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Improvement of Control Performance by Data Fusion of Sensors

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Abstract

In this paper, we propose a general framework for sensor data fusion applied to control systems. Since many kinds of disturbances are introduced to a control system, it is necessary to rely on multisensor data fusion to improve control performance in spite of the disturbances. Multisensor data fusion for a control system is considered a sequence of making decisions for a combination of sensor data to make a proper control input in uncertain conditions of disturbance effects on sensors.

The proposed method is applied to a typical control system of a flexible link system in which reduction of oscillation is obtained using a photo sensor at the tip of the link. But the control performance depends heavily on the environmental light conditions. To overcome the light disturbance difficulties, an accelerometer is used in addition to the existing photo sensor. Improvement of control performance is possible by utilizing multisensor data fusion for various output responses to show the feasibility of the proposed method in this paper.

Key Words : Multisensor data fusion, control system, a sequence of making decisions, accelerometer

1. Introduction

In simulations of a set of defined variables or in real systems under ideal operating conditions, very satisfying control performance can be obtained using various controller design methods. But for a typical control system, there are usually many kinds of parasitic disturbances other than major measurement variables. Also there is a finite resolution limit for each sensor.

The most urgent problem for a sensor is the fail-safe. Therefore many approaches have been developed to detect faults and isolate them [1, 2]. When some faults occur to sensor components, the measurement values of the sensors cause the malfunction of the plant. A self-validating sensor detects the sensor state from the measurement values, reconstruct a soft sensor and can improve reliability of the sensor.

However, even without malfunction of the sensors, external disturbances deteriorate control performances due to incorrect measurements of sensors. For example, photo sensors produce output signals corresponding to the desired light sources as well as to the unwanted environmental light disturbances.

But it is usually not clear to make a difference between the signals and disturbance for the sensors which have the same characteristics. Hence other types of sensors that have the capability of measuring signals while insensitve to disturbances. This is the basic necessity for sensor data fusion, that is, measuring essential information which is not recognizable in any of the single sensor data [3].

In this paper, we propose a general framework for sensor data fusion applied to control systems. Since many kinds of extraneous disturbance signals are introduced to a control system, it is necessary to provide methods to control and eliminate inaccurate outputs [4]. Modern control theory is now quite well developed to provide genuine design techniques for synthesizing practical control systems. Design of a robust digital controller using a blend of state space and frequency response methods is available easily for the most of target systems. But the success of the sophisticated controller depends heavily on the provision of the accurate measurement data. This is the reason we address the role of multisensor data fusion for control systems.

Data fusion is an effective method to capture and perceive the essential information embedded in the sensor data from a set of raw data which may be noisy, distorted, and partial. It is applied successfully to the areas of diagnostic systems, image processing, machine vision, and remote sensing [6, 7, 8]. As well it can be further applied to the control systems to improve performance in spite of the disturbances. Decision making in control systems corresponds to the implementation of a control law. Thus multisensor data fusion for a control system is considered a sequence of making decisions for a combination of sensor data to make a proper control input in uncertain conditions of disturbance effects on sensors. Sensor data fusion rules based on fuzzy logic are optimized through neural network learning methods to minimize control performance indices.

The proposed method is applied to a typical control system of a flexible link system in which reduction of oscillation is obtained using a photo sensor at the tip of the link. But the control performance depends heavily on the environmental light conditions. To overcome the light disturbance difficulties,

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an accelerometer is used in addition to the existing photo sensors. The experiments on the flexible link system showed the feasibility of the proposed multisensor data fusion method for control systems in terms of control performance improvement in spite of disturbances.

II. Rotary-type Flexible Link System

The flexible link system is a typical control system that has been widely used as a test bed to show the control performance improvement of a proposed algorithm. We apply the proposed multisensor data fusion method to this system. Figure 1 shows the structure of a rotary-type flexible link system(FLS, Quanser Consulting).

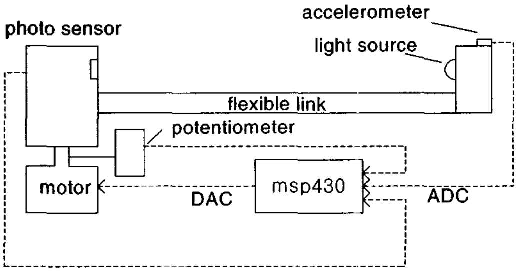


Fig. 1. Schematic illustration of a flexible link system setup.

