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China-US Workshop on

SMART STRUCTURES AND SMART SYSTEMS

Hongsheng Jiang   Qihui Chen   Chuanguo Fu

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Preface

Sensor and control technologies play a key role in the design and construction of modern engineering and mechatronic systems. The convergence of enabling technologies such as the Internet, communications, information technology and miniaturization technology has elevated the research and development of sensors to a higher level. New sensor technologies bring paradigm shifts in the way we design modern engineering systems at all physical dimensions. Sensor technologies include the sensors themselves, signal processing, sensor networking and interpretation of data. Control technologies include control theories for real time feedback control/decision making and implementations of control algorithms on computers and digital signal processors. For successful applications, the designer must consider sensor technologies and control technologies as well as the design of physical systems jointly for their synergistic integration, which is the essence of mechatronics. Mechatronics refer to the synergistic integration of sensors, actuators, physical plants and computing devices for closed loop decision making. Synergy may be considered in terms of dealing with complexity, performance, overall cost of machinery, physical dimension, time for development, ease of installation, and so on. Exciting applications of mechatronics are happening in aerospace, biomedical, civil and mechanical engineering.

Civil infrastructure systems are generally the most important assets of a nation. They are large, distributed systems which are constantly used by public and communities to perform day-to-day activities and commerce. They comprise of transportation systems, communication systems, power generation and distribution systems, water supply and sewage treatment systems, and the systems and facilities used for the education, medical treatment, societal governance. The well being and prosperity of a nation is greatly determined by the adequacy and health of its infrastructure system. These systems are constructed to have long lives, and are not easily replaceable once constructed. In order to sustain the performance and reliability of such structures, it is essential to have accurate and real-time information about the condition of the structures. Today, information regarding the health of a structure is obtained through scheduled and labor-intensive inspections and analysis which may not provide the necessary hard information during the critical time before a catastrophic failure strikes. This sets the background for active research in the civil engineering community to develop Structural Health Monitoring (SHM) systems by taking advantage of the new generation of sensors.

The multi-sensor data fusion of smart sensors may elevate aerospace structural health monitoring (SHM) to a higher level. The smart sensors are capable of generating exciting diagnostic signals, measuring physical parameters, interpreting and collaborating data into information, and communicating with a monitoring station over a wireless link. Hardware devices to realize smart nodes of such a link are already commercially available. The time is right to pursue research to lay the groundwork for a novel wireless smart sensor network technology for near real-time intelligent monitoring of complex aerospace systems and a broad set of physical phenomena.

Designing and producing high-performance machineries and consumer products in a cost effective and timely manner is one of the ultimate challenges to engineers today. The mechatronics approach has been recognized to meet such challenges. Mechanical engineers are in the center of such activities, and exciting developments in the areas of integrated sensor technology and mechatronics are taking place in mechanical engineering. If automation is introduced in a system, the designer is responsible to make the automated system prepared for full or partial system failure and to maintain the safety of the system. Fault detection and identification (FDI) as well as failure tolerant control are gaining increased attention in the research community for this reason. For example, safety is critically important in automated systems in automobiles such as drive-by-wire and throttle-by-wire systems. FDI is nothing but health monitoring of automated mechanical systems.

This provides the motivation to organize the China-US joint workshop with multi-disciplinary representations from the aerospace, civil and mechanical engineering communities.

The intellectual merits of this workshop are embedded in the identification of high impact research issues of mutual interest to the US and China in the area of advanced sensing systems, mechatronics and smart structures technologies, and in strengthening the US-China network for conducting joint collaborative studies to address these research issues for the benefit of the research community and general public in the two countries. The collaborative research activities are expected to develop (a) advanced sensors and sensing systems, (b) innovative utilization of sensor systems and mecharonics approaches in smart structural systems, (c) reduction of disaster risks through the utilization of smart devices and systems, and (d) effective prognostic and diagnostic evaluation of mechanical and civil infrastructure systems.

