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ABSTRACT

Operational modal analysis and vibration based damage detection of engineering structures have become important issues for Structural Health Monitoring (SHM) and maintenance operations, e.g. on transport infrastructure. Methods from control engineering have been adopted and converted for the application on civil structures. Approaches like subspace-based system identification combine excellent theoretical properties under the unknown excitation properties of a structure with practical usefulness.

In this paper, the implementation of covariance-driven stochastic subspace identification (SSI) on the smart wireless sensor platform PEGASE is described. Special care is taken about the fast implementation of this technique since the computations are embedded on the platform and perform in real-time. The most efficient and current version of subspace algorithms has been implemented. Efficiency and memory consumption are primary criteria in this implementation.

First validated results will be given for each step of the algorithms: cross-correlation on natural inputs signal from sensors; Hankel matrix output; SSI implementation using the LAPACK library to get a SVD, pseudo-inverse, eigenvalues etc. Results validation has been correlated between PEGASE implementation and the previous processing in static situation: the same data was collected by wired sensors and data-loggers, then, later, processed on a PC using traditional Matlab software.

In parallel, from an engineering point of view, a description of the PEGASE wireless platform will be given: generic usage, wide capacities, embedded Digital Signal Processing (DSP) processor and Library over a small embedded Linux Operating System, a very accurate synchronization principle based on a GPS/PPS principle, etc. Perspectives about a complete technical in-situ installation will also be given.

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INTRODUCTION

Considering the need of safe infrastructures (for industry, transport or energy) and the practical difficulties to access a structure, to collect data and then perform off-line and remote computation, the topic of self-monitored structures under unknown excitation by means of smart wireless sensors systems performing real-time algorithms is investigated through the convergence of two maturing fields: Smart Wireless Sensor Networks (WSN) whose capacities increase [10]: computation, energy consumption, wireless communication, etc, and control methods for modal analysis adapted to civil engineering applications, particularly with the covariance-driven stochastic subspace identification (SSI). Practical implementation of such algorithms is investigated in this paper, including shifting from a PC based Matlab environment to a WSN small capacity C based environment such as the PEGASE platform.

SSI METHOD DESCRIPTION

Stochastic Subspace Identification (SSI) methods are state of the art methods for modal parameter estimation [1-3]. In this section, an overview of the algorithm and the fast computation of modal parameters for a stabilization diagram is given.

Models and Parameters

The behavior of a structure is assumed to be described by a linear time-invariant (LTI) dynamical system

$$\mathbf{M}\ddot{z}(t) + \mathbf{C}\dot{z}(t) + \mathbf{K}z(t) = v(t) \quad (1)$$

where t denotes continuous time, \mathbf{M} , \mathbf{C} and \mathbf{K} are the mass, damping and stiffness matrices, high-dimensional vector z collects the displacements of the degrees of freedom of the structure and v is the non-measured external force that is modeled as white noise. Let accelerations, velocities or displacements of system (1) be observed at r coordinates. With $x = [z^T \quad \dot{z}^T]^T$ and after discretizing at time steps $t = k\tau$, where τ is the sampling time step, this yields the *discrete-time state space model*

$$\begin{aligned} x_{k+1} &= Ax_k + v_k \\ y_k &= Cx_k + w_k \end{aligned} \quad (2)$$

with the state transition matrix $A \in \mathbb{R}^{n \times n}$, output mapping matrix $C \in \mathbb{R}^{r \times n}$, the states $x_k \in \mathbb{R}^n$, the measurements $y_k \in \mathbb{R}^r$, the unknown process and measurement noise vectors v_k and w_k , respectively, and where n is the model order. The eigenvalues and mode shapes (λ_i, ϕ_i) of system (2) yield

$$\det(A - \lambda_i I) = 0, \quad (A - \lambda_i I)\phi_i = 0, \quad \phi_i = C\phi_i \quad (3)$$

and the natural frequencies f_i and damping ratios ξ_i of the system

$$f_i = \frac{\sqrt{a_i^2 + b_i^2}}{2\pi\tau}, \quad \xi_i = \frac{-100b_i}{\sqrt{a_i^2 + b_i^2}} \quad \text{where} \quad a_i = \left| \arctan \frac{\text{Im}(\lambda_i)}{\text{Re}(\lambda_i)} \right|, \quad b_i = \ln |\lambda_i|. \quad (4)$$

Covariance-Driven SSI

To obtain the modal parameters from measurements $(y_k)_{k=1,\dots,N}$, the covariance-driven stochastic subspace identification algorithm is used [2]. From measurements a block Hankel matrix \mathbf{H} is filled with the correlation lags R_i of the output data

$$\mathbf{H} = \begin{pmatrix} R_1 & R_2 & \cdots & R_q \\ R_2 & R_3 & \cdots & R_{q+1} \\ \vdots & \vdots & \ddots & \\ R_{p+1} & R_{p+2} & & R_{p+q} \end{pmatrix}, \quad R_i = \frac{1}{N} \sum_{k=1}^N y_k y_{k-i}^T \quad (5)$$

where parameters p and q are chosen, such that $\min(pr, qr) \geq n$, with usually $p+1=q$.

