritmo, en una primera etapa, un grupo de sensores de ultrasonido recoge una medida que se interpreta para obtener el desplazamiento relativo del piso. En una segunda etapa, un motor de inferencia realiza la evaluación de esta medida obtenida. Los resultados se presentan utilizando un modelo de una estructura en el que se verificó que el sistema era capaz de determinar la estabilidad de la estructura experimental a partir del parámetro de desplazamiento relativo de la entreplanta.

Palabras clave: desplazamiento relativo, lógica programable, monitoreo de salud estructural, sistema basado en reglas.

Abstract

The objective of this work was to develop a rule-based system that determines and evaluates the relative displacement variable of the mezzanine. Hardware description techniques with programmable logic using entity integration and hierarchical design with VHDL programming are used. For its control, the system is integrated into a field programmable gate array (FPGA). Using an algorithm, in a first stage, a set of ultrasound sensors collects a measurement that is interpreted to obtain the relative displacement of the floor. In a second stage, an inference engine performs the evaluation of this obtained measurement. The results are presented using a model of a structure in which it was verified that the system was able to determine the stability of the experimental structure from the relative displacement parameter of the mezzanine.

Keywords: relative displacement, programmable logic, structural health monitoring, rules-based system.

Resumo

O objetivo deste trabalho foi desenvolver um sistema baseado em regras que determinasse e avaliasse a variável de deslocamento relativo da história. Técnicas de descrição de hardware são usadas com lógica programável por meio de integração de entidades e design hierárquico com programação VHDL. Para seu controle, o sistema é integrado a um FPGA (Field Programmable Gate Array). Por meio de um algoritmo, em uma primeira etapa, um grupo de sensores de ultrassom coleta uma medida que é interpretada para obter o deslocamento relativo do piso. Em uma segunda etapa, um motor de inferência realiza a avaliação dessa medida obtida. Os resultados são apresentados a partir de um modelo de estrutura em que se verificou que o sistema foi capaz de determinar a estabilidade da estrutura experimental a partir do parâmetro de deslocamento relativo do mezanino.

Palavras-chave: deslocamento relativo, lógica programável, monitoramento de integridade estrutural, sistema baseado em regras.

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Introduction

Structural Health Monitoring (SHM, all abbreviations) employs sensor technology for safety assessments of engineering structures. In an SHM, the responses of a structure are measured using various technologies, such as accelerometers (Arias and De la Colina, 2018), fiber optic sensors (Bao and Chen, 2012), laser displacement sensors (LDS) (Park, Kim, Choi, and Kim, 2013; Song, Wang, Ma, Cai, and Cao, 2006), global positioning system (GPS) (Breuer, Chmielewski, Górski, and Konopka, 2002; Tamura, Matsui, Pagnini, Ishibashi, and Yoshida, 2002), linear variable displacement transducers (LVDT) (Arias and De la Colina, 2018), wireless sensors (Guo, Xie, Bie, and Sun, 2014; Li, Chen, and Ding, 2019; Zrelli and Ezzedine, 2017), and bridge circuits Wheatstone (Li and Hao, 2016). For this purpose, various data processing and evaluation techniques have been used, such as deep learning (Li et al., 2019; Guo et al., 2014), particle swarm optimization (PSO) (Chatterjee et al., 2017; Moosazadeh et al., 2019) and genetic algorithms (Ghasemi, Nobahari and Shabakhty, 2018). Finally, the data is transferred to a monitoring server for analysis of the recorded historical information and evaluation by specialists in the area. The characteristics of the structure and of the various loads (wind load, seismic load, and service load) determine the target structural elements, response types, and measurement sensors required. Therefore, the selection of a response index that can accurately assess damage to a structure is critical.

For the development of application-specific integrated circuits (ASIC) there are several development alternatives (Maxinez and Alcalá, 2007). Programmable logic is a type of design that resorts to the use of programmable logic devices (PLDs), for example, field programmable gate arrays (FPGAs), which can be characterized externally by various programming techniques using a language. hardware description (HDL).

The objective of this work is to provide a proposal for the development of a system that is capable of determining the stability of a multi-story building based on the evaluation of the measurement of the relative displacement of the story, which is obtained by a network of ultrasonic sensors. and that acquire measurements directly from the vertical structural elements of the building in a non-invasive way.

Methodology

In this section we present the development of our proposal. First we propose the specifications and the scenarios, then we undertake the modeling of the proposal, we continue with the approach of the solution algorithms and their programming and we finish with the implementation of the system.