Masayoshi Tomizuka
University of California, Berkeley,
California, US
October 17, 2005

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Sensing Rich Approach to the Design of Modern Mechatronic Systems

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Abstract: In this paper, the advantages of sensing rich approaches to the design of mechatronic systems are explored. Such advantages include enhanced system performance, flexible operation of the system and reduced operational costs. Some advantages will be illustrated by two examples. The first example is the power transmission mechanism or drive train under servo control, which represents a fundamental element of any motion control system. The sensing rich design is based on distributed measurements of positions and accelerations at multiple points of a drive train. These measurements improve the performance of drive train servo systems in terms of speed, positioning accuracy and vibration suppression. The second example is motion control of papers in copiers and printers. Distributed sensing and actuation of papers in the paperpath results in reduced rate of machine shut downs due to paper jamming.

Keywords: mechatronics, sensing, motion control

1. INTRODUCTION

The design and production of high-performance machineries and consumer products in a cost effective and timely manner is one of the ultimate challenges to engineers today. Mechatronics approach has been recognized to meet such challenges. Mechatronics is the synergistic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacture of industrial products and processes. Figure 1 shows a modern mechatronic system. As shown in the figure, the physical system and the computer (DSP) are interfaced by senso rs and actuators; in fact, modern mechatronic systems may not exist without sensors. Innovations and progress in sensor technologies have stimulated the advancement and development of control theories and technologies. In fact, the sensor technology and control technology are almost the left and right wheels of a cart. A good example is the computer hard disk drive (HDD). The track density of HDDs continued double every 18 months or so during the past several decades, and it is currently at about 100K TPI (tracks per inch). This impressive improvement is largely due to the advancement and innovations in sensing technologies for the recording head: thin film heads, MR (magnetoresistive) heads and GMR (giant magnetoresistive) heads introduced around 1980, 1990 and 2000, respectively.

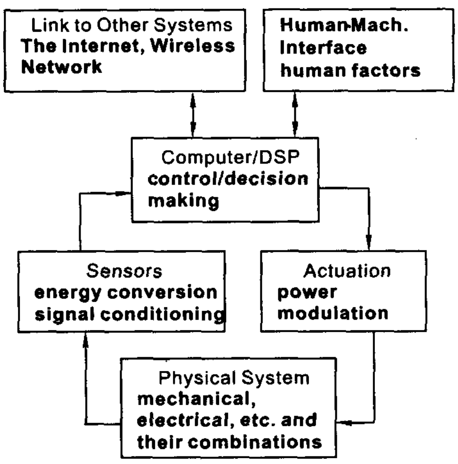

Figure 1 Modern Mechatronic System

The emphasis in this paper is the advantages of aggressive usage of sensors in the design and operation of mechatronic systems, i. e. sensing rich approach. Enabling technologies such as mini aturization and high-speed computational devices combined with advanced signal processing and decision making theories provide vast opportunities for the development and application of sensor systems to mechanical and other types of engineering systems with a wide range of advantages. Such advantages include enhanced system performance, flexible operation of the system and reduced operational costs. Advantages of sensing rich approach will be illustrated by two examples.

The first example is the power transmission mechanism or drive train under servo control, which represents a fundamental element of any motion control system. A typical drive train includes an actuator (electrical motor), a set of gears, bearings and an inertia load (link), which may be connected to another drive train or an end effector. Advantages of measuring accelerations will be the main theme. Sensing of both the acceleration and position of any mechanical element makes it possible to utilize the idea of kinematic Kalman filtering for accurate and robust estimation of the velocity[1,2]. Given information on acceleration, velocity and position, a number of control ideas may be applied for performance enhancements in terms of speed, accuracy and vibration suppression.

The second example is motion control of papers in copiers and printers[3]. In modern copiers, papers are moved from the feeder to the image transfer station by actuated rollers called nips, which are driven by a single motor. This approach may assure that motions of all papers in the paperpath are synchronized. In the approach, however, the papers remain equally spaced only if they are fed without errors by the feeder and they do not slip at any nips. Unfortunately, the feeder introduces feeding errors and papers do slip at nips, and the copier may shut down when errors are accumulated beyond a threshold. To eliminate or reduce the occurrence of such shutting downs, the position of each paper relative to the preceding paper, i. e. spacing, may be measured in real time and be corrected at multiple points of the paper path. This requires distributed sensing and actuation of papers in the paper path. The advantages of this approach have been experimentally demonstrated.

