Proceedings of the American Control Conference
Arlington, VA June 25-27, 2001

Asynchronous measurement and control: motor synchronization for mailing systems

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1 Introduction

In industrial manufacturing systems one often encounters situations in which the position of several electrical motors (slaves) should follow the position of a master motor. Examples are product handling machines and multi-conveyor-belt-systems. Traditionally, this kind of synchronization is achieved with a single mechanical axis that drives all modules. Nowadays, these mechanical axes are replaced by 'electrical axes' to obtain more flexibility, in the sense that modules can easily be added or removed ('plug and play concept'). In case of an electrical axis, a small motor is connected to each tool separately. Automatic control, based on shared signals, is used to synchronize the tools.

A specific example is provided by the company Buhrs-Zaandam B.V. in The Netherlands, which builds mailing systems that automatically compose mailings consisting of several brochures. A mailing system is depicted in Figure 1. The main component of the mailing (e.g. a book or a magazine) enters the conveyor belt (lug chain) at the loader module ((1) in Figure 1). Several supplements are added to the main product by a feeder module consisting of sheet-feeders (2). Sheet-feeders basically grab a brochure from a stack and put it on the conveyor belt (the master in this case). The main product, together with the supplements, form a package that is wrapped in plastic foil by a packaging module (3). The foil is being supplied by a reel stand (4). Incorrect packages are removed at the rejection module (5). Finally, the product is released after which an address is printed on it, using a label or directly, via an inkjet printer (6). After this the product is put on a stack (7). For such a mailing system it is clear that synchronization is required between one master (the conveyor belt) and many slaves.

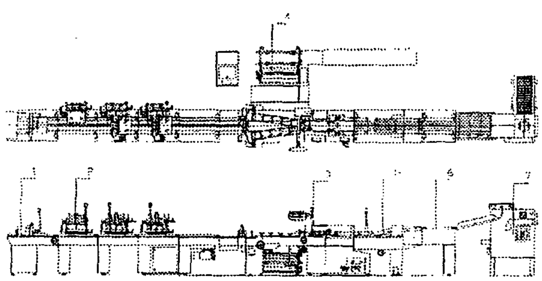

Figure 1: Mailing system.

In general the angular position of a motor driving one of the modules is measured by an encoder, which only gives pulses at fixed positions of the motor axis. Hence, the times at which information about the motor axis position becomes available are not equally spaced in time. Encoders usually have a high resolution, typically 1000 to 5000 individual measured positions (pulses) per revolution of the motor axis. In practice, high resolution encoders are read out after fixed time intervals and the discrete-event character of the encoder is neglected.

To reduce the total costs of a mailing system, Buhrs-Zaandam would like to replace the expensive high resolution encoders of the slaves with cheap low resolution encoders (with 1 to 8 measurements per revolution) and use simple control structures (e.g. PID like) without losing the tight synchronization between the conveyor belt and the sheet-feeders. With these low resolutions it is no longer possible to neglect the discrete-event character of the sensors.

In the motor/encoder combination, measurements are not available at fixed time instants, but at fixed "positions." Other examples of asynchronous sensors include level sensors for measuring the height of a fluid in a tank, (magnetic/optic) disk drives with similar measurement devices and transportation systems where the longitudinal position is only known when certain markers are passed. Such combinations of discrete-event sensors (with a countable number of outputs) and continuous dynamics can be considered to fall in the realm of hybrid dynamical systems.

2 Problem formulation

The slave motor and the mechanical system corresponding to the sheet-feeder are described by a simple model (Leonhard, (1984)) given by

$$\dot{\theta}_s(t) = \omega_s(t) \quad (1a)$$

$$\dot{\omega}_s(t) = \frac{1}{J}[T(t) - B\omega_s(t) - d(t)] \quad (1b)$$

$$\dot{T}(t) = \frac{1}{\tau}[-K_t\omega_s(t) - T(t) + K_tK_f u(t)], \quad (1c)$$