Specifications and scenarios

The most important parameter for determining the magnitude of possible damage to buildings is the story distortion γ, that is, the relative displacement of the story Δ divided by the story height H.

$$\gamma = \frac{\Delta}{H} \qquad (1)$$

To do this, we base ourselves on what was established by Paulay (2001), who proposes that the measure of permissible mean displacement be between 2.0% and 2.5% of H. From this premise, the system inference engine table will be built and from this the system will react in a predetermined way to activate the intended actuators.

For the practical case, it is proposed to use the model of a structure with height of each mezzanine Hi = 3.5 m. The purpose of the model used is solely the collection of measurements to obtain the variable: relative displacement of the mezzanine. The model structure consists of independent control at each level for the generation of inclinations.

To obtain the value of the lower limit state of the case in question, we use equation (1) and formulate it as follows:

$$\gamma = \frac{\Delta}{H} \leq 0.02Hi \tag{2}$$

We must consider that 2.0% of Hi is 0.07. So, for the given case:

$$\frac{\Delta}{H} \leq 0.07 \tag{3}$$

We clear and obtain the relative displacement of the limit story for this consideration:

$$\Delta \leq 0.245 \text{ m} = 24.5 \text{ cm} \tag{4}$$

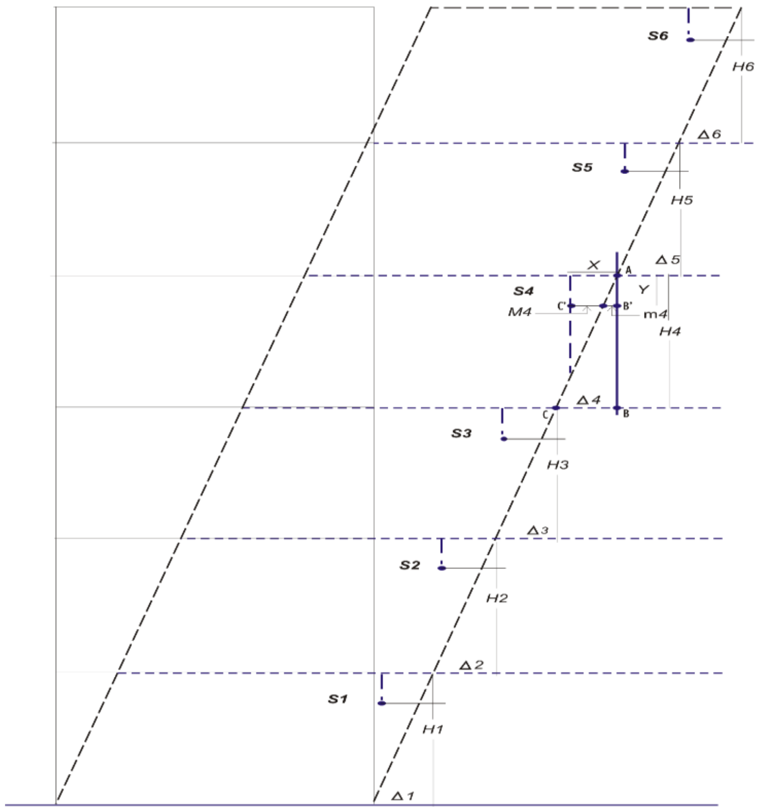
In the same way, to obtain the value of the upper limit state, we must consider that 2.5% of Hi is 0.0875. and we get:

$$\Delta \leq 0.30625 \text{ m} = 30.625 \text{ cm} \tag{5}$$

Modeling

In a first stage, to obtain the measurement of the relative displacement of the mezzanine of a six-story model structure, the parameters to consider are: measurement obtained by the Mi sensor, measurement of the base of the similar triangle that is generated in the triangle on the right mi, relative displacement of the mezzanine Δi and the height of the mezzanine Hi, which is a known data (see figure 1). When the structure suffers an inclination, the sensors for Mi, due to the effect of gravity, will remain in the original vertical axis of the ordinates and the mezzanine wall will follow the inclination of the mezzanine. Thus, when making the projection of the inclination, we must consider that the references of the coordinate axes are translated and that said projection describes two triangles: both triangles contain two similar triangles that would comply with Thales's first theorem. Then, applying the similarity relations for similar triangles, we can obtain the value of the bases. It should be noted that we are interested in the triangle on the right side, since, as we represent it in the diagram, we identify it as the relative displacement of the mezzanine Δi. The measurement Mi obtained by each sensor varies, undergoing a decrease that will be used so that, through the similarity relation applicable to the case, the length of the base of the triangle on the right can be obtained, which, as indicated, corresponds to the displacement relative to the mezzanine Δi. With these data, the distortion of the mezzanine of each level is calculated and it is determined which of the measurements is the largest to enter the limit state evaluation.