The purpose of the controller is to design a feedback system which reduces the undamped oscillations of the tip while commanding the tip to a desired position. A light source is attached to the tip of the flexible link which is detected by a photo sensor mounted to the rotating base. System parameters are given as in Table 1.

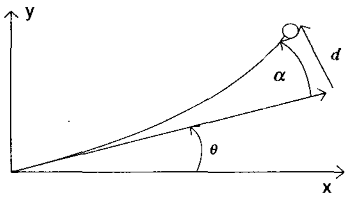


Fig. 2. FLS and its variables.

Table 1. Parameters of the Flexible Link System

Parameters	values
Photo Sensor Module Inertia (includes motor inertia)	0.002Kgm^2
Link Length	0.45m
Link Height	0.02m
Link Thickness	0.0008m
Link Mass	0.06Kg
Link Rigid Body Innertia	0.0042Kgm^2
Bulb Module Mass	0.0535Kg

Dynamic equations are derived using the Euler Lagrange formulation as follows. θ is the servo plant output angle, while α is the relative angle of the flexible link to the plant output. This means α is the measurement of the angular deflection of the arm by a photo-sensor. The total output angle is $\theta+\alpha$. The total inertia at the motor output is given by J_{hub} and the total inertia of the arm is given as J_{load}. The stiffness of the clamped joint is K_{stiff}. The kinetic and potential energies in the system are given by

$$PE_{flex} = \frac{1}{2}K_{stiff}\alpha^2 \tag{1}$$

$$KE_{hub} = \frac{1}{2}J_{hub}\dot{\theta}^2 \tag{2}$$

$$KE_{load} = \frac{1}{2}J_{load}(\dot{\theta}+\dot{\alpha})^2 \tag{3}$$

The total kinetic and potential energies are

$$T = KE_{hub} + KE_{load} \tag{4}$$

$$V = PE_{flex} \tag{5}$$

And the lagrangian is given by

$$L = T - V \tag{6}$$

We can now proceed to develop the equations of motion using the generalized Lagrangian formulation resulting in

$$(J_{hub} + J_{load})\ddot{\theta} + J_{load}\ddot{\alpha} = \tau \tag{7}$$

$$J_{load}\ddot{\theta} + J_{load}\ddot{\alpha} + K_{stiff}\alpha = 0 \tag{8}$$

The torque is generated by a DC motor with the following equations

$$\tau = \frac{K_m K_g}{R}v - \frac{K_m^2 K_g^2}{R}\omega \tag{9}$$

The system model can be derived as follows,

$$\ddot{\theta} = \frac{K_{stiff}}{J_{hub}}\alpha - \frac{K_m^2 K_g^2}{RJ_{hub}}\dot{\theta} + \frac{K_m K_g}{RJ_{hub}}v \tag{10}$$

$$\ddot{\alpha} = -\frac{K_{stiff}(J_{load}+J_{hub})}{J_{load}J_{hub}}\alpha + \frac{K_m^2 K_g^2}{RJ_{hub}}\dot{\theta} - \frac{K_m K_g}{RJ_{hub}}v \tag{11}$$

$$a = L(\ddot{\theta}+\ddot{\alpha}) = -L\frac{K_{stiff}}{J_{load}}\alpha = -\frac{K_{stiff}}{J_{load}}d \tag{12}$$

$$\alpha = \frac{d}{L},\ \theta = \frac{l}{L} \tag{13}$$

$$x = \left|\, \theta \quad d \quad \dot{\theta} \quad \dot{d} \,\right|^T \tag{14}$$