Although not discussed in this paper, sensing rich approaches are attractive from the viewpoint of fault detection and identification and fault tolerant control[4].

2. SENSING RICH DRIVETRAINS

2.1 Drive Trains

A typical drive train in mechanical systems begins with an electrical motor and ends with a link, which may be connected to another drive train or an end effector. In robots or assembly machines, the end effector may be a gripper carrying a peg and inserting it to a hole. In almost all mechanical systems, the user wants the end effector to move in a controlled manner a) along the desired trajectory, i. e. tracking problem, or b) to the desired point, i. e. point-to-point control. In point-to-point control, it is important to reach the target point quickly and precisely with no residual vibration.

The performance of servo-systems is normally judged in terms of speed, positioning/tracking accuracy and vibration suppression.

Drive trains for motion control systems are classified into two types: direct drive and indirect drive. Direct drive uses low-speed and high-torque motors (direct drive (DD) motors), and the motor shaft is directly connected to the link. This arrangement simplifies the dynamics, but DD motors are heavy and expensive. In indirect drive mechanisms, the actuator (electric motor) and the link are connected via gears for speed reduction and torque amplification. In robots, the harmonic gear is the most popular means for this purpose; it is compact and may reduce the speed on the order of 100 in one stage. This allows the use of high speed and low torque motors resulting in various advantages such as lower costs and lighter weights. Another popular speed reducer is a ball screw, which transforms rotational motion of the motor to translational motion.

Our focus is on modern mechanical systems, the objective of which is precise and fast positioning of an object, which may be grabbed by an end effector. The selection of control strategies and algorithms may utilize measurements or sensing of various signals in the drive trains:

- Motor: current, acceleration, velocity and position
- Gear reducer: transmission torque, relative displacement across gear reducer
- Link: acceleration, velocity and position
- End effector: acceleration, velocity and position

Among the variables listed above, accelerations have been under utilized in motion control. Accelerometers based on MEMS technology have become popular and offer economical ways to measure accelerations. In the following subsection, we will explore the benefits of utilizing acceleration measurements along with other measurements.

2.2 Kinamatic Kalman Filter[1,2]

The kinematic Kalman filtering (KKF) method fuses acceleration measurement and position measurement of a moving element for simple and robust estimation of the velocity (Lee and Tomizuka, 2001). Consider a single degree of freedom motion system described by

$$m\ddot{x} + b\dot{x} + kx = u \tag{1}$$

where x is the position, u is the force input, and m, b and k respectively denote mass, damping coefficient and spring constant. The upper dot on x denotes time differentiation. When the position is measured, the velocity may be estimated by a model based Kalman filter or state observer. Defining two state variables by $x_1 = x$ and $x_2 = dx/dt$, the system and the Kalman filter are obtained in the following form.

System

$$\frac{d}{dt}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -b/m \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1/m \end{bmatrix}[u(t)+w(t)]$$

$$y(t) = x_1(t) + v(t)$$

where $w(t)$ and $v(t)$ are input noise and measurement noise, respectively. $w(t)$ and $v(t)$ are independent Gaussian white noise processes.

Model Based Kalman Filter

$$\frac{d}{dt}\begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -b/m \end{bmatrix}\begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1/m \end{bmatrix}u(t) + \begin{bmatrix} f_1 \\ f_2 \end{bmatrix}[y(t) - \hat{x}_1(t)]$$

where f_1 and f_2 are the filter gains.

Note that the model based Kalman filter depends on the plant parameters. Thus, if the plant parameters are poorly known or subject to change, the performance may deteriorate.

If the position and acceleration are both measured, we note that two quantities are related by double integrators. Thus the system equation and the KKF are obtained in the following form.

System

$$\frac{d}{dt}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}[a_M(t) + w_a(t)]$$

$$y(t) = x_1(t) + v(t)$$

where $w_a(t)$ and $v(t)$ are accelerometer measurement noise and position measurement noise, respectively.