Figure 1. Parameters for the measurement of relative displacements between stories



Source: self made

As already explained, we can base ourselves on Thales's first theorem and establish a relationship for similar triangles:

$$AB/(AB') = AC/(AC') = BC/(B'C') \quad (6)$$

The items we have are as follows:

- Measure AB = H
- Measure B´C´= m
- Measure m = X - M
- Measure BC = Δ

Then, from equation (6) we take:

$$AB/(AB') = BC/(B'C') \quad (7)$$

Substituting, we get:

$$H/(AB') = \Delta/m \quad (8)$$

We clear for Δ and we have the expression:

$$\Delta = Hm/(AB') \quad (9)$$

In a second stage, the value of the measurement of the relative displacement of the mezzanine is received, whose magnitude is the largest of the six measurements that were determined. This parameter will be the input variable to a Rule Based System (RBS) for which, firstly, we assign a universe of discourse in the desired interval, in this case from 0 cm to 50 cm, since it represents the initial state and Calibrated from the perpendicular of the building, as well as its base, and the latter, 50 cm, we consider it a sufficiently permissible value, since from (4) and (5) it was obtained that the limit state for the case is between 24.5 cm and 30.625 cm. Consequently, we decided to raise the limits between 21.0 cm and 31.0 cm, which means that a measurement greater than 31.0 cm would represent that the structure would be in danger of collapsing, for which the interval that we propose is more than enough to allow that the inference system can work in a greater interval to the established limits and not act immediately if these measures are exceeded.

Based on the above, we determined to use four membership functions: two trapezoids and two triangular ones, to give meaning to each linguistic variable. Each membership function identifies the range of input values that correspond to a linguistic variable, the membership functions map to the present data to determine the degree of membership. That is, the physical values of the input variable, which is the largest of the measurements obtained by the sensors, are converted into linguistic values.

In table 1 we show how the input variable is partitioned. It is worth pointing out that the intervals were defined subjectively, with the support of an expert in that engineering area, who adjusted said intervals so that the behavior of the input measure observed the correct assignment of membership according to the function in which get the highest value.

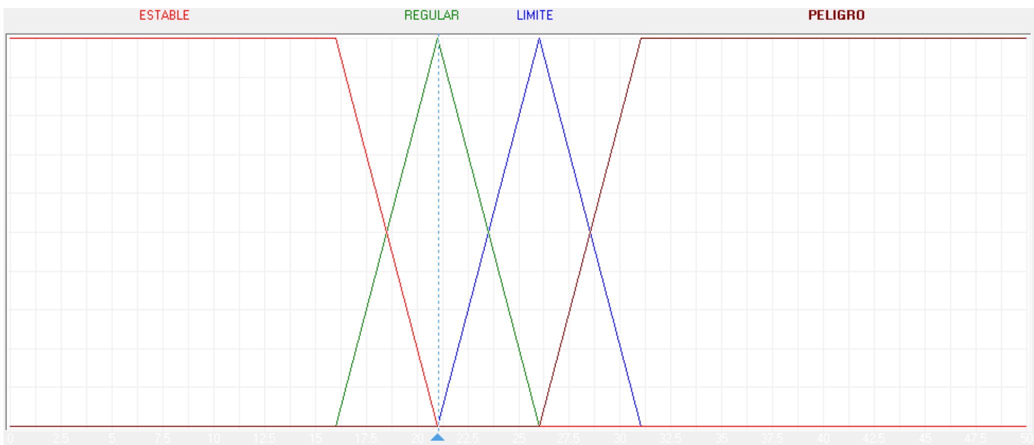
Table 1. DESP_REL input variable intervals

Conjunto	Intervalo (cm)
Estable	0-21
Regular	16-26
Límite	21-31
Peligro	26-50

Source: self made

We apply what we have determined and feed it into the fuzzyTECH software. There we use a membership function for each established interval, these being two triangular and two trapezoidal. In figure 2 we can identify the membership functions for the input variable DESP_REL, which corresponds to the largest of the relative displacement measures, and which are defined with the linguistic terms: Stable, Regular, Limit and Danger. The four membership functions used allow the limit intervals calculated for the practical case not to activate the outputs towards the actuators when reaching a maximum limit. In other words, proposing two triangular membership functions for the terms Regular and Limit allows us to handle values between 16.0 cm and 31.0 cm, to identify the membership value of a physical value of the input variable, to be able to observe its behavior and what In this interval, a degree of belonging is assigned that corresponds to a linguistic variable that allows us to dose the operation of the actuators in the following phase.