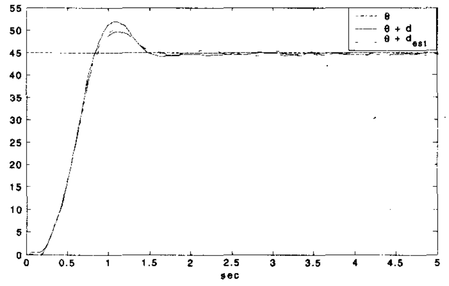
where

$$A=\begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{K_{stiff}}{J_{hub}L} & -\dfrac{K_m^2K_g^2}{RJ_{hub}} & 0 \\ 0 & -\dfrac{K_{stiff}(J_{load}+J_{hub})}{J_{load}J_{hub}} & \dfrac{LK_m^2K_g^2}{RJ_{hub}} & 0 \end{vmatrix}$$

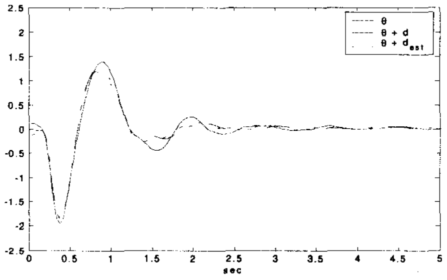
$$B=\begin{vmatrix} 0 & 0 & \dfrac{K_mK_g}{RJ_{hub}} & -\dfrac{LK_mK_g}{RJ_{hub}} \end{vmatrix}^T$$

$$\dot{x}=Ax+Bv \qquad (15)$$

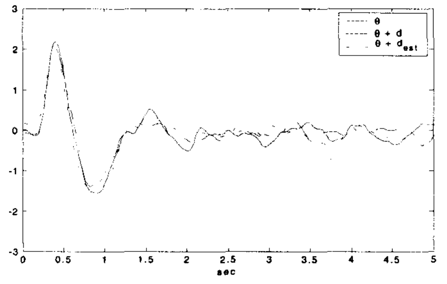
$$y=|\,\theta \quad (\theta+\alpha) \quad d\,|^T \qquad (16)$$



(a) Angle (θ) of motor base



(b) Deflection (d) of the tip



(c) Acceleration of the tip
Fig. 3. Step(45 degrees) responses of FLS.

Fig. 3 shows typical responses of the flexible link system to a step input without interfering disturbance signals. Although the link is very flexible, the settling time is less than 3 sec. with remaining oscillation due to the limitation of sensor resolution. Satisfying responses can be obtained through the compensation of the oscillations by a pair of photo sensors. However, control response deteriorates when disturbance signals or even a slight change of ambient light are applied to the system. In other words, the photo sensor needs enhancement in the ability of discriminating between signals and disturbances in actual noisy situations to maintain satisfying control performance.

III. Sensor Data Fusion

We propose a multisensor data fusion method for the FLS control system to provide enhancement in the ability of discriminating between signals and disturbances in actual noisy situations to maintain satisfying control performance. When the error ($\theta_{ref}-\theta$) is negligible after measuring the link angle θ in steady state, photo sensors are used directly assuming no disturbances are present. Otherwise we can assume that disturbance affects photo sensors to make incorrect outputs. Thus the photo sensor data are replaced by sensor fused data.

Acceleration(a) at the tip of the link is related directly with displacement(d) by equation (12). Since acceleration data are not affected by disturbance light signals at all, displacement data by a pair of photo sensors are fused with acceleration and link angle data when it is determined that the error ($\theta_{ref}-\theta$) is not negligible in steady state.

Fuzzy logic to estimate deflection

We apply TSK method of fuzzy inference to produce a sensor data fusion for photo sensors. We use ($\theta_{ref}-\theta$), $-\frac{d\theta}{dt}$, α, $\frac{d\alpha}{dt}$ for input variables, and d as an output variable. As a training routine for Sugeno-type fuzzy inference, ANFISEDIT of Matlab is used for optimization.

i-th fuzzy rule R^i is given by

R^i : IF $x_1(t)$ is M_1^i and ... and $x_k(t)$ is M_k^i , Then z is c^i

$X_k(t)$: premise variables,
M_i^k : fuzzy sets, i = 1, ..,. 2, I, k = 1, 2, ..., K
I : Number of fuzzy rules,
K : number of fuzzy inputs,
c^i: singleton value of fuzzy output

Acceleration data were obtained using MEMS-type acceleration sensor chip by MEMSIC. The module was implemented at the tip of the flexible link.

