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Structural Identification using a Low-Cost Search Method

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***Abstract*— An easily implementable and trainable damage detection method is proposed and implemented for a simple truss structure. The approach uses the iterative search identification method and is compatible with low-cost and low-power microcontroller hardware. This method employs pattern matching for a data set from a strain sensor array and predicts location (truss member) and severity (member cross sectional area) of damage. As a health monitoring approach, the method is not as robust or rigorous as more complex methods. However, it has modest processing requirements and can handle noisy signals. The work presents an algorithm applied to a truss structure, the simulation performance from a finite-element-analysis, and a discussion of capabilities. The simulation demonstrates differing damage locations, damage severity, and signal noise. Its suitability for low-cost and low-power field processors is discussed.**

***Index Terms*—Sensor networks, strain sensing, structural monitoring, system identification, smart structures**

I. Introduction

Field health monitoring of structures offer benefits for proper maintenance, repair, and usage management. Quantitative assessment using acquired field data can provide improvements compared to qualitative and scheduled inspections. Automated approaches can save time, effort, and cost for dealing with infrastructure components such as bridges. An intelligent or smart system for structures must integrate structural analysis, sensor networks, embedded processors, and processing methods.

Embedded smart sensors and instrumentation have been investigated extensively for bridges [1-8]. Strain and displacement are effective structural measurands. Related sensors using resistance gauges, fiber optics, piezoelectrics, etc. have been developed and tested in field applications. Wireless motes and sensor nodes use advances in microelectronics to provide embedded demodulation, processing, and data acquisition capabilities [9-11].

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Intelligent processing methods must interpret sensor data and must assess performance, damage, traffic, etc. efficiently. Methods differ in requirements for a-priori structural analysis, structural model complexity, sensor network data, processing power, analysis time, and instrumentation. System identification methods can provide estimation of critical structural parameters. In the case of a multi-component structure such as a truss, truss member strains can be related to member stiffness. Methods for structural identification have been implemented for health and traffic monitoring [12-17]. These methods include adaptive filtering techniques, least-squares regression algorithms, and iterative search approaches. The processing may occur remote to the structure or in situ with dedicated processors. However, the instrumentation requirements differ. Instrumentation for remote processing is not as limited in processing speed and power. In situ processing instrumentation reduces the amount of data transmission (information can be transmitted verses raw signals) and addresses multiplexing and demodulation issues. Dedicated, embedded instrumentation is limited by cost, power, size, data storage, etc. Processing algorithms typically need to be chosen and adapted for such instrumentation constraints [18]. Iterative search methods have been used for model parameter identification [19, 20].

In this work, the iterative search method is applied to a simple truss structure and is designed to be compatible with low-cost and low-power microcontroller hardware. The method employs pattern matching for a data set from a strain sensor array and predicts location (truss member) and severity (member cross sectional area) of damage. A truss structure was used due to the number of aging in-service truss structures that still exist and due to ease of finite-element-analysis (FEA). This implementation uses predefined loading patterns and simulated results to prepare a searchable database of structural readings. The work presents an algorithm applied to a truss structure, the simulation performance from a FEA, and a discussion of capabilities. Results show that the iterative search method provides a useful approach when pre-deployment training is viable and when small, embedded systems are preferred. The processing requirements are modest and the performance is noise tolerant. The work complements similar truss studies with adaptive structural identification [16].

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II. Structural Identification and Modeling

A. System Identification

System identification is illustrated in Figure 1. In the context of this work, the input P(x,t) is the loading condition, i.e. a structural load of a given magnitude and position with a potential time dependence. The load-induced metrics are the health parameters of member strain. Identification error is calculated between the output variable, i.e. the measured strain, and the model output of analytical strain. The error function will be described later. The error determines estimated parameters for the model comparison. Estimated parameters for the model are coefficients of the global-stiffness matrix based on the estimation of parameters for structural components.

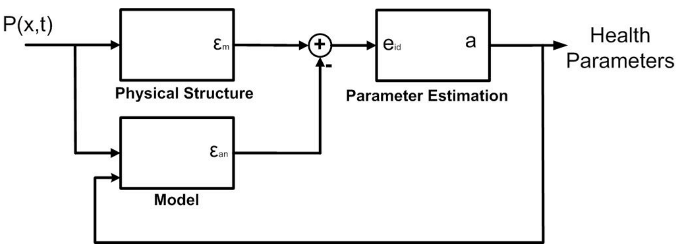

Fig. 1 System identification overview where P(x,t) is the loading function, ε_m is the measured strain, ε_{an} is the calculated strain, e_{id} is the identification error, and a is the cross sectional area of the members

Note that multiple strain signals result from the loading input and are related to the degrees of freedom (DOF) of the structure. System equations are based on the structural model and provide an estimate of the defined damage.

