Complex Control Systems, Applications of DIAPM-RTAI at DIAPM

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Abstract

The DIAPM (Dipartimento di Ingegneria Aerospaziale del Politecnico di Milano) is involved in many theoretical and experimental researches on active control of the dynamics of complex systems, such as the vibration and noise reduction of light aeronautical structural panels, and the damping increment of large space structures having many modules, trusses, and subsystems connected together. The challenge is to have a full controlled and low cost scientific laboratory environment in order to develop good experiments, which can (in)validate present theories and shape the direction of theoretical research. The development of RTAI (Real Time Application Interface) plays an important role in this project, since it allows a reliable, effective and low cost PC-based hard real time implementation of our applications. This paper shows two of them with particular regard to RTAI performances and software solutions.

1 Introduction

Within the last two decades, much attention has been focused on active control of structures to suppress their structural vibrations. This challenge is crucial for the new generation of aeronautical and space systems. The more and more stressed minimization of weight in spacecraft and airplane design, the increment of size and components of structures, and the low rigidity of new materials combine to make the modern aerospace structures extremely mechanically flexible and sensitive to the low-frequency structural modes. Active control methods can be used to damp out undesirable structural vibrations, and obtain better performances than interventions based on passively modified structures, for a wide range of operating conditions along with a significant save in weight.

Classical and well known active control techniques have become obsolete for such complex structures. New issues have recently rised to topical subjects. The following

have to be especially pointed out:
1) robustness of the controller in presence of modeling uncertainties;
2) suitable type and number of sensors and actuators;
3) adaptivity of the controller for slowly time-varying system parameters and along a large number of varying configurations.

The mathematical model used in the controller design may often contain significant uncertainties such as model truncation errors and parameter perturbations. A flexible structure has theoretically an infinite number of vibration modes, a different number of which can be excited at different times. Large-scale models (e.g., finite element models) are suitable for dynamic simulation, but cannot be used as a basis for real time controller implementation due to the resulting computational load. Therefore, control algorithms are often based on reduced-order models of the structure dynamics and so un-modeled dynamics may cause unwanted controller-structure interactions and lead to instabilities. Furthermore some system parameters are poorly known due to the inherent modeling error present in even the best structural analysis computer code and to the limitation of modal testing on earth. Thus one of the key issues for the controller design is to meet the requirement of sufficient robustness with respect to model uncertainties.

The second issue involves the choice of sensing and actuating devices, their number and location along the structure. A flexible and large aerospace structure has closely spaced and numerous low-frequency modes that fall in the controller bandwidth. Good system observability and controllability require many sensors and effectors and thus multi-input-multi-output (MIMO) control techniques. Since it is ridiculous to think to control all the dynamics of the structure, the devices have to be located so as to maximize their effectiveness for the first frequency modes, which are usually the less damped. Finally they must be lightweight, compact and wideband, allowing the implementation of low invasive control systems.

The need for adaptive control in modern aerospace structures arises both of ignorance of the system and changing control regimes. The former is related to the first issue when the plant is so unknown that an on-line identification is highly recommended. The latter occurs because of changing configuration, that may be due for example to construction in-space, thermal distortion, or reorientation of subsystems. Adaptive schemes may be direct, i.e. the availabe control parameters are directly adjusted to improve the overall system performance, or indirect, i.e. the system parameters are identified (based on an assumed system structure) and the control commands are generated from these parameter estimates as though they were the actual values.

These issues lead to the development of new and complex control techniques, which must be studied and validated via thorough ground testing, first of all in controlled laboratory environments. The DIAPM (Dipartimento di Ingegneria Aerospaziale del Politecnico di Milano) is involved in many experimental researches on this topic. The most important are the following:

- development and realization of active control methodologies for flutter suppression of wing models;
- realization of active vibration and noise control systems on light panels;
- development of control strategies for landing gears;
- experimental verification of active control systems for large space structures;
- control of the dynamics of flexible manipulators.