Kinematic Kalman Filter

$$\frac{d}{dt}\begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}a_M(t) + \begin{bmatrix} f_{k1} \\ f_{k2} \end{bmatrix}[y(t) - \hat{x}_1(t)]$$

where f_{k1} and f_{k2} are the filter gains

Note that KKF does not depend on model parameters at all. Thus, if the acceleration and the position are both measured, the velocity may be reliably estimated by KKF. Since the encoder measurement is obtained only at sampling instances, it is more natural to develop KKF in the discrete time domain.

In a recent paper[2], Jeon and Tomizuka investigated the use of an accelerometer and encoder along with the idea of KKFs for velocity estimation and control of a motor. As shown in Fig. 2, the KKF provides an accurate estimate of the velocity even when the resolution of an encoder is low.

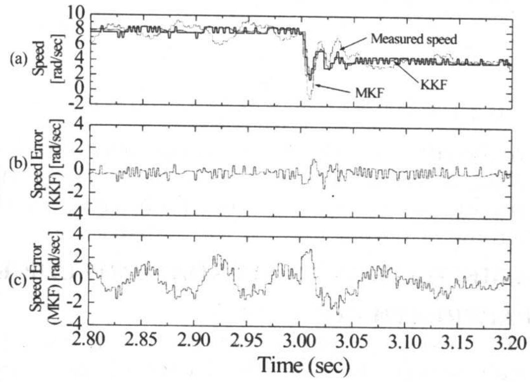

Figure 2 Estimation and control of speed by kinematic Kalman filter and model based Kalman filter

2. 3 Advantages of Sensing Rich Approach

Accurate estimation of velocity by KKF brings a number of advantages to the design of servo systems. Such advantages are reviewed in this subsection.

Robust compensation of nonlinear friction: Friction force is nonlinear. If we add a nonlinear friction term to Eq. (1), the system equation becomes

$$m\ddot{x} + b\dot{x} + f(\dot{x}) + kx = u \qquad (2)$$

If we have an accurate estimate of the velocity, the nonlinear friction term may be reliably cancelled by letting the control input be

$$u(t) = u'(t) + \hat{f}(\dot{x})$$

where $\hat{f}$ is the estimate of the nonlinear friction force.

Easy implementation of state feedback control: One of the most fundamental discoveries in the state space control theory is the way that state feedback control alters the dynamics of the open loop system[5]. For example, given a linear controllable system, the closed loop eigenvalues may be arbitrarily assigned via state feedback control. If the state feedback control gain is determined based on the linear quadratic regulator (LQR) theory, the closed loop system exhibits excellent robustness[5]. At an early stage of development of the state space control theory, researchers noted that it was not trivial to have direct access to the entire state variables for state feedback control. This motivated the state estimation theory and the estimator state feedback control theory. While estimator feedback control systems, such as linear quadratic Gaussian (LQG) control systems, have nice analytical properties such as the separation theorem, they do not possess the nice robustness properties of LQR systems. Stability robustness is essential in feedback control systems, which motivated the development of modern robust control theories such as the H_∞ theory[6].

As an example, consider a two inertia system in Fig. 3, which is often used as a simplified model for typical drive trains. For simplicity, the gear ratio has been assumed to be unity and the gear is not shown in the figure. Various parameters defined in the figure are: J_m = motor inertia, J_l = load inertia, b_m = motor side friction coefficient, b_l = load side friction coefficient, k = stiffness of the drive and b = damping of the drive. θ_m and θ_l are respectively the motor position and load position, u is the input torque, and d_m and d_l are the disturbance torques acting on the motor and load, respectively.