Fuzzy output is given by

$$z=\frac{\sum_{i=1}^{I}\prod_{k=1}^{K}M_k^i(x_i(t))c^i}{\sum_{i=1}^{I}\prod_{k=1}^{K}M_k^i(x_i(t))} \qquad (17)$$

Three triangular membership functions are used for each input variable of base angle error, rate of base angle, acceleration, and acceleration rate, and the trained results are shown in Fig. 4.

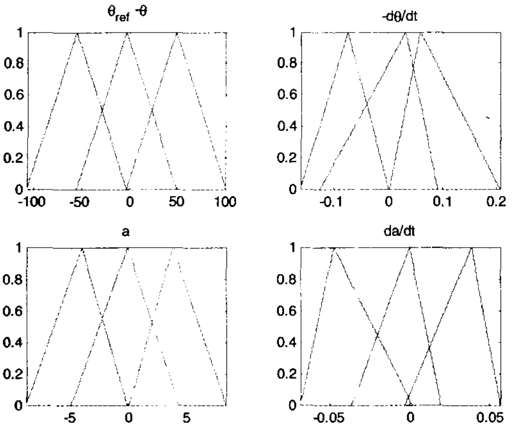


Fig. 4. Results of four input variables.

Training data

For a set of input data of $(\theta_{ref}-\theta)$, $-\frac{d\theta}{dt}$, α, and $\frac{da}{dt}$, we use LQR controller with

q = diag([800 14500 1 0]),
r = 10

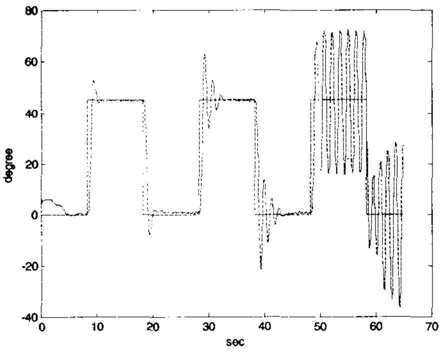
for step input of 45 degrees. The feedback gains are

k1 = 0.1562, k2 = −0.1783, k3 = 0.0190, k4 = 0.0194

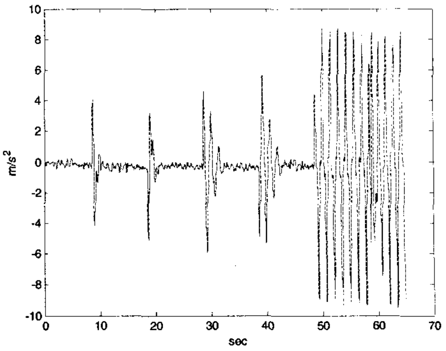
The first gain k1 is changed to 0.2730 and 0.4057 to obtain different sets of input training data. Fig. 5 shows corresponding three sets of input data.

Trained results

For three sets of previous input data, we obtain trained fuzzy variables of Fig.4 through the routine of ANFISEDIT of Matlab to produce output variable of displacement d in Figure 6. The routine is by a backpropagation gradient descent method to minimize MSE of estimated output data to reference deflection data when there are no disturbance signals.



(a) Three sets of reference input of 45 degrees and their output responses.



(b) Acceleration of the tip

Fig. 5. Three sets of input training data.

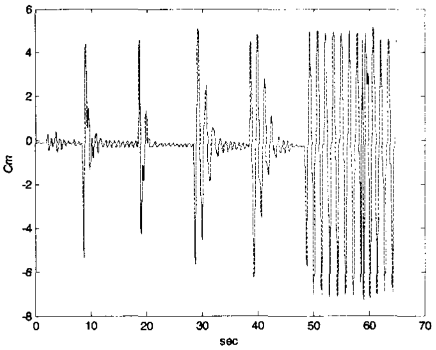
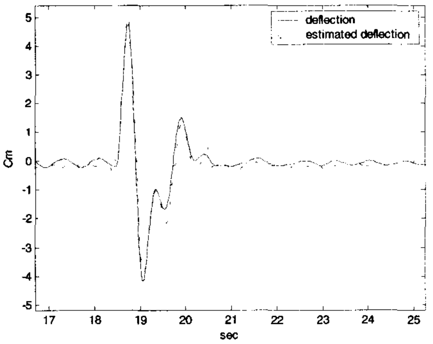
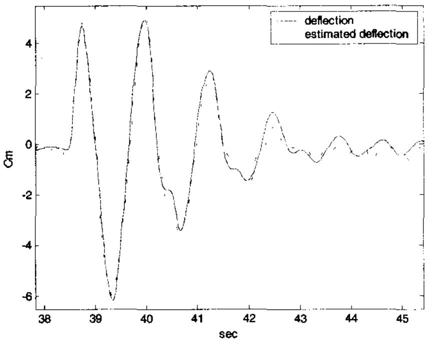