The challenge is to develop good experiments, which can (in)validate present theories and shape the direction of theoretical research. RTAI makes available a low cost PC-based hard real time tool for digital implementation of new control laws and architectures. The results presented here are the proof. They concern two digital adaptive vibration suppression experiments: the increase of the natural damping of a large flexible truss using on/off air jet thrusters; and the reduction of the acoustic emissions of a panel using piezoelectric materials as distributed sensors and actuators. In the first case the adaptation of the controller is obtained by combining an identification step using a Vector-Channel Lattice Filter, recursive both in time and order, and a full state controller based on a robust multi-input-multi-output pole placement technique; in the second one the adaptive scheme is based on a Diagonal Recurrent Neural Network. The truss experiment is a significant example of a complex control architecture using two PC and many cooperating tasks, while the panel one demonstrates the RTAI performances in high-frequency control systems.

2 Adaptive Control of a Large Flexible Structure

The present and future of space missions involve the realization of advanced space systems, called Large Space Structures (LSS), whose features are so special that have encouraged the emergence of a new distinct technological field. In fact the development of more and more light materials and complex and articulate designs entails that structural flexibility is not merely a matter of marginal impact, like for the older generations of spacecraft, but dominates projected system performance. Such a system has tolerances on pointing accuracy and rapid manoeuvres so severe that require theoretical development of suitable advanced control design techniques, that must be verified via ground-based experiments like that presented here.

The system we have tested is a flexible structure called TESS (Truss Experiment for Space Structure) at DIAPM. The structure is a modular beam-like truss, with a basic cubic bay with one diagonal on each side, suspended from the ceiling with horizontal axis.

In our tests we used two capacitive accelerometres co-located to air jet actuators, one at the tip of the structure and one in a middle position, as depicted in Fig.1. These devices represent only a subset of the available ones, but their number had to be constrained to suite the available computational power. The positions along the truss of the two couples of sensors/actuators maximizes the controllability and observability of the first rigid and four bending modes. The detection of the second rigid mode would require a symmetric position of the sensors. The sensors measure accelerations in the horizontal plane, have a voltage range of (1 V and an output of 2.5 V at 0 g. The actuators produce a maximum force of 2.1 N in the same plane and are made by an electrovalve having a convergent nozzle.

As any distributed system, TESS structural dynamics can be described by partial differential equations. For practical control system design, modal and finite-element analyses are used to obtain a truncated, finite-order model which can be represented in the standard discrete-time state-space form. However, for the above mentioned reasons, an adaptive identification is highly recommended to determine a more appropriate and precise model on-line. To this aim it's easier to use an input/output ARX (autoregressive with exogenous inputs) representation in the form

$$y_t = \sum_{i=1}^{n} A_i y_{t-i} + \sum_{i=0}^{n} B_i u_{t-i} + e_t \tag{2.1}$$

where $A_i \in \Re^{n_y \times n_y}$, $B_i \in \Re^{n_y \times n_u}$ are unknown matrices, n is the order of the model, y_t is the output vector, u_t is the input vector and e_t is the unmodeled/unmeasured white noise vector forcing the system at time t and corresponding to an "equation error". The identification method used here is a vector-channel lattice filter (VCLF), recursive both in order and time, that determine on-line the parameters of (2.1) which are the basis for the one-step-ahead output prediction used by the controller. The crucial order-recursive property of lattice filters makes them a powerful tool for applications to large flexible structures because they allow to increase the effective order of the structure, to accomodate new excitations or decrease it as faster transients in the structure are damped out. In fact the recursive (in time) fixed order least-squares methods, widely used for adaptive parameter estimation, represent, according to what previously said, a serious limitation for the identification of a LSS.

There are two main features that a control system, based on an on-line identification algorithm, must have to be profitably implemented digitally. First, it does not have to require an excessive computational burden, to avoid compromising the control action and effectiveness, because of inadequate computer power relative to the available technology. In fact VCLF, like most adaptive identification techniques, involve many operations within each sampling interval and so they take up hardware resources widely. Second, the controller must be robust, because it is applied to an identified system that may be fairly inaccurate. Robustness is here related to how much can a stable linear system change while remaining stable. A MIMO pole-placement technique can be adequate if the closed loop eigenvectors can be constrained to remain similar to the open loop mode shapes. In fact we increase the natural damping of the structure by an eigenstructure assignment requiring complex closed-loop eigenvalues to have a minimum damping factor of 0.15 and the corresponding eigenvectors to be as orthogonal as possible. The choice of maintaining the open-loop natural vibration modes for the closed-loop eigenvectors has demonstrated to work well because the control system does not change in a particular way the mode shapes of the structure.