Figure 2. DESP_REL variable membership functions in the range [0-50]



Source: self made

Now, we conveniently extract the intervals for each membership function. To describe each of these we use the equation of the point slope line and obtain:

$$\begin{cases} 0 < X \leq 16 & \{Y = 10; \\ 16 < X \leq 21 & \begin{cases} Y = 2X - 32; \\ Y = -2X + 42 \end{cases} \\ 21 < X \leq 26 & \begin{cases} Y = 2X - 42; \\ Y = -2X + 52; \end{cases} \\ 26 < X \leq 31 & \begin{cases} Y = 2X - 52; \\ Y = -2X + 62; \end{cases} \\ 31 < X & \{Y = 10; \end{cases} \tag{10}$$

During the third stage, in the reasoning process, the most suitable output of the system is determined based on two implications: on the one hand, the input data and on the other, the knowledge base. Inference is a computation consisting of two main steps: aggregation and conclusion. It will allow us to obtain logical deductions from propositions. Knowledge is presented by rules of the form IF…THEN; the actual behavior of the system is defined in the individual rules. To prototype an appropriate set of rules, you begin by creating rules that represent unambiguous controller strategies at specific operating points. Once these have been established, the construction of the set of rules can proceed. In table 2 we present the four rules that were established as sufficient to determine the desired behavior of the system. This was done by directly assigning behavior to the actuators that was determined with the help of the expert.

Table 2. production rules

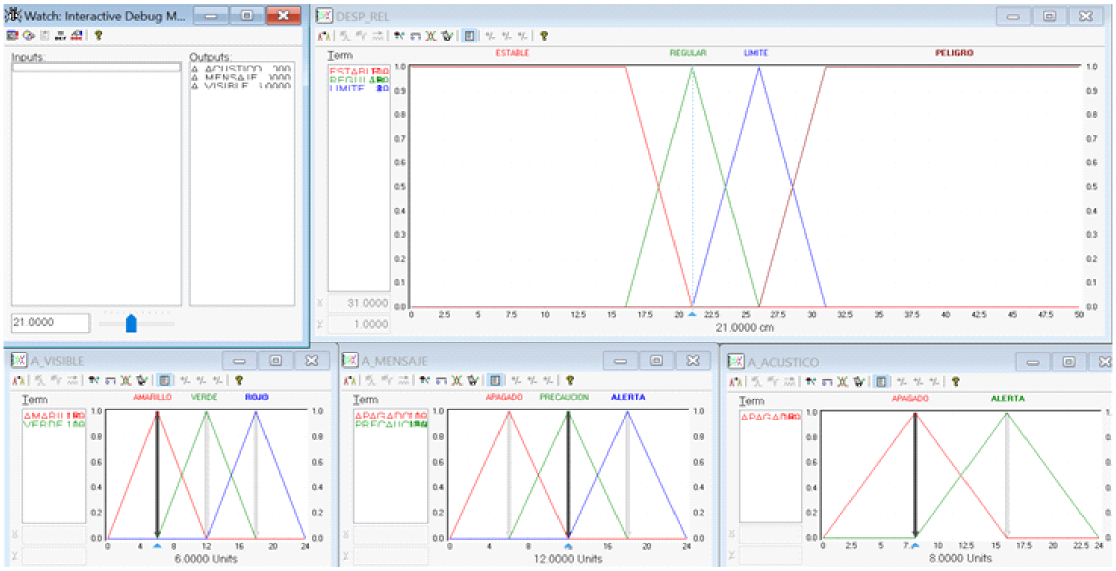
DESP_REL	A_VISUAL	A_ACUSTICO	A_MENSAJE
Estable	AVVerde	Apaga	Apaga
Regular	AVAmarillo	Apaga	AMPrecaución
Límite	AVAmarillo	Apaga	AMAlerta
Peligro	AVRojo	Alerta	AMAlerta

Source: self made

In the fourth and final stage we obtain the exact value of the output. So, we only need to transform the membership values returned by the inference engine into a real value for practical purposes from the consequents of the rules that have been activated. It is necessary to obtain a single control action, combining the result proposed by each of them.