Fig. 6. Trained data of displacement of the tip.

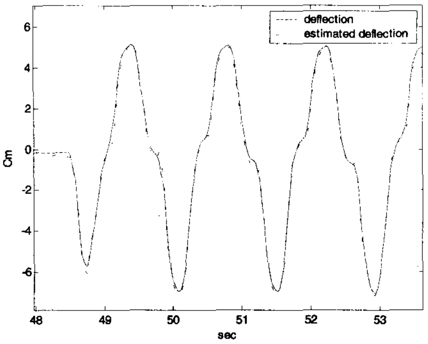
In typical movements of the flexible link, Fig. 7 shows sensor data fusion of displacement d through sensor data of θ by a potentiometer and α by an accelerometer chip without using photo sensors.



(a) Comparison of data fusion for deflection.



(b) Comparison of data fusion for deflection.



(c) Comparison of data fusion for deflection.

Fig. 7. Typical movements of FLS by data fusion for deflection.

IV. Experiments

4.1 Experiments on a Flexible Link System

The proposed multisensor data fusion is applied to a typical control system of a flexible link system (Fig. 1, Fig. 8) in which reduction of oscillation is obtained using a photo sensor at the tip of the link. The system is a modular control system by Quanser Consulting, Inc. But signal processing for data fusion and control action are provided by MSP430F149 based controller (Fig. 9).

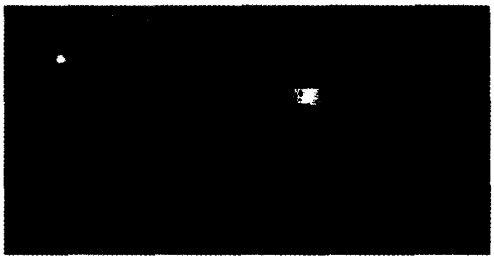


Fig. 8. Flexible Link System

Since the control performance of FLS depends heavily on the environmental light conditions, sensor data fusion becomes necessary and it replaces photo sensors when ambient light disturbance interferes control performance.

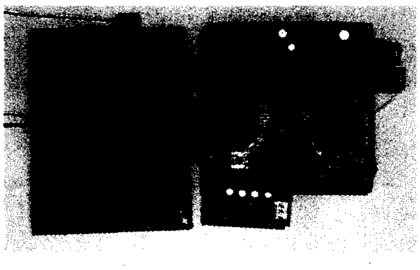


Fig. 9. MSP430F149 based FLS controller.

To overcome the light disturbance problems, an accelerometer, which is not affected by light at all, by MEMSIC, Inc. is used in addition to the existing photo sensors. External circuit to MXR2999U is shown in Fig. 10 and the accelerometer mounted at the top of a light bulb module is shown in Fig. 11.

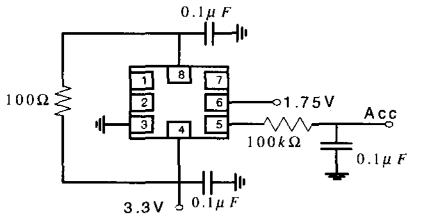


Fig. 10. MXR2999U based accelerometer circuit.