where θ_s $[rad]$ is the position of the slave motor axis, ω_s $[rad/s]$ the speed of the motor axis, T $[Nm]$ the torque generated by the motor, u $[V]$ is the voltage applied to the frequency converter (control input) and d $[Nm]$ the torque disturbance generated by the sheet-feeder. The slave encoder measures θ_s $[rad]$ with N pulses per revolution of the motor axis. Hence, θ_s is exactly measured only on times t satisfying

$$\theta_s(t) \in \{k\delta_s \mid k \in \mathbb{Z}\}, \quad (2)$$

where $\delta_s := \frac{2\pi}{N}$ $[rad]$. The position of the master θ_m will be measured by a high resolution encoder and is considered to be known exactly for explanatory reasons.

The controller must keep the error between master and slave *load* axis between -0.1 $[rad]$ and 0.1 $[rad]$. Incorporating the gear ratios gives a maximal allowed error between the position of the *motor* axes of slave and master, θ_s and θ_m, respectively, of 1.25 $[rad]$:

$$\max_{t\geq 0} \mid \underbrace{\theta_m(t) - \theta_s(t)}_{e_\theta(t)} \mid \leq 1.25\ [rad] \quad (3)$$

irrespective of disturbances and actuator limitations.

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0-7803-6495-3/01/$10.00 © 2001 AACC

One approach to the problem that incorporates the discrete-event character is described in Philips and Tomizuka (1995). In that paper a discrete-time controller with a fixed control rate is designed based on a state observer with asynchronous updates. The state observer is based on a time-varying Luenberger observer and uses a model to estimate the state of the system between two measurements. This calls for fast processors, since on-line calculation of matrix exponentials and time varying Luenberger gains is required at every new measurement. Similar approaches can be based on Kalman filtering techniques using time-varying linear models (see e.g. Friedland (1996)). Both approaches lead to too complicated structures for the company Buhrs.

3 Asynchronous measurement and control

Feedforward control of the signal coming from the frequency converter of the master is applied to the slave frequency converter. In the ideal case when both motors are identical and driving the same load, and moreover, disturbance are absent, no additional control action is necessary to keep the motors running synchronously. In the non-ideal case, θ_s will not be equal to θ_m and a feedback controller is needed to keep the position error bounded as in (3).

3.1 Asynchronous measurement

The feedback can only use the measured slave position, denoted by $\theta_{s,mea}$, and the master position θ_m. Note that $\theta_{s,mea}$ is piecewise constant with discontinuities at the time instances that new measurements become available. The difference between the true position θ_s and the measured $\theta_{s,mea}$ can increase up to $\delta_s = \frac{2\pi}{N}$ $[rad]$. However, at the times that the slave measurement becomes available, the position error $e_\theta(t) = \theta_m(t) - \theta_s(t)$ can be determined exactly, since the slave position is exactly known as well ($\theta_{s,mea}(t) = \theta_s(t)$). These times are collected in the set $\mathcal{D}$. As the slave position measurements are not distributed equally in time, we call this 'asynchronous measurement.'

3.2 Synchronous feedback controller

The controller output is updated at a fixed rate of 2 $[kHz]$, but acts on the asynchronously updated error signal $\theta_m - \theta_{s,mea}$, which is kept constant between two subsequent times in $\mathcal{D}$. Hence, a kind of zero-order hold is used that is updated only at the slave measurement instances. This means that the input of the controller at time t, is equal to

$$e_{\theta,hyb}(t) := e_\theta(t') \text{ with } t' = \max\{\tau \in \mathcal{D} \mid \tau \leq t\}. \quad (4)$$

By using standard techniques a suitably tuned PI controller has been obtained, which resulted in a successful implementation on the experimental set-up (i.e. satisfying (3)).

3.3 Asynchronous feedback controller

In the "asynchronous" scheme both the position error estimate and the control signal will be updated at slave measurement times only (i.e. when $t \in \mathcal{D}$). Although the measurements and control updates are asynchronous in time, they are equally spaced as a function of the motor position, because the notches (levels) of the encoder have an equidistant distribution along the axis of the slave. For design purposes the idea is to transform the model description (1) with independent variable time into an equivalent model in which the slave motor position is the independent variable and the measurements are equidistant.