A designed system check is initiated by invoking a debug mode of the fuzzyTECH software. All changes made to the driver are immediately implemented in the current debugged driver task, this allows a test of the changes entered into the driver due to specific input data, that is, to verify the behavior of the system with manually entered data. The range from 0 cm to 50 cm is covered completely. Figure 3 shows a case in which the input is manually fed with a value of 21 cm and the value that would correspond to the outputs.

Figure 3. Debugging of the designed system



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We then propose to proceed in the manner established in Table 3.

Table 3. SBR Algorithm for the Pendulum Ultrasonic Relative Displacement Sensing System (SSDRUP)

```
Inicio
Declaración del tipo de dato inferencia (estable, regular, límite, peligro)
Proceso PERTENENCIA
Convierte distancia (BCD) a dis (integer);
  Evalúa dis
        Asigna PendienteNegativa y PendientePositiva
        Asigna PerteneceNegativa y PertenecePositiva
  Fin Evalúa
Fin PERTENENCIA
Proceso RAZÓN
Declaración de variables del proceso
mientras PendienteNegativa < PendientePositiva
resultado = PendientePositiva y pertenece = PertenecePositivo
Si no resultado = PendienteNegativa y pertenece = PerteneceNegativa
  Fin Mientras
Fin RAZÓN
Proceso SALIDA
  Si flanco de subida
        Evalúa Pertenece
        Asigna valores a las salidas
        Fin Evalúa
Fin SALIDA
```

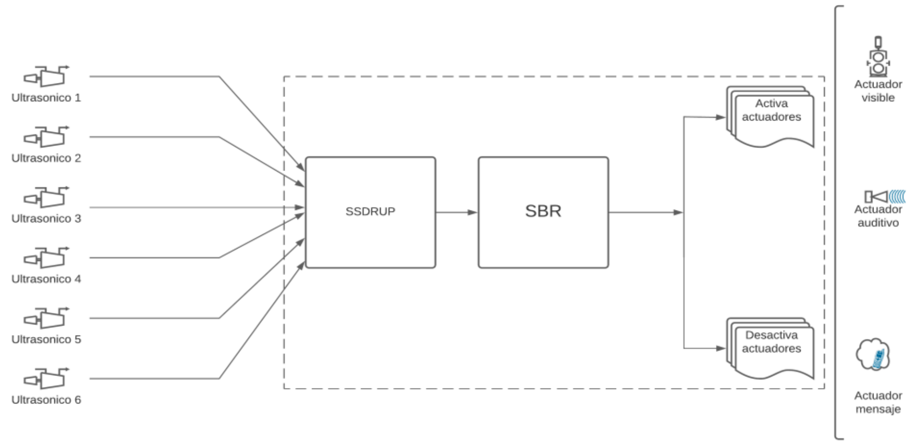
Source: self made

Implementation

Once the system has been debugged, verified and optimized, we can program the necessary modules to implement the SBR for the SSDRUP that we call SBR for SSDRUP.

Then, SBR for SSDRUP embeds the inference engine that is responsible for performing the evaluation of all the measurements collected by the sensors, determines the largest of the measurements, evaluates and establishes the structural health status with the inference rules, and generates the levels. of logic of the outputs of the system to activate or not the operation of the foreseen actuators. Finally, figure 4 shows the complete SBR system for SSDRUP.

Figure 4. General scheme of the system



Source: self made

Materials and methods

A model built of wood with flexible vertices was used to manipulate the inclinations manually and independently for each level. Instrumented with a system of six HC-SR04 ultrasonic sensors, one at each level suspended 45 cm from the mezzanine ceiling and at a distance of 50 cm from the limit wall located at the entrance of the lateral force, the purpose of suspending the sensor in the ceiling of the level to be analyzed is to generate a pendulum effect when the inclination occurs (see figure 5). The system only requires a simple calibration with the vertical reference axis.

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Figure 5. Instrumentation of the model with HC-SR04 sensors

Source: self made

For the modeling and verification phase, the fuzzyTECH 6.03 IA-S7 software was used, which allows the graphic definition of the membership functions of each term used and the debugging of the designed system.

The designed system was implemented following the methodology for the hierarchical design and the integration of programmable logic entities and its programming in the VHDL hardware description language on the Intel Quartus II V.13.0.1 Web Edition platform. SBR for SSDRUP was embedded in an EP2C5T144C8 FPGA (see figure 6) and the conditioning of the output signals to the actuators has visual indicators of the logic levels present.