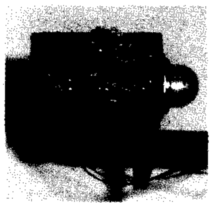
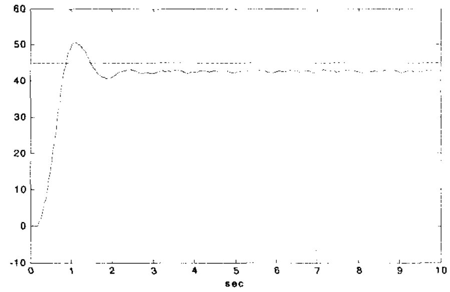
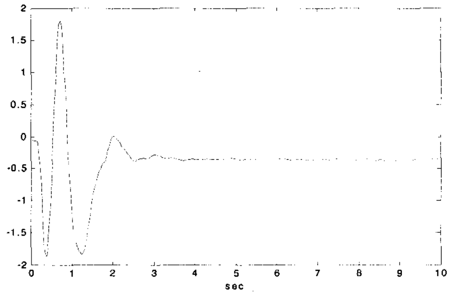


Fig. 11. MXR2999U based accelerometer at the tip of FLS.

For a typical control output response to a step input of 45 degrees, Fig. 12 shows a set of responses with a disturbing light source. There appear intolerable errors in the base angle and deflection as well for the same controller of a reference case of no disturbance (Fig. 3). However, Fig. 13 shows the same set of responses which show no interfering errors in angles even with the same disturbing light source when sensor data fusion is applied. The fusion is made by a potentiometer for the base angle and accelerometer MXR2999U chip without using photo sensors for the displacement data.

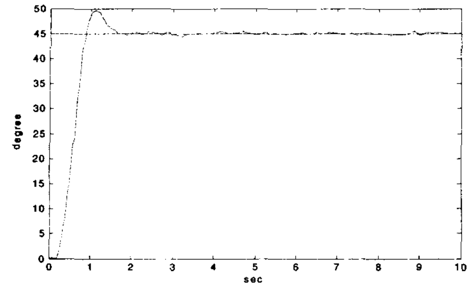


(a) Angle (θ) error with disturbance

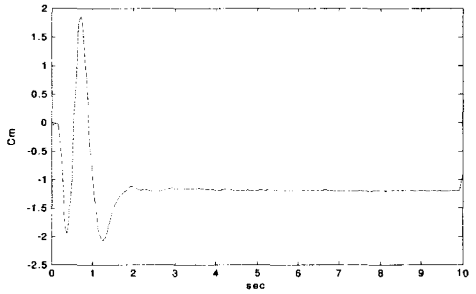


(b) Deflection(d) error of the tip with disturbance

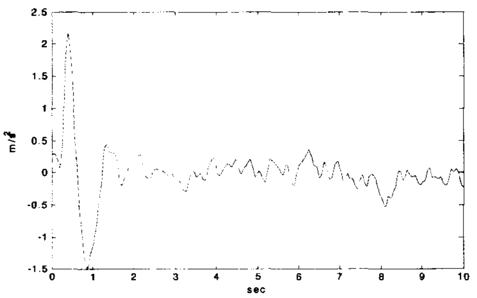
Fig. 12. Step(45 degrees) responses of FLS with a disturbance light.



(a) Angle (θ) of motor base: error is deleted by sensor data fusion



(b) Deflection(d) by photo sensors



(c) Acceleration of the tip

Fig. 13. Step(45 degrees) responses of FLS with data fusion for a disturbance light.

V. Conclusion

We propose a multisensor data fusion method for the FLS control system to provide enhancement in the ability of discriminating between signals and disturbances in actual noisy situations to maintain satisfying control performance. Since acceleration data are not affected by disturbance light signals at all, displacement data by a pair of photo sensors are replaced with the fusion of acceleration and link angle data when it is determined that the error is not negligible in steady state. Acceleration data were obtained using MEMS-type acceleration sensor chip by MEMSIC. The module was implemented at the tip of the flexible link.

The data fusion routine is made by a backpropagation gradient descent method to minimize MSE of estimated output data to reference deflection data when there are no disturbance signals.

The experimental results on the flexible link system showed the feasibility of the proposed multisensor data fusion method for control systems in terms of control performance improvement in spite of disturbances.

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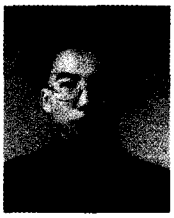

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