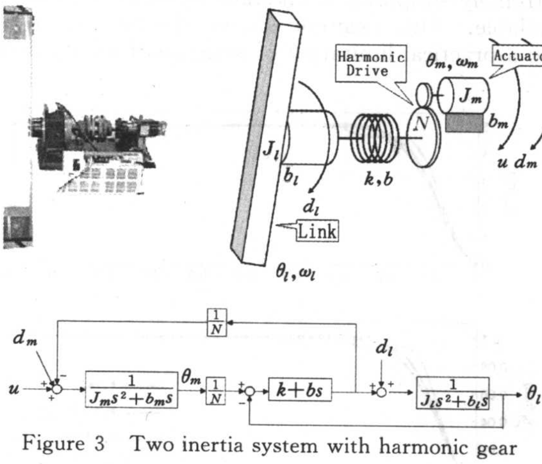

Figure 3 Two inertia system with harmonic gear

Defining four state variables by $x_1 = \theta_m$, $x_2 = d\theta_m/dt = \omega_m$, $x_3 = \theta_l$ and $x_4 = d\theta_l/dt = \omega_l$, the state equation becomes

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k/N^2J_m & -(b_m+b/N^2)/J_m & k/NJ_m & b/NJ_m \\ 0 & 0 & 0 & 1 \\ k/NJ_l & b/NJ_l & -k/J_l & -(b+b_l)/J_l \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 1/J_m \\ 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 & 0 \\ 1/J_m & 0 \\ 0 & 0 \\ 0 & 1/J_l \end{bmatrix}\begin{bmatrix} d_m \\ d_l \end{bmatrix} \qquad (3)$$

Assume that the following quantities are measured: u = input torque, x_1 and x_3 = motor position and load position and dx_2/dt and dx_4/dt = motor acceleration and load acceleration. Then, it is easy to implement the following ideas for real time control.

(1) The idea of kinematic Kalman filter may be utilized to develop a simple and robust estimator to estimate the motor velocity, x_2, based on two measurements for x_1 and dx_2/dt. Similarly, the load velocity x_4 may be estimated from x_3 and dx_4/dt. If the two velocities are estimated, we know all the state variables and their derivatives and the torque.

(2) As described above, the instantaneous values of the four state variables may be obtained without relying on a model-based observer based on Eq. (3). It is then mathematically possible to assign real closed loop eigenvalues to let the state feedback system not exhibit oscillations. Figure 4 shows simulation results when the closed loop eigenvalues are all assigned to -40 (1/sec). Figure 4 (a) shows how the motor and load responses vary when there is 10% error in the value of the spring constant. Responses for the load inertia changes (±58% changes) are shown in Fig. 4(b).

As seen in the simulation results, the closed loop system remains asymptotically stable in all cases, which is the advantage of state feedback control. The response shapes (i. e. the closed loop locations), however, significantly depend on parameter values. Under the nominal condition, the responses are nonoscillatory, but the motor is working hard reversing the direction of torque several times. When parameter changes take place, the motor appears to be working even harder, but the responses change their shapes. This necessitates auto-tuning of the controller, and one method is adaptive control. This aspect has been studied in the robotics community, and it is well known that the implementation of adaptive control becomes extremely simplified if all state variables are directly available. This example shows the advantage and also a practical limitation of state feedback control.

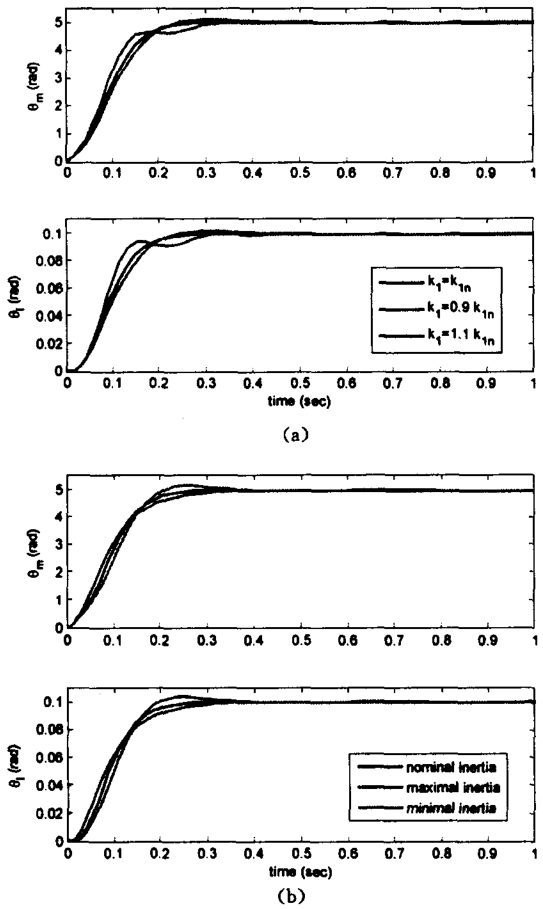

Figure 4 Step responses of drive train under state feedback control
(a) ±10% changes of spring constant
(b) ± 58% changes of load inertia