Figure 6. SBR for SSDRUP embedded in the FPGA EP2C5T144C8

Source: self made

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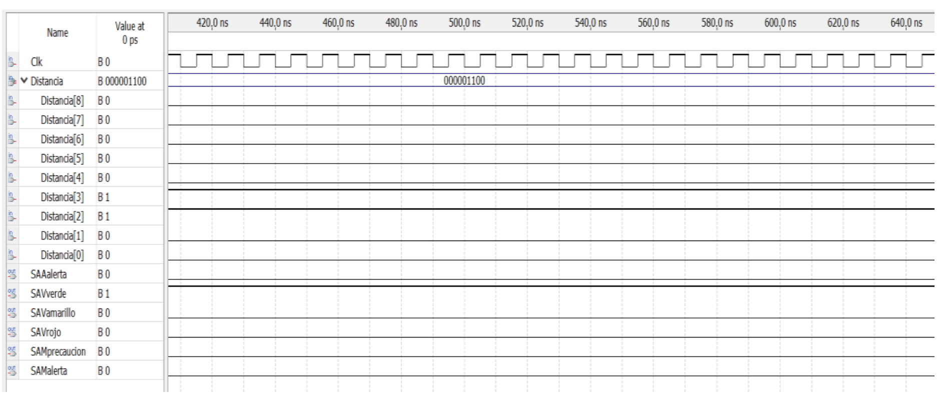
Experiments and results

To validate the implemented system, the described model was implemented and a set of tests was designed. In each experiment, each of the six levels of the model used is manipulated independently, so that different inclinations are generated in each of them. SSDRUP obtains the relative displacement measurements of each mezzanine and determines the largest of these measurements, the which SBR for SSDRUP enters for evaluation.

One Proof

SSDRUP determined 12 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the membership of the input variable to the Stable linguistic value and establishes the logical levels for the outputs of the actuators, as we can verify in figure 7.

Figure 7. Test One Timing Diagram



Source: self made

Two proof

SSDRUP determined 22 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the membership of the input variable to the Regular linguistic value and establishes the logical levels for the outputs of the actuators, as we can verify in figure 8.

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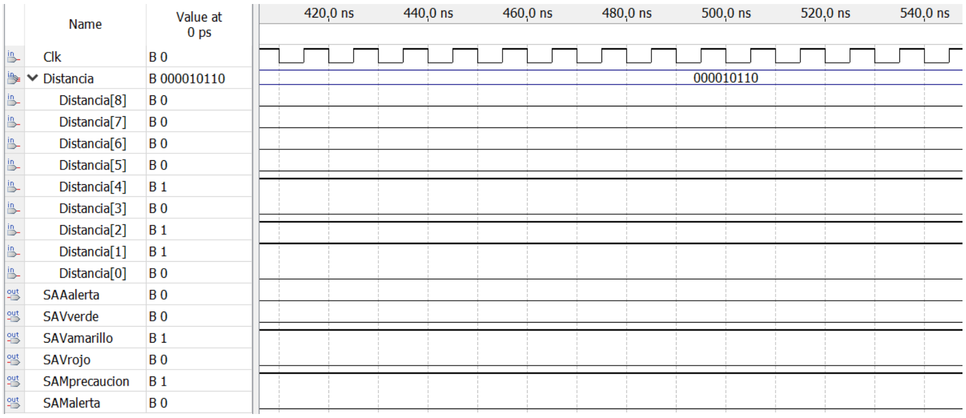
Figure 8. Test Two Timing Diagram



Source: self made

Three Proof

SSDRUP determined 29 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the belonging of the input variable to the linguistic value Danger and establishes the logical levels for the outputs of the actuators, as we can verify in figure 9.

Figure 9. Test Three Timing Diagram

Source: self made

Four Proof

SSDRUP determined 32 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the belonging of the input variable to the linguistic value Danger and establishes the logical levels for the outputs of the actuators, as we can verify in figure 10.

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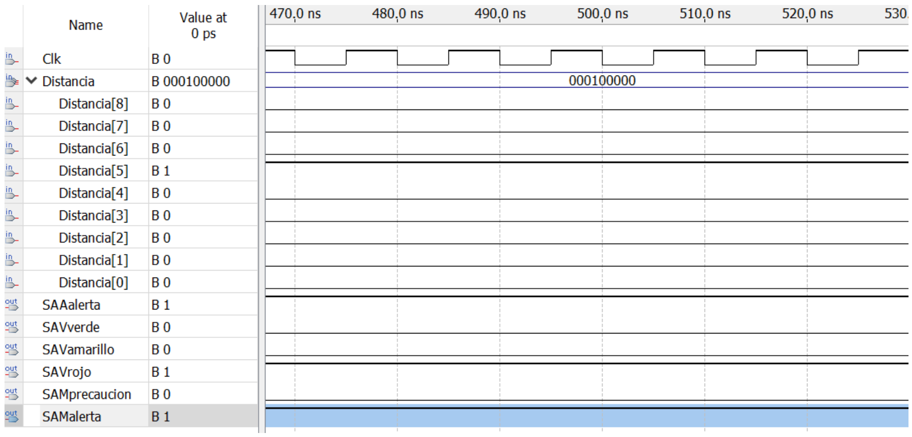
Figure 10. Test Four Timing Diagram

