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Model-Based Control of Continuous-Time Systems with Limited Intermittent Feedback.

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Abstract—**This paper presents a practical alternative for the implementation of Model-Based Networked Control Systems (MB-NCS) with intermittent feedback. Our approach does not require continuous communication over a limited bandwidth channel during the closed-loop time intervals; instead, we propose a communication format that implements a fast rate for updating the state of the model. During the closed-loop interval the sensor transmits measurements at a fast rate but without assuming continuous communication. We consider uncertain continuous-time systems and study the state feedback and output feedback cases. For both cases, we provide necessary and sufficient conditions for stability as a function of the update periods.**

I. INTRODUCTION

MODERN control applications make use of different communication channels with limited access to interconnect elements in a control system instead of traditional point-to-point connections that can transmit signals continuously. Challenges concerning the use of common-bus communication media are well documented in the literature [1]-[3]. Reduction of network bandwidth has been an important research topic. This problem relates to the feedback information needed in order to stabilize a control system while using network resources efficiently. Different approaches include minimum bit rate stabilization [4]-[5], packet-based control [6]-[7], and model-based control [8]-[15].

Estrada and Antsaklis [16]-[18] presented a model-based approach for stabilization using intermittent feedback. This work combined the Model-Based Networked Control Systems (MB-NCS) framework and the intermittent feedback notion resulting in a Networked Control System (NCS) that operates using two modes: open-loop and closed-loop modes. The open-loop mode provides reduction on the number of measurements transmitted from the sensor node to the controller node while the closed-loop mode requires continuous feedback in order to improve the control action and the performance of the system that is typically degraded during the previous open-loop time interval due to lack of feedback measurements. The results presented in those references provided stabilizing conditions that depend on the appropriate selections of the open-loop and the closed-loop time intervals. Continuous-time and discrete-time systems were considered.

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The stability conditions in [16]-[18] require that continuous feedback measurements are transmitted during the closed-loop intervals. These measurements are transmitted over a limited bandwidth communication network. While this assumption may not be a strong condition when dealing with discrete-time systems, it is clearly not possible to transmit a continuous-time signal over a digital network for a finite period of time. Therefore, in this paper, we relax the closed-loop assumption for continuous-time systems and we propose a practical implementation of MB-NCS with intermittent feedback relaxing the constraint that during the closed-loop mode the sensor needs to transmit its current measurements continuously over a digital channel.

In this paper we consider continuous-time linear time-invariant systems with model uncertainties. We use the MB-NCS framework introduced in [8]-[9]. Lehmann and Lunze [10]-[12] also consider the same approach than [8]-[9], the main difference is that in the work presented in [10]-[12] it is assumed that the model and system are represented by exactly the same parameters, no model uncertainty is considered, and the system is perturbed by an unknown external disturbance while the model operates without the perturbation. The authors of [13] also use the model-based approach in human learning and human operations. Analysis and simulations are presented in the presence of measurement noise.

The remainder of the paper is organized as follows: Section II describes the MB-NCS framework. Section III considers intermittent feedback in the form of slow and fast update rates. Stability conditions are given for the state feedback case. Section IV extends the approach to the output feedback case. Section V provides examples and Section VI concludes the paper.

II. MODEL-BASED FRAMEWORK

MB-NCS were introduced in [8]-[9]; this configuration makes use of an explicit model of the plant which is added to the actuator/controller node to compute the control input based on the state of the model rather than on the plant state. In [8]-[9] the state of the model is updated when the controller receives the measured state of the plant that is sent from the sensor node every h time units. Fig. 1 shows the interconnection of several NCSs. The labeled small blocks correspond to each system’s actuator and sensor nodes. The actuator/controller node in MB-NCS can be represented as in Fig. 2. We assume that the systems are decoupled, i.e. the dynamics of each system in Fig. 1 depend only on its own state. Without loss of generality we will focus on a particular system/model pair. The dynamics of the plant and the model can be described respectively by:

$$\dot{x} = Ax + Bu \tag{1}$$

$$\dot{\hat{x}} = \hat{A}\hat{x} + \hat{B}u \tag{2}$$

where $x, \hat{x} \in \mathbb{R}^n$ and the matrices $\hat{A}, \hat{B}$ represent the available model of the system matrices *A,B*. The control input is given by:

$$u = K\hat{x}\,. \tag{3}$$

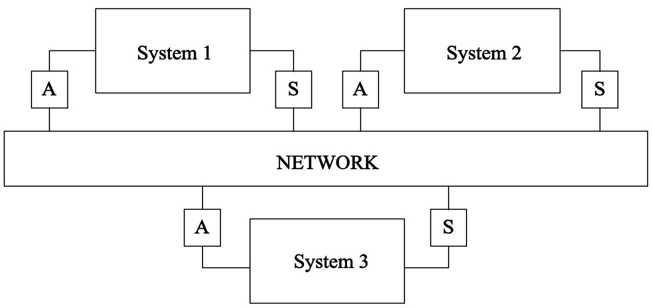

Fig. 1. Networked Control Systems.