Easy identification of system parameters: If all the state variables are directly accessible, parameter identification becomes extremely simple. For the two inertia system in Fig. 3, if the disturbance is negligible, given the values of all the state variables and their derivatives and the torque input, state equation (3) may be utilized for easy identification of system parameters. For example, the equation for x_2 may be written as

$$\frac{dx_2(t)}{dt} = [\theta_1\ \theta_2\ \theta_3]\begin{bmatrix} x_3(t) - x_1(t) \\ x_4(t) - x_2(t) \\ u(t) \end{bmatrix} = \theta^T\phi(t), \qquad (4)$$

$$\theta^T = [\theta_1\ \theta_2\ \theta_3]$$

$$\phi^T(t) = [x_3(t) - x_1(t), x_4(t) - x_2(t), u(t)]$$

where $[\theta_1\ \theta_2\ \theta_3] = [k/J_m\ b/J_m\ l/J_m]$. Equation (4) is in a standard form for parameter identification for the parameter vector θ, and least square identification may be performed either in the continuous time domain or the sampled discrete time domain. One possible algorithm is

$$\hat{\theta}(k+1) = \hat{\theta}(k) + F(k+1)\phi(k)[(dx_2/dt_{|t=kT}) - \hat{\theta}^T(k)\phi(k)]$$

$$\hat{\theta}(0) = \theta_0$$

$$F(k+1) = F(k) - \frac{F(k)\phi(k)\phi^T(k)F(k)}{1+\phi^T(k)F(k)\phi(k)} \quad F(0) = \lambda I, \lambda \gg 1$$

where $dx_2/dt_{|t=kT}$ is the accelerometer output at k-th sampling instance. In view that the accelerometer measurements are noisy, some prefiltering of the accelerometer output may be warranted.

3. A MECHATRONICS APPROACH TO COPIER PAPERPATH CONTROL[3]

In modern copiers, papers are transported through paperpath from the feeder to the image transfer station by actuated rollers called nips, which are driven by a single motor. This approach may assure that motions of all papers in the paper path are synchronized. In the approach, however, the papers remain equally spaced only if they are fed without errors by the feeder and they do not slip at any nips. Unfortunately, the feeder introduces feeding errors and papers do slip at nips, and the copier may shut down when errors are accumulated beyond a threshold. To eliminate or reduce the occurrence of such shutting downs, the position of each paper relative to the preceding paper, i. e. spacing, may be measured in real time and be corrected at multiple points of the paper path. This requires distributed sensing and actuation of papers in the paper path. Figure 5 illustrate the conventional paperpath and redesigned paperpath along with other copier subsystems.

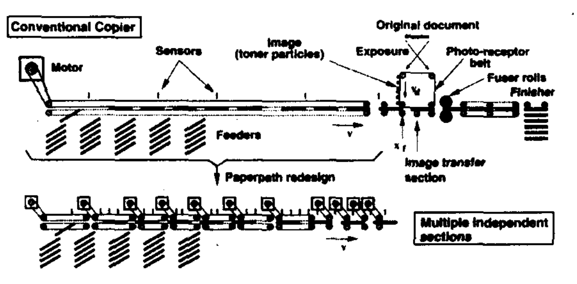

Figure 5 Schematic overview of the conventional and redesigned paperpath

In the new approach, the paperpath is divided into multiple sections as shown in Fig. 5. Each section is driven by its own motor. This added flexibility enables independent position control of sheets in different sections by running the sections at different velocities. Additional optical sensors and encoders are used to improve the sheet position estimates, or observability of the system. The increased level of flexibility naturally leads to a more complicated machine and a need for intelligent control to coordinate the motions of the different sections. The control goal is to synchronize the position and velocity of every sheet with those of its image on the photoreceptor below, despite variations in media properties and feeding times and various disturbances along the paperpath.