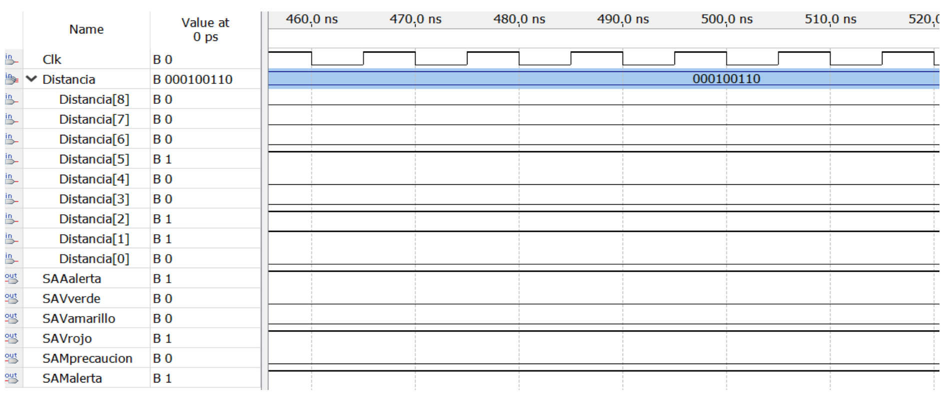


Source: self made

Five Proof

SSDRUP determined 38 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the belonging of the input variable to the linguistic value Danger and establishes the logical levels for the outputs of the actuators, as we can verify in figure 11.

Figure 11. Test Five Timing Diagram



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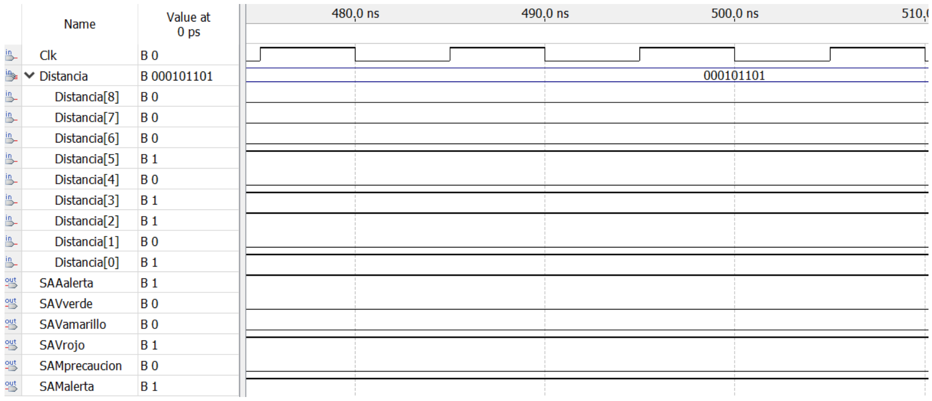
Six Proof

SSDRUP determined 45 cm as the largest of the six measurements, with which SBR for SSDRUP assigns the belonging of the input variable to the linguistic value Danger and establishes the logical levels for the outputs of the actuators, as we can verify in figure 12.

Figure 12. Test Six Timing Diagram



Source: self made

The logical values present in the outputs to the actuators are physically verified in the visual indicators of the conditioned outputs and are listed in table 4.