The control is implemented using two PC connected through their parallel ports. One is a 100 MHz Pentium and manages data acquisition and conditioning. The other is a 200 MHz PentiumPro and attends to adaptive identification and control. The accelerations, captured via a 12 bit A/D converter at a sampling rate of 10 KHz, are filtered through a digital 5 Hz fourth-order low pass Thomson filter and through a 0.05 Hz high pass filter which eliminates steady state offsets, and are finally sent to the PentiumPro at a rate of 10 Hz. The PentiumPro receives data, calculates output predictions and input controls, and applies the control forces using digital outputs, that drive the air through the jet thrusters. The sampling rate of the control action is 10 Hz; in this way on/off actuators can operate correctly and all computations of lattice filters can be done in real time. The great oversampling on the Pentium100 eliminates every analogic conditioning. In fact, in relation to an accelerometres bandwidth of about 100 Hz, a sampling of 10000 Hz allows to overcome all aliasing problems. Moreover the high sampling acts as a dithering mechanism that increases the effective digital resolution of the signal. The PC-to-PC communication is done through the standard parallel port, that offers a good interface for transferring information between two PCs, besides being an interface between a PC and a printer or other peripherical.

The Pentium100 carries out data acquisition and filtering at 10 KHz, and data transfer to PentiumPro at 10 Hz. To this aim two real-time tasks have been created. The first one, called `acquisition_task` operates in periodic mode and guarantees the correct timing. In fact it has the highest priority, so it can never be preempted. The second task, called `communication_task`, is at lower priority and the intertask synchronization is got with messages. The communication_task is waked up after inizialization and does a Remote Procedure Call (RPC), i.e. sends a message to the other task and blocks itself until a return message is received. The `acquisition_task` has a counter that increases every period; when it's equal to 1000, that is every 100 msec, sends to the other task the return message containing accelerations in that instant and resets the counter to zero. Now the `communication_task` can transfer the received data to the PentiumPro and block itself yet with another RPC.

The data transfer protocol through the parallel ports makes use of a special cable having two D-Type 25 pin maleconnector. The Pentium100-plug has pins 2-5 as data and pin 8 as flag bit, whereas the PentiumPro flag bit is at pin 10. In this way we can transfer four bits each time permitting to divide a 12 bit data in three nibble. Flag bits are used to activate and synchronize the PC-to-PC communication. Pentium100 activates the transfer protocol using flag-bit as interrupt. PentiumPro, ready to receive an interrupt request on the parallel port for IRQ7, executes the corresponding interrupt service routine. Now the communication begins: Pentium100 writes a nibble on the Data Register of the Parallel Port and PentiumPro reads it on its Status Register until the data transfer is complete. The communication is optimized by the inversion of the flag bit value at each transfer. It has been calculated that transmission time is about 40 microseconds and it has been verified that there is no data loss.