The physical system imposes two constraints on the control of sections (papers): the photo receptor belt (see Fig. 5) travels at a constant velocity due to constraints of the xerographic process and all sheets in the same section have identical velocities. This constraint makes it impossible to control individual sheet positions. Care must also be exercised to synchronize neighbouring sections during sheet transfer. This ensures sheets do not buckle or stretch during transfers. A hierarchical control algorithm to achieve control objective while satisfying the constraints is presented in[3].

To evaluate the control algorithm, an experimental copier paperpath was built at UC Berkeley using standard copier parts supplied by Xerox Corporation. In consists of 18 rollers axes connected by timing belts to form 3 sections, independently driven by DC motors and arranged in a loop configuration (see Fig. 6). The experimental setup is controlled by a dSPACE controller board that interfaces directly with eocoders, optical sensors and motor drives. Sheet velocities are estimated by an observer that combines optical sensor and encoder measurements.

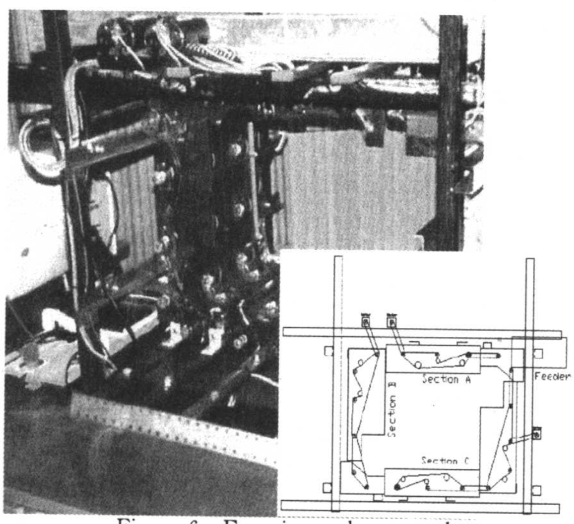

Figure 6 Experimental paperpath at UC Berkeley

Figure 7 shows the experimental results for a

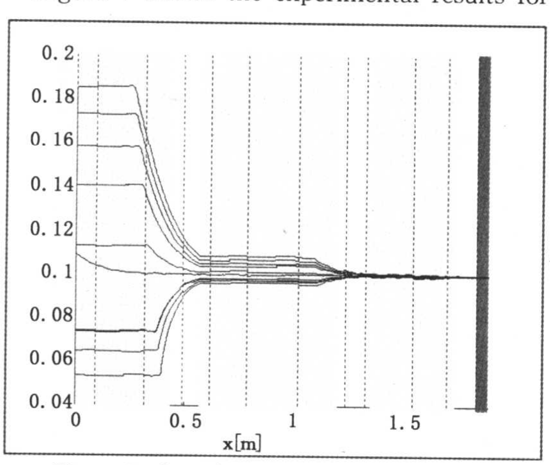

Figure 7 Intersheet spacing versus position along paperpath for a copy job with 10 sheets

copy job consisting of 10 sheets. The horizontal (x) denotes position along the paperpath, the shaded areas represents sections. Sheets move from left to right. The vertical axis corresponds to the intersheet spacing (ISS). The desired spacing equals 0.1 m. In the experiment, various feeder errors were introduced. Notice how all ISSs converge to the desired value. The final position errors are within 0.5 mm. Spacing changes only when a sheet becomes the leading sheet in a section. Until then, they are uncontrollable and remain constant. Control of ISS will dramatically reduce or eliminate paper jams and machine shut downs.

4. CONCLUDING REMARKS

This paper emphasized sensing rich approaches to the design of mechatronic systems. Such advantages were illustrated by the design of drive trains for modern mechatronic systems and the design of paperpaths for paper copiers. The convergence of enabling technologies such as the Internet, communications, information technology and miniaturization technology has elevated the research and development of sensors to a higher level. New sensor technologies bring paradigm shifts in the way we design modern engineering systems. Sensor technologies include the sensors themselves, signal processing, sensor networking and interpretation of data. Control technologies include control theories for real time feedback control/decision making and implementations of control algorithms on computers and digital signal processors. For successful applications, the designer must consider sensor technologies and control technologies as well as the design of physical systems jointly for their synergistic integration, which is the essence of mechatronics.