Table 4. Logic values present in the outputs to the actuators

Prueba	Δ(cm)	Pertenece	SAA alerta	SAV verde	SAV amarillo	SAV rojo	SAM precaución	SAM alerta
1	12	Estable	0	1	0	0	0	0
2	22	Regular	0	0	1	0	1	0
3	29	Peligro	1	0	0	1	0	1
4	32	Peligro	1	0	0	1	0	1
5	38	Peligro	1	0	0	1	0	1
6	45	Peligro	1	0	0	1	0	1

Source: self made

In test one, the system determines that the 12 cm relative displacement measurement belongs to a category determined as stable and only activates the output to the green visual actuator and keeps the other actuators off, thus indicating that the structure is stable and without risk of collapse. In test two, with the 22 cm measurement, the system goes to regular status, turning on the yellow visual actuators and the caution message and keeping the other actuators off, which would visually alert that the structure is in a committed situation. In tests three, four, five and six, it is observed that the measurements of 29 cm, 32 cm, 38 cm and 45 cm are placed in a danger status by the system and in these cases activate the three corresponding actuators to alert such situation. : acoustic actuator on, red visual actuator on, alert message actuator on and the other actuators off, thus visually alerting that the structure is seriously compromised and at risk of collapse.

The lower limit state calculated in (4) is 24.5 cm, so it would be expected that a relative displacement measurement higher than this will activate the alerts and a lower measurement would not activate them. In test two, with a measurement of 22 cm, the precautionary alerts are activated, thus verifying that the system does not wait for the lower limit to react. Likewise, the upper limit state calculated in (5) is 30.625 cm, so it would be expected that from this measurement of relative displacement of the story, the stability of the structure would be seriously compromised. In the results of test three, it is observed that with a measurement of 29 cm, that is, a measurement lower than the upper limit, the system locates a danger status and activates the three corresponding actuators to alert such situation, this validates that the system reacts in a dosed way and does not respond only to maximums and minimums according to the design carried out.

Discussion

Structural health monitoring mainly uses laser displacement sensors and accelerometers, which represents, for its management, a high cost and a high technical complexity, in addition to generally requiring fixed points to carry out said measurement.

Li and Hao (2016) document the development of a relative displacement sensor that uses the principle of a Wheatstone bridge circuit and determines a damage index, with the limitation that the sensor measures local relative movement and is only sensitive to condition changes locally.

On the other hand, Park et al. (2013) use an LDS and a custom wireless sensor node that measures displacement as a damage index with which they implement a SHM to verify and correct the design parameters of an irregular building. This method involves using the LDS optical technique to obtain the target distance by triangulation with its inherent complexity.

Our proposal, based on a SSDRUP, is capable of providing the measurement of the relative displacement of the story by taking a single measurement, and it only requires that the sensors be placed pointing at the vertical structural element on the side of the incoming horizontal force that is applied. identifies and the collection of the measurement will be carried out taking advantage of the pendulum effect that is fostered. We adjust to what was determined by Paulay (2001), which indicates that to evaluate we must consider that the magnitudes of average displacement between floors of the last between floors should not exceed 2% to 2.5% of the height of the mezzanine and with this we establish the limit of the relative displacement measure and our own damage index for the SHM.

In the three proposals, different relative displacement sensors were developed and a particular damage index was proposed for each case, so it is not possible to establish a comparison of efficiency.

Conclusions

The proposal for the location of the sensors and the pendulum effect caused by their suspended placement was successful. The geometric projections generated made it possible through the collection of a single measurement for each suspended sensor and through the relationship of similarities that can be applied, as is the case, to similar triangles, to obtain the measurement of the relative displacement of the mezzanine. The system only requires a simple calibration with the vertical reference axis.

The application of the hierarchical design of the programmable logic with VHDL programming allowed the design of an electronic device capable of obtaining measurements collected by the sensor network to be processed by the SSDRUP algorithm, delivering relative displacement measurements of the story, as well as identifying the one with the highest magnitude with which the SBR algorithm for SSDRUP performs the evaluation to determine the stability of the structure through the index proposed in this work.

The instrumentation with SBR for SSDRUP of the model used in this investigation provided the necessary information for the evaluation. In the results section, it can be verified how the system was able to determine in each case outputs to the actuators and that all the tests implemented corresponded exactly to the established design, the actions defined by an expert from that engineering area. Therefore, we can conclude that the SBR system for SSDRUP is capable of determining the stability of a model structure in a non-invasive way, in real time, without the need to require fixed points for data collection and based on one parameter: displacement. relative to mezzanine, so it can be recommended as a support tool for use in SHM to estimate damage in multi-story buildings.

Future lines of research

Integrating SBR for SSDRUP to an instrumentation system for SHM could incorporate the stability evaluation of a structure through the relative displacement parameter of the story to the set of variables that these systems use for the analysis, not only of SHM, but also for the determination of structural damage.

It would be advisable, then, to continue with the integration into an embedded system of more modules that evaluate other variables, either independently or jointly with the one developed in this work, in order to propose new objectives aimed at determining structural damage.

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