In the PentiumPro it's set the oneshot mode for the timer, which is based on the CPU clock frequency and allows tasks to be timed arbitrarily with an uncertainty of about 10-20 us. Two real-time tasks have been created whose timing is guaranteed by the interrupt request from Pentium100. One task, called computation_task, manages the identification and control algorithms, and the other task, called `fire_task`, at higher priority, drives actuators through digital outputs. Because at one instant the `fire_task` makes use of values calculated by the computation_task one instant before, a synchronization strategy, which in our case is based on semaphores, is needed. Two semaphores are created: one (sem1) as to interrupt request and one (sem2) as to intertask communication (Figure 2). At first the `fire_task` is resumed and immediately waits for an event on sem2; if none is available, the process queues up in priority order. Then the computation_task is resumed and waits for an event on sem1. The interrupt service routine, executed whenever an interrupt on the parallel port occurs, signals that an event is available and in this way allows the computation_task blocked on sem1 waiting list to receive the available event. This task activates the PC-to-PC data transfer protocol, calls sem2 in order to control the dynamics of the structure with force values calculated at previous instant and then makes all computations of adaptive algorithm using actual data. Finally it blocks itself again. The `fire_task` opens and closes the valves at fixed instants inside the sampling interval. Note that the jet thrusters mounted on TESS are on/off actuators, which can produce either a plus-minus constant or null force. In order to apply our linear control law, we must operate a PAM (Pulse Amplitude Modulation) to PWM (Pulse Width Modulation) conversion, which is based on the equivalence between responses to corresponding input histories. The first-order equivalence used here can be obtained by a single maximum amplitude PWM impulse, centered within the sampling interval, having an area equal to that of the parent PAM input. In this way, if our actuator produces 2.1 N, a value of 1.05 N becomes a pulse covering half sampling interval; if the input gets saturated, the equivalence degenerates in a pulse covering the whole sampling interval. This philosophy is reached using a table, called `firing_table`, of initial and final time instants of the two pulses and a temporized function on sem2 inside a `while` loop. In this way, if no event is available, the `fire_task` is blocked in priority order on semaphore waiting list until a certain time delay, taken from the `firing_table`, has expired. After it, the `fire_task` opens or closes the corresponding valve according to the state of a counter in the loop. If an event is available, a `goto` instruction allows to exit from the `while` loop, because the sampling interval is finished. This procedure permits to manage as well as possible the saturation of inputs.

In Figure 3 is shown a significant result. The dotted line represents the free response of TESS after sine excitation of the second pendulum mode of the structure, whereas the solid line represents PWM controlled response. The excitation is applied using the same control air jet actuators. The lines relate to the velocities of the tip of the structure, got with a pseudo-integration of the accelerations to avoid integration of the accelerometer offset and measurement noise. In the Laplace domain this is accomplished with a high pass second order filter followed by the ideal integration stage, resulting in the following transfer function

$$\frac{s}{s^2 + 2\xi\omega s + \omega^2} \tag{2.2}$$

with $\xi = 0.707$ and $\omega = 2 \cdot \pi \cdot 0.15$ rad/s. The excitation lasts 30 seconds, while the duration of the experiment is 70 seconds. You can appreciate that the tip velocity of the truss is damped out in approximately 15 seconds. This good qualitative behaviour is also supported by a quantitative measure of the damping increment calculated in the first 10 seconds of active control action. The damping estimate ξ is obtained using

$$q = \frac{\omega_p}{\omega_{right} - \omega_{left}} \tag{2.3}$$

$$\xi = \frac{1}{2q} \tag{2.4}$$

where ω_p is the frequency corresponding to the peak in the fast Fourier analysis of the output signal, and ω_{right} and ω_{left} are the frequencies corresponding to the half-peak respectively at the right and left of ω_p. ξ results 0.152 in good agreement with the control objective.

3 Adaptive Control of a Panel

In recent years there has been considerable interest in the design and the implementation of active vibration control systems, using piezoelectric materials as distributed sensors and actuators, to improve the quality of life with particular regard to the reduction of acoustic emissions, and to improve the comfort in transport vehicles. Piezoelectric devices are lightweight, compact and wideband, hence they allow the implementation of very compact and low invasive control systems. We have developed a MIMO adaptive vibration control system based on a Diagonal Recurrent Neural Networks (DRNN), that is very promising for the control of non-linear systems and complex structures due to its adaptivity. Moreover, the synthesis of this class of regulators does not require any numerical model of the plant. Available results, obtained with a MIMO conventional sub-optimal regulator that exploits a direct feedback of the measurements, have been used as a reference to evaluate the DRNN control system performance. For the experimental activity, an aluminum alloy flat panel (600x400mm) has been used, clamped on all sides and mechanically excited. The sensors and the actuators have been applied on the two opposite sides of the panel at the same locations, so that a group of four could be used as sensors and the others as co-located actuators. Piezoelectrics have been positioned in a heuristic manner after an exhaustive analysis of modal curvatures, to achieve the highest controllability of the first four structural modes. The disturbances are generated by an electro-mechanical shaker, driven by a signal generator. The measurement apparatus is reported in Figure 4. The signals from the sensors are conditioned by three anti aliasing filters. The control signals generated by the NN regulator are transferred by a D/A output card to three power amplifiers to obtain the desired control voltage level; the resulting signals are conditioned by three passive RC low-pass smoothing filters.