The matrix \mathbf{H} possesses the factorization property $\mathbf{H} = \mathbf{O}\mathbf{C}$ into observability and controllability matrix, where \mathbf{O} is obtained from \mathbf{H} by a singular value decomposition (SVD) and truncation at the desired model order n

$$\mathbf{H} = (U_1 \quad U_0) \begin{pmatrix} \Delta_1 & \\ & \Delta_0 \end{pmatrix} V^T, \quad \mathbf{O} = U_1 \Delta_1^{1/2} \stackrel{\text{def}}{=} \begin{pmatrix} C \\ CA \\ \vdots \\ CA^p \end{pmatrix} \quad (6)$$

From the observability matrix \mathbf{O} the matrices C in the first block row and A from a least squares solution of

$$\bar{\mathbf{O}} A = \underline{\mathbf{O}}, \quad (7)$$

are obtained, where $\bar{\mathbf{O}}$ and $\underline{\mathbf{O}}$ are the matrix \mathbf{O} with the last resp. first block row removed. This solution can be obtained as

$$A = \bar{\mathbf{O}}^\dagger \underline{\mathbf{O}} \quad (8)$$

where † denotes the Moore-Penrose pseudoinverse, or with the thin QR decomposition

$$\bar{\mathbf{O}} = QR, \quad S = Q^T \underline{\mathbf{O}}, \quad A = R^{-1}S. \quad (9)$$

The modal parameters are then obtained from (3)-(4).

Fast Multi-Order SSI

In practice, the model order n of the system for the truncation in (6) is never known and a sufficiently high model order is considered. Then, spurious modes are contained in the identified models due to colored noise and unknown non-stationary excitation. Since spurious modes tend to vary at different model orders, they can be distinguished using the well-known stabilization diagrams, where the system is identified at successive model orders and the resulting frequencies are plotted against the model order [2,4]. The matrices \mathbf{O} , A , C , R and S get the sub index n to denote different model orders $n = 1, \dots, t$, where t is the maximal desired model order.

Solving (7) at multiple model orders is a big computational burden, especially when using a large number of sensors and high model orders. In [4] a fast algorithm was proposed, which exploits the structure of (7) at multiple model orders, since \mathbf{O}_n

consists of the first n columns of \mathbf{O}_t . Instead of using the pseudoinverse (8) for the solution of the least squares problem, the algorithm relies on the QR decomposition (9). It was shown that the matrices R_t and S_t for its solution in (9) only need to be computed at the maximal desired order t . Then, instead of computing R_n and S_n for obtaining the state transition matrices A_n at all the lower model orders $n = 1, \dots, t$, it was shown in [4] that they are simply submatrices of R_t and S_t yielding

$$R_t = \begin{pmatrix} R_n & * \\ 0 & * \end{pmatrix}, S_t = \begin{pmatrix} S_n & * \\ * & * \end{pmatrix}. \quad (10)$$

Thus, once R_t and S_t are computed at the maximal model order, A_n can be computed very efficiently at lower model orders n from

$$A_n = R_n^{-1} S_n. \quad (11)$$

PEGASE PLATFORM DESCRIPTION

Wireless Platform

Implementation of previous algorithms is made on PEGASE target. PEGASE is a generic wireless sensor platform (Fig. 1) dedicated to wireless and smart instrumentation [8]. Specified and designed by IFSTTAR, PEGASE generic platform is sold through a third-party company partner (A3IP) in hundreds of units since 2008 and has been subject of various applications (see below). Its major characteristics are:

- A **generic behavior** : by means of a Linux embedded Operating System and a free Single Development Kit (SDK) in C-language that allows a wide panel of user to develop its own application without constraint
- A set of **plug-and-play daughter / mother board** to connect a variety of sensors (accelerometers, strain gauges, temperature...). For example: an 8 analog inputs signal board; +/-5 V; 16 bits digitalization; up to 250 kHz of sampling frequency
- **IP/ WiFi** interface for wireless, high-rate and standard IP communications and then contribute to the *Internet of things* based on sensors
- A **Digital Signal Processor (DSP)** as core processor to perform optimized mathematical algorithms
- An **integrated GPS receiver** to make applications able of geo-localization and accurate synchronization