B. Truss Model

The structure for this work is a two-dimensional truss with nine members as shown in Figure 2. This plane truss is modeled with frictionless pin connections. All members are assumed to have an axial strain sensor. A point load is applied anywhere along the top horizontal member and may be static or dynamic (rolling). The defined damage is a reduction in the cross sectional area of any member. The desired information for the truss is no damage on any member or an identification of which member is damaged and the severity of the damage. If more than one member is damaged, the member with the most serve damage should be identified.

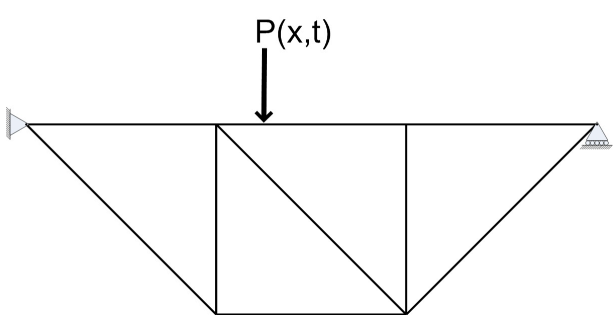

Fig. 2 Example of a plane truss system with loading function P(x,t)

The analysis of the truss has been reported before [16] and follows analysis in the literature [21-23]. Matrix analysis methods use stiffness coefficients to relate forces to displacements and associated member strains.

The truss is composed of nine members. Each of these structural elements is fastened with smooth pins at the ends. Each fastener is assumed to be frictionless and produce no moment at the end of the member. Only tension or compression exists for these conditions. Each joint in the structure then has two degrees of freedom (DOF) as determined by the member connectivity.

C. Plane Truss Elements and Simulation

The plane element stiffness matrix K^e is given in Equation (1) where E, A, and L are the Young's Modulus, the cross sectional area, and the length of the truss element respectively [22]. A rotation matrix operation can be applied to each truss element and summed to produce the global stiffness matrix for a truss structure as shown in Equation (2). The matrix T of Equation (3) is a coordinate transform from a local to a global system where the angle θ is the angle made from the x axis in the global system.

$$K^e = \frac{EA}{L}\begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{1}$$

$$K_g^e = TK^eT^T \tag{2}$$

$$T = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \end{bmatrix} \tag{3}$$

As in prior work, a global stiffness matrix is formed from the element stiffness matrices. A FEA is made using the code number method and truss behavior is calculated for any desired input.

An actual truss could depart from this ideal model. Non-ideal fasteners introduce pin friction at the pins and the structure will take on more complex behavior. Also, the joints may have some play. Decking would introduce additional considerations.

D. System Identification

An iterative search identification method is implemented for this project [17]. The truss was modeled with a stiffness analysis. (Such an analysis has the capability to incorporate dynamic behavior in possible future work.) The global stiffness matrix, K_g, is determined for the structure as described by Equation (2). The associated K_g states of the system are displacements at each pin connection. From these states, output strains for each member are determined.

The state space description of the system can be represented by the mass-spring-damper differential equation shown in Equation (4). The variables x are the displacements of the pin connections. For the static case with no damping term C_1, the equation reduces to Equation (5). The final relationship between the displacements, x, and the DOF forces, F is shown in Equation (6). The relationship between x, F, and K_g, is referred to as the global-stiffness matrix. A transformation of displacements, x, to strains, ε, allows the model to produce outputs that are comparable to sensor outputs on an actual structure. B_0 is the displacement-to-strain transformation.

$$\ddot{x} = K_g x + C_1 \dot{x} - F(x,t) \tag{4}$$

$$K_g x = F(x,t) \tag{5}$$

$$\varepsilon = B_o x = B_o inv(K_g) F \tag{6}$$

The matrix B_0 is constructed to provide strain measurements at defined points on the structure. Nodal displacements relate truss geometry to the member strains as given in Equation (7). The matrix has a non-zero B_k for each member. The basic form for the k-th member, i.e. the member between the i-th and j-th nodes, is shown in the Equation (7). Parameters are member length, L_k, the angles of the member to the x-axis and the y-axis, θ_x, and θ_y respectively [22,23]. If nodes are not connected by a member, the transformation is concatenated with zeros to bring it to full dimension.

$$B_k = \frac{1}{L_k}\left[-\cos(\theta_x) \quad -\cos(\theta_y) \quad \cos(\theta_x) \quad \cos(\theta_y)\right] \tag{7}$$

E. Structural Loading

Each structure that is to be evaluated must have a loading pattern developed. This pattern may be constructed with static or dynamic inputs. For this work static loading is considered for the iterative search method. The necessary steps to determine the loading inputs to the structure are based on a truss with decking plates installed for a roadway. The exact configuration of the loading parameters and solution can vary from structure to structure; however, the general case is described below.