A widely used Neural Network architecture is the so called feedforward network (FRNN); it is made of a given number of layers, each of which has a specified number of nodes; only nodes that belong to adjacent layers are connected together, and each node belonging to a layer is connected to all nodes of an adjacent layer. FRNN can be regarded as a static network. Dynamic models and controllers can be implemented more effectively using network structures that involve different kinds of signal feedback. Feedback connections between all the nodes involve an unnecessary complexity, that can be reduced by local feedback connections: e.g. within every single layer of internal nodes, or for the network outputs, to the network inputs, or locally for each neurone only. In this work a DRNN, characterized by one input layer, one output layer and one recursive hidden layer, has been implemented. In this class of networks, the feedback connections are from the output of every hidden neurone to the corresponding input only. Since there are no crosslinks among neurones in the hidden layer, the DRNN has considerably fewer weights than the FRNN and thus it is simplified and more numerically efficient.

To implement the real-time control system, two processes are created. The first one is a hard real time process that manages the `read/write` operations and the control routines, while the second one is a soft temporized operator interface that loads or saves data files and turns on/off the control task, following the commands of the peripheral device. RTAI feature allows a PC to manage both the real time tasks and any front-end software that receives operators command and attempts to file I/O operations. In fact the Linux operating system is run as the lowest priority task under a small real time operating system, so that Linux processes are only permitted to execute when there are no real time tasks executing. One way for data transmission between processes and real time tasks is based on FIFO (first in first out) streams. Our control software is made up of two real time tasks called `control_task` and `monitor_task` and one Linux process called Interface.

The control_task is the higher priority task and manages the read/write operations on I/O boards and the control routines, while the monitor_task is a lower priority task that manages the data transmission from/to the Interface process by means of the FIFO streams allowing to turn on/off the control session following the operator commands. The scheme represented in figure 5 shows the software architecture: two FIFO are created for data transmission, one allows communications directed from Interface to the monitor_task, while the other is for the opposite direction.

The performance of the control system have been tested in presence of various structural harmonic excitations and the reduction rate of the signals of the sensors due to the control action were measured; in addition, an accelerometric signal was also monitored. The sample frequencies adopted to test the control systems were different because of the unequal computational burden: for the sub-optimal regulator, characterized by a simple feedback, the sample frequency was 20 KHz, while for the neural network control system it was only 2 KHz, with alternate adaptation of the identifier and of the controller network. The results of the tests obtained with the two regulators are presented in figure 6. It is worth stressing that the missing results indicate the ineffectiveness of a particular couple of piezoelectric devices with regard to the curvature of the particular mode due to their location. Despite its low control frequency, the DRNN regulator has effectively reduced the vibration amplitude in all the control tests.

4 Concluding remarks

This paper has demonstrated that the Real Time Application Interface RTAI developed at Dip. di Ingegneria Aerospaziale of Politecnico di Milano is viable and capable to implement complex digital controllers with high effectiveness. This tool, with its versatility, allows to obtain significant results for our structural dynamics laboratory researches. In fact the two ground-based experiments described here are believed to present some points of originality and to provide useful direction for the applicability of the adopted methods. The least-squares VCLF has demonstrated to be suitable for applications in real world complex adaptive control of large structures, in particular regarding its order-recursive property, The DRNN control system showed its ability to reduce the amplitude of structural vibrations induced on a panel by harmonic excitation and its simplified structure, together with the RTAI performances, allowed to work with a sufficiently high control frequency.

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