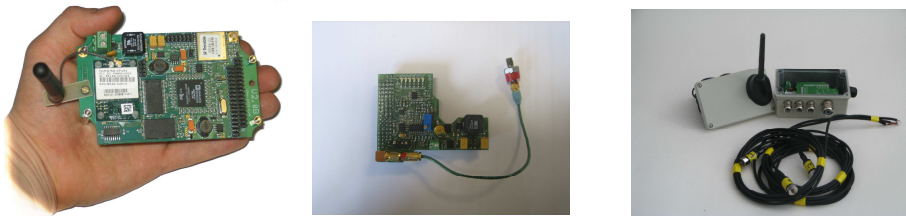


Figure 1. a) PEGASE generic board b) daughter board c) specific use-case.

PEGASE applications

In 5 years, many applications of PEGASE on real Civil Engineering structures have been implemented to answer a variety of SHM use-cases (Figure 2):

- **Bridge cables monitoring** for wire-break detection and localization by an acoustic wave detection and analysis
- **Wireless 8 strain gauges sensor:** typical and very disseminated application for deck deformation, structural constraints evaluation,
- **Smart water probe:** based on a complex daughter board, that application measures 12 physical and chemical properties of potable water (PH, pressure, turbidity, etc)
- **Road gantry vibration monitoring:** typical use-case where embedded high rate sampling of vibration (accelerometer) coupled to the computational capacity of PEGASE allows default prediction
- **Bridge deck cracking:** using from 1 up to 8 displacement sensors, PEGASE monitors cracks and sends alarms on threshold exceeding,

For each application, an energy daughter board can be regarded. This specific board allows PEGASE application to harvest energy from a small solar cell while paying attention to the battery loading law. In addition to the platform itself, academic and professional tutorials have been set up.



Figure 2. a) cable-monitoring b) water-network monitoring c) deck monitoring.

Focus on the very accurate synchronization principle and result

Most of mentioned applications produce data issued from sensors and input scientific algorithms (e.g. SHM algorithms). In most of the known wireless solutions, an important function is missing [9]: an accurate time-base in the WSN. In many applications, the synchronization of the sensor network is mandatory; e.g. vibration, wave-propagation, mode-shape reconstruction, etc. On the PEGASE platform a complex algorithm has been designed by IFSTTAR (implemented in a real-time driver on Linux OS, Fig. 3). Based on the propensity of each GPS receiver to output a PPS binary signal with an accuracy of about ± 20 ns, the driver evaluates natural quartz drift, correct it and enslave the system timebase to an accuracy of 4 μ s Universal Time. Moreover, by knowing the quasi-static quartz drift, PEGASE synchronization driver allows to switch off the GPS receiver most of the time; in this way the system offers an accurate timebase while keeping a reduced power consumption.

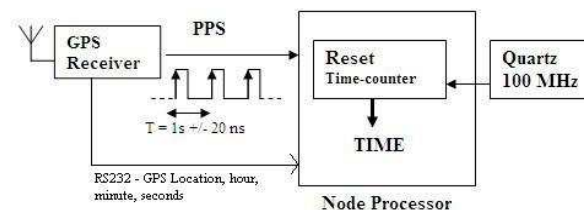


Figure 3. GPS/PPS synchronization principle embedded on PEGASE.

SSI METHOD ON PEGASE: IMPLEMENTATION AND FIRST RESULTS

General description of the implementation task

First implementation step consisted in the transcription of Matlab theoretical source codes to the Scilab software. Algorithms running under Scilab is a gage of portability on small target using C language (as PEGASE is) due to its natural architecture while Matlab is fully made for the PC world.

Then the portability on PEGASE was done with a massive usage of its intrinsic Signal Processing capacities (processor with DSP architecture). Following functions have employed on PEGASE wireless target: crossed-correlation, FFT, data scaling factor, Inverse FFT, root mean square, matrix multiplication, etc. A specific macro (CycleCount()) allows to count the number of processor cycles and to validate time-spent per each part of the algorithm.

Nevertheless, various algebraic functions are missing in PEGASE DSP library. Then LAPACK library and Lapacke interface have been cross-compiled to the embedded uClinux OS of PEGASE. Then LAPACK library answer the lack of algebraic capacities and offer a simple C-language interface for direct calls to:

- LAPACKE_dgesvd: Singular Value Decomposition
- LAPACKE_dgeev: spec / eig
- LAPACKE_dgelss: pinv
- LAPACKE_dgeqrf: QR decomposition
- LAPACKE_dorgqr: Q Matrix extraction

A specific CMatrix class has been developed in C language and added to PEGASE SDK in order to get a suitable and unified model for data computing.