The transformation from the time domain (t) to the (slave) position domain (θ_s) can be made by reversing the first relation in (1), which gives

$$\frac{dt}{d\theta}(\theta) = \frac{1}{\omega_s(\theta)}. \quad (5)$$

under the condition $\omega_s(t) \neq 0$. This condition is not a severe practical constraint as the conveyor belt is running in one direction only. The variable θ_s is no longer considered as a function of time t, but time t as a function of the angular position θ_s. The notation $t(\theta)$ then denotes the time at which the slave reaches position θ and $\omega_s(\theta)$ is the angular velocity of the slave motor when the axis is at position θ. Using (5), the system description (1) can be rewritten as:

$$\frac{dt}{d\theta}(\theta) = \frac{1}{\omega_s(\theta)} \quad (6a)$$

$$\frac{d\omega_s}{d\theta}(\theta) = \frac{1}{J}[\frac{T(\theta)}{\omega_s(\theta)} - \frac{d(\theta)}{\omega_s(\theta)} - B] \quad (6b)$$

$$\frac{dT}{d\theta}(\theta) = \frac{1}{\tau}[K_t K_f \frac{u(\theta)}{\omega_s(\theta)} - \frac{T(\theta)}{\omega_s(\theta)} - K_t], \quad (6c)$$

where $T(\theta)$, $d(\theta)$, $u(\theta)$ denote the torque generated by the slave motor, the disturbance torque and the control value, respectively, when the slave position is equal to θ. Moreover, the output of the new representation will be the time $t(\theta)$, i.e. $y(\theta) = t(\theta)$. Note that the output is only available when θ is equal to an integer-multiple of δ_s and hence, synchronous in the new independent variable. Hence, we transformed the *linear* system (1) with *asynchronous* measurements into the *nonlinear* system (6) with *synchronous* measurements.

The PI-feedback is now designed by using classical gain-scheduling techniques based on discretized and linearized versions of (6) with sample time δ_s. This results in a gain-scheduled controller depending on the reference velocity w_r in the working point. By transforming the controller from the position domain back to the time domain the w_r-dependence drops out, which results in updates of the control value u at times $t_j \in \mathcal{D}$ according to

$$u(t_j) = u(t_{j-1}) + 0.18e_\theta(t_j) - 0.16e_\theta(t_{j-1}). \quad (7)$$

Note that the controller updates are given by an *asynchronous* PI-controller. Hence, the only difference with the implementation of a normal PI-controller is that a standard PI-implementation is timer driven (fixed rate), while the implementation of (7) is event (pulse detected) driven. This control regime satisfied the specifications (3) for the experimental set-up.

4 Conclusions

The design of controllers for the synchronization of a master and slave motor in a mailing system has been studied. To reduce the manufacturing costs of a mailing system, the resolution of the encoder should be low and the resulting control structure simple. Two approaches to the corresponding hybrid control problem consisting of a continuous-time plant and a discrete-event sensor have been discussed. Both methods have been tested successfully on an experimental set-up consisting of a master motor and a sheet-feeder with only 1 measurement pulse per revolution of the slave motor axis. The reader is referred to Heemels *et al.* (1999) for more details on the techniques and the experiments.

References

Friedland, B. (1996). *Advanced control system design*. Prentice-Hall, Englewood Cliffs, New Jersey (USA).

Heemels, W.P.M.H., R.J.A. Gorter, A. van Zijl, P.P.J. van den Bosch, S. Weiland, W.H.A. Hendrix and M.R. Vonder (1999). Asynchronous measurement and control: a case study on motor synchronization. *Control Engineering Practice*, Vol. 7, pp. 1467-1482.

Leonhard, W.(1984). *Control of electrical drives*. Springer Verlag Berlin, Heidelberg pp. 204-237.

Phillips, A.M. and M. Tomizuka (1995). Multirate estimation and control under time-varying data sampling with applications to information storage devices. *Proceedings ACC 1995*, Vol. 6, pp. 4151-4155, Evanston, Illinois.