The input forces are calculated by the free body diagram of a piece of bridge decking, as shown in Figure 3, and using equations of mechanical equilibrium. The use of the decking and the equilibrium equations results in Equations (8) and (9). These equations give the information to load the DOFs of the structure properly.

$$R_1 = \frac{P \cdot x}{L} \tag{8}$$

$$R_2 = \frac{P \cdot (L - x)}{L} \tag{9}$$

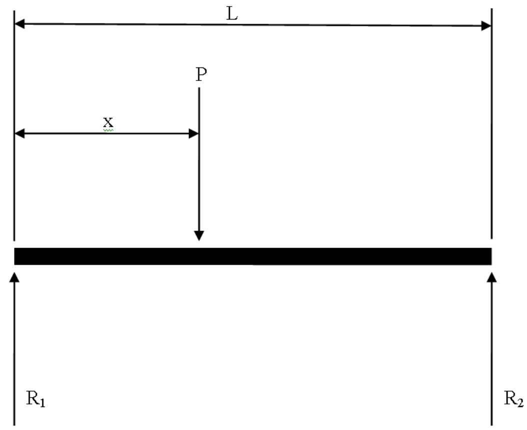

Fig. 3 Free body diagram of loaded decking and reactions

III. ITERATIVE SEARCH IDENTIFICATION

The proposed method using the iterative search identification finds damaged members through a simple pattern matching procedure via the current displacements/strains of the structure. For the results presented here damage is defined as a reduction in member stiffness represented by a reduction in cross sectional area of the member. The iterative procedure uses a parametric search technique to find the set of analytical strain data that best fits the measured data. The method uses pre-defined data sets that describe common errors to diagnose the current state. The pre-defined data construction represents the only training required; meaning that the modeling of the structure is the most challenging component of the implementation. Therefore, in order to accurately classify the type and severity of a particular fault, the method requires a sample of the appropriate data profile to match the measured data.

Additionally, a provision for cases when an unknown fault is detected is incorporated by the use of a threshold. If the threshold is exceeded for all the cases in the training set then the method returns an unknown.

After all of the sets have been evaluated and the errors stored, the next step is to evaluate the relative error level for each damage case and damage level. Next, the algorithm finds the minimum relative error, i.e. determining the damage case which is the closest match to the real data. Finally, the algorithm output is the classification of this best-fit data set which is passed to the user.

The iterative search identification algorithm uses a simple-to-implement, least-error search method. The proposed solution lends itself to small, embedded devices that have some memory capacity but limited processing capabilities. The implementation of the method relies on look-up table. The defining equation is

$$\min_i \{[S_i - \varepsilon_m]^T [S_i - \varepsilon_m]\} \tag{10}$$

where S_i is a vector from simulated data based on the structural model, and ε_m is the measured strain to be classified. By searching through the set of model outputs the status of the truss can be determined. The S_i term can be a function of any of the structural parameters, in the case of this work it is a function of cross-sectional area. The estimated variables for the model are the coefficients of the K_g matrix based on the estimation of cross sectional areas of the members. Using strain readings, the proper model, and the estimation scheme, the cross sectional areas are found to provide strength information about the truss structure. In particular, the axial stiffness values for each member may be extracted as K_{11}^{e}, which is an entry in the stiffness matrix of each member in the system.

The iterative search method is not suitable for all classes of structural identification. The method is suitable for static loading scenarios; however, it is not well suited for dynamic loading scenarios. For other loading scenarios methods such as adaptive estimation and neural networks are well suited due to the ability to react to dynamic conditions. While the iterative search is suited for static loading only, that does not disqualify it from selective use. The method could be used to process peak strain events or to help automate static testing for diagnostics of a structure's health.

IV. Simulation Results

The simulations were performed using the FEA model in Matlab®. To evaluate the ability of the iterative search identification method to operate in various conditions, it was tested using normal, noisy channel, scaling error, and reduced sensor selection conditions. For each case the simulation involved a member having a simulated damage that is introduced by a reduction in cross-sectional area. For each trial the damage severity and location (which member of the nine possible truss components) were changed to provide variation. Damage is then detected by the iterative search method and reported in terms of which member has the damage and its severity. To provide noisy channel readings a random number was added to all channels using a Gaussian distribution. The random number provides an emulation of sensor noise and by adjusting the variance of the noise the severity of noise corruption is increased. The variance was tested for σ = [0.01, 0.1, 0.25, 0.5] cases. To demonstrate the ability of the method to operate during a sensor scaling error a random number was multiplied to a single channel with a variance of σ=3. The scaling error was introduced by using a simple linear multiplier.