PC to PEGASE implementation, moving to the real wireless world

Implementation of Matlab source code in C on PEGASE target has been performed and validated with two parallel approaches:

- unitary tests for each sub-function (from Blackfin DSP library as from LAPACK library): coherence between results on PEGASE and results on PC+Matlab were validated
- a complete implementation of the algorithm in C language on PEGASE to validate the ability of the method to compute in real-time with respect to memory and processing capacities

Method step	Comparison / result
Cross-correlation	Results of PEGASE cross-correlation function usage are in perfect adequation with initial results under Matlab with a maximum drift of less than 0.05% (see graph below).
FFT+iFFT correlation	This correlation method is supposed to gain in time-spent for computation by a direct call of appropriate DSP functions. Nevertheless the data format imposed an input matrix adaptation that requires new computation. This step should be performed.
Hankel construction	The Hankel matrix is filled with the previous matrices issued from correlation step. In a first step, a Singular Value Decomposition (SVD) allows to minimize Hankel matrix size while keeping data pertinence.

SSI	A pseudo-inverse matrix is computed for each system order to extract the system matrices, and finally damping values, natural frequencies and mode shapes. This allows the construction of the stability diagram.
Fast SSI	Contrarily from previous traditional SSI method, the fast method computes: <ul style="list-style-type: none"> • QR decomposition to the maximum order of the system • Solve least squares equation for maximum order and then lower orders that ask for much computation step; only one operation for each order • Damping values, natural frequencies and mode-shapes are directly extracted for each order without the need of pseudo-inverse matrix or QR computation

Application

A first comparison of the computation time within the PEGASE environment with both implementations of the SSI algorithm (using pseudoinverse or QR decomposition approaches) illustrates the advantage of using the QR decomposition by showing a clear reduction for duration of the process. For a size of 15x10, matrix pseudo inverse is performed in 88,714 μ s, while the QR decomposition takes only 6412 μ s (Fig. 4).

To validate the SSI implementation on PEGASE wireless target, vibration records from a composite panel [5] have been used. This campaign involved 15 sensors (accelerometers): one as a reference sensor and the 14 other sensors where moved

rows		3	4	6	10
5		59079	59601		
8		59102	60662	65138	
10		59632	61101	66706	
15		60516	61038	68817	88714
in μ s					

QR fonction	columns	3	4	6	10
rows	5	504	688		
	8	765	1066	1770	
	10	–	–	2148	
	15	912	1348	3042	6412
in μ s					

Figure 4. Time comparison between pseudoinverse (top) and QR decomposition functions.

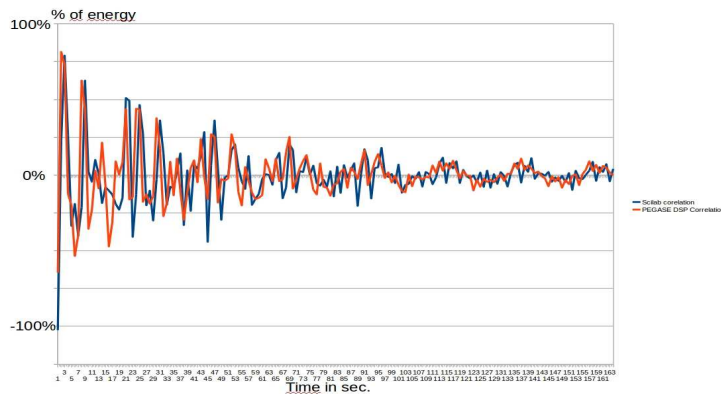


Figure 5. Matlab (blue) and C-PEGASE (red) comparison for cross-correlation.

between different measurement setups. Here we use only 100000 data samples from the first data set for modal analysis and show results of the computed cross-correlations in Figure 5.

CONCLUSION AND PERSPECTIVES

A full implementation of a complex but robust SSI method has been ported on a Smart Wireless Sensor platform named PEGASE. Most of the steps have been passed but some have to be performed. Nevertheless the global objective of portability and feasibility is proven. This opens the way of promising results: wireless, embedded and real-time complex modal analysis algorithms to perform structural default detection is possible. In that way, the “smart” concept of WSN really makes sense. Last performing task are probably due to memory limits of PEGASE and should be solved by the next version of this product planned at the end of 2013. A final validation campaign will be performed in situ on a real bridge in France under controlled conditions. From the scientific point of view, it is envisaged to complement the subspace-based modal parameter estimation with information on their confidence bounds, which can be obtained from efficient algorithms as in [6], and to extend it to measurements from moving sensor setups [7].

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