5. ACKNOWLEDGEMENT

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Vibration-based Structural Damage Detection: Theory and Experiments

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Abstract: Current research in the Dynamic Systems and Vibrations Laboratory at the University of Maryland Baltimore County is divided into two main areas: 1) dynamics and control of distributed structural systems, and 2) vibration testing, model updating, and structural damage detection. This paper gives an overview of the theoretical and experimental research activities in the second area. Structural damage detection using changes of vibration characteristics such as natural frequencies and mode shapes has advantages over conventional nondestructive tests and is treated as an inverse problem. A robust iterative algorithm is developed to accurately detect the locations and extent of small to large levels of damage using a small number of vibration measurements. It is applied to various engineering structures including mass-spring systems, beams, lightning masts, and space structures. The method, which combines a multiple-parameter perturbation method and an optimization method, can handle underdetermined and ill-conditioned system equations.

Updating the mathematical model of a structure using test data is a prerequisite for vibration-based structural damage detection. This is a challenging task when the structure has bolted joints. A new physically based model updating technique is developed for a structure with bolted joints. The iterative algorithm developed can be used to detect damage in bolted joints, such as loosening of joints.

In addition to the work on damage detection and model updating, a novel stochastic model is developed for the random impact series method in modal testing. It can be used in modeling the random impact series applied manually and in the development of a novel random impact device. Extracting the eigenparameters of a structure is a necessary step in vibration-based structural damage detection. The random impact test can combine the advantages of the single impact test and the shaker test.

Keywords: structural damage detection, inverse modeling, iterative algorithm, perturbation method, generalized inverse, model updating, bolted joints, detection of loosening joints, random impact test, stochastic modelling

1. INTRODUCTION

Engineering structures are subjected to various environmental loadings such as winds, snow, ice, and earthquakes. For instance, the lightning masts and transmission towers in the electric power industry are subjected to extensive stresses due to wind loads and corrosion due to rain. In September 2000, a lightning mast at an electric substation of the Baltimore Gas and Electric (BGE) Company collapsed, leading to power outage and damage to the surrounding structures. Damage in a structure can be defined as a reduction of its load-bearing capacity, which can result from a deterioration of its components, connections, and boundaries. All load-bearing structures continuously accumulate damage; early detection, assessment, and monitoring of this damage can avoid catastrophic failures.

A number of conventional nondestructive test (NDT) methods are used to inspect load-bearing structures[1]. Visual inspection testing (VT) of structural members is the most common one for identifying damage but often unquantifiable and unreliable, especially in instances where access to damaged areas is impeded or damage is concealed by paint, rust, or other coverings. Penetrant testing (PT) requires that an entire surface of the structure be covered with a dye solution, and then be inspected. PT reveals only surface cracks and imperfections, and can require a large amount of potentially hazardous dye be applied and disposed of. Likewise, magnetic particle testing (MT) requires that an entire surface of the structure be treated. It can be applied only to ferrous materials, and detects only relatively shallow cracks. Further, due to the current required to generate a strong enough magnetic field to detect cracks, MT is not practically applied to large structures. Eddy current testing (ET) uses changes in the flow of eddy currents to detect flaws, and only works on materials that are electrically conductive. Ultrasonic testing (UT) uses transmission of high frequency sound waves into a material to detect imperfections. Radiographic testing (RT) is based on differential absorption of penetrating radiation by the material being inspected. RT presents a potential radiation hazard to personnel, is costly and relatively time consuming, and requires that discontinuities be favorably aligned with the radiation beam for a reliable detection. Results generated by all of these methods can be skewed due to surface conditions, and cannot easily identify damage at joints and boundaries of the structure. Unless a general vicinity of a damage location is known prior to inspection and is readily accessible, none of the above NDT methods are easily or practically applied to large structures that require a high degree of structural integrity.

Because of these shortfalls in existing NDT methods when inspecting relatively large structures, structural damage detection using changes in vibration characteristics has received much attention