Each type of damage was simulated for 100 different cases. Damage was represented as a reduction in cross sectional area for a member in the nine-member truss of Figure 2. The severity of the damage was selected from a random number generator with a normal distribution. All nine members were represented in the single-member-damage cases. The same 100 data sets were used for all of the various noise and scaling cases. Table I shows the distribution of the damage cases in terms of the number of members for different damage severity ranges. Damage severity is classified as low if the cross sectional area is above 75% of the original specification. The damage is considered moderate from 45-75% and severe below 45%.

TABLE I: BEAM DAMAGE DISTRIBUTION

	Cases at Damage Level		
Test Type	Low	Moderate	Severe
Normal	23	42	35
Noisy σ =0.01	22	50	28
Noisy σ =0.1	29	43	28
Noisy σ =0.25	22	50	28
Noisy σ =0.5	27	40	33
Scaling	31	40	29

The iterative search procedure was used in each of the 100 trials to report the final result. The identification results consisted of the identification of the truss member which was damaged and the reduction in cross sectional area for that member. Table II provides an overview of the simulation results. The table shows the number of correct identifications of the damage location and for the correct cases what the percent difference was between the actual severity and the estimated severity. Only the cases where the damaged member location was correctly identified were used in the third column. In all cases, the identification of damage location was only counted as correct if the correct damaged member was identified.

TABLE II: SIMULATION RESULTS

Test Type	% Correct	Mean Severity % Difference
Normal	100	5.5%
Noisy σ =0.01	97	8.8%
Noisy σ =0.1	90	4.3%
Noisy σ =0.25	80	8.4%
Noisy σ =0.5	53	18.8%
Scaling	72	3.8%

Simulation results show that the iterative search algorithm performs well under slightly noisy conditions as well as adequately under scaling errors. This provides a particular level of confidence that the method could be used as a screening for structural identification. The method is not as robust as some others, but the cost of implementation is low and therefore the deployed processing power is low. This characteristic is a key advantage when the use of microcontrollers on remote structures is desired.

V. Conclusion

A damage detection method is proposed and implemented for a simple truss structure. The algorithm is based on the iterative search identification method and is designed for use with low-cost and low-power microcontroller hardware. Axial strain patterns are used to predict damage location (truss member) and severity (member cross sectional area). The processing requirements are modest and the performance is noise tolerant. It is suitable for embeddable hardware. It does require reference strain data from an accurate model for comparison. The truss application provided a useful structure for testing. Its model is easily characterized and allows different approaches to be compared. The truss structure also offers opportunities for convenient laboratory implementation. Other structures may have more complex models and damage modes. However, practical structures typically are well analyzed and subjected to failure testing. Embedded applications may be valuable as health screenings to complement qualitative evaluations even if complete characterization is difficult.

The simulation results for the iterative search identification algorithm demonstrated successful damage detection. In noise-less conditions, the algorithm detected the location of damage in all cases and closely estimated the damage severity. For noisy conditions, the algorithm detected damage location for most cases with some loss of capability to estimate severity.

The iterative search identification algorithm compares well with a least-squares regression approach. While the least-squares regression approach can detect smaller changes and has similar processing requirements, the iterative search identification approach detects location better and handles noise better [17]. Other structural identification options include neural network and adaptive filtering approaches [16]. While these options offer higher performance, they require much higher processing power and have high training requirements. The latter methods are not guaranteed to converge under all conditions.

The iterative search identification approach is well suited for non-critical, embedded applications. An algorithm loaded on an in-situ processor should give reasonable indication of the onset and location of damage or structural weakness. More extensive assessment and inspection can be deployed to the identified structural component. The long-term management requirements for many infrastructure components such as short-span bridges and multi-span bridge decks are modest and could be efficiently handled by a low-cost screening health monitor.

Availability of a structural model and reference data is required for this method. This requirement is a constraint that may be overcome using model development, simulation, and calibration based on existing load tests. In some cases the availability of this reference data may be challenging. In such cases the appropriate model may be supported with rough guidelines for the damage thresholds. When load testing data and appropriate models are both available this method can be suitably deployed with greater confidence.

The future work should include more comprehensive comparison of numerical estimation methods, integration with sensor nodes/motes, and testing with more complex loading patterns. One assumption of this work was that strains for all members of the truss are known. The performance of the system identification for a reduced number of known strains is needed and a determination of the minimum number of instrumented members for satisfactory analysis is needed. In particular, dynamic loading of structures and dynamic modeling may provide more flexibility and performance as well as traffic applications. The approach should be developed for non-truss structures made of reinforced concrete and composites.

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