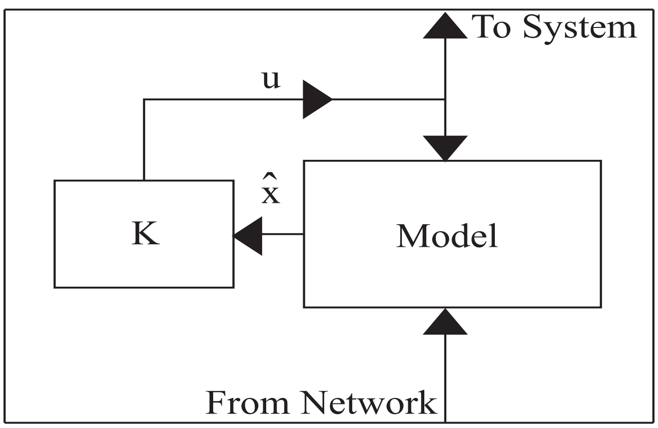

Fig. 2. Model-Based Networked Control System actuator/controller node.

The plant may be unstable i.e. not all eigenvalues of A have negative real parts. The aim using this configuration is to operate in open-loop mode for as long as possible and using the estimated state provided by the model to generate the control input u. The work presented in [16]-[18] considered the use of intermittent feedback. In this case the networked system operates using two modes: open-loop and closed-loop modes. During the open-loop period no measurement updates are sent from the sensor to the controller. During the closed-loop period it is assumed that the controller receives continuous measurements from the sensor.

The main contribution in this paper is to relax the assumption that during the closed-loop mode of operation it is possible to obtain continuous measurements of the state. In this paper we propose a more practical implementation of intermittent feedback over networks and using the model-based approach. In the present paper we do not assume continuous communication over a network for finite periods of time; instead, we consider a fast update rate during the closed-loop period and we provide conditions for stability for two cases: the state feedback and the output feedback cases.

III. State Feedback Control with Intermittent Feedback

When considering continuous time systems we are not really capable of implementing a closed-loop mode of operation since it requires continuous feedback from the sensor to the controller using a limited-bandwidth network as a communication medium.

A more realistic way of implementing intermittent feedback for continuous time systems is to consider fast and slow update rates. During the closed-loop time interval the sensor sends measurements at discrete points of time in a periodic fashion and during the open-loop mode the sensor never attempts to establish communication.

Open-loop. No measurements are received.

Closed-loop. Updates are received at a high rate but no continuous feedback is assumed.

There are several parameters that are used for the analysis of this type of intermittent feedback MB-NCS.

h: represents the duration of the entire cycle.

τ: represents the interval of time when the controller is receiving updates at higher frequency, this interval corresponds to the closed-loop duration of the cycle.

f: is the time interval between successive fast updates.

$\tau_f = \dfrac{\tau}{f}$: represents the number of fast updates during the closed-loop duration of the cycle and it is assumed to be an integer.

Fig. 3 presents a general illustration of the time-related parameters (h, τ, f) described above. The dark arrows represent the update instants.

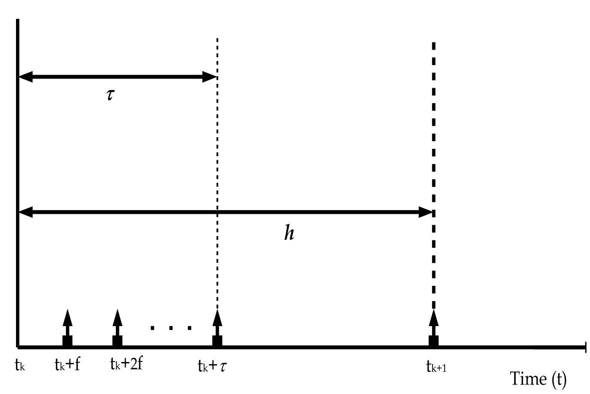

Fig. 3. Representation of parameters involved in the model based approach with intermittent feedback.

Consider the plant, model, and control input (1)-(3). Define the state error

$$e = x - \hat{x} \tag{4}$$

and the error matrices $\tilde{A} = A - \hat{A}$, $\tilde{B} = B - \hat{B}$.

The response of the MB-NCS with fast and slow update rates is given in the following proposition.

Proposition 1. *The system described by (1)-(2) and input (3) with initial conditions* $z(t_0) = \begin{bmatrix} x(t_0) \\ e(t_0) \end{bmatrix} = z_0$, *has the following response:*

$$z(t_k) = \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k z_0 \tag{5}$$

where $\Lambda = \begin{bmatrix} A+BK & -BK \\ \tilde{A}+\tilde{B}K & \hat{A}-\tilde{B}K \end{bmatrix}$, $z(t) = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$, *and* $h = t_{k+1} - t_k$.

Proof. Between any two updates of the state of the model we have that the dynamics of the system and model can be represented by

$$\begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \end{bmatrix} = \begin{bmatrix} A & BK \\ 0 & \hat{A}+\hat{B}K \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \end{bmatrix}. \tag{6}$$

Rewriting in terms of *x* and *e*, that is, of the vector *z*, we have the following:

$$\dot{z}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A+BK & -BK \\ \tilde{A}+\tilde{B}K & \hat{A}-\tilde{B}K \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}. \tag{7}$$

When any of the update measurements are received at the controller node the following update takes place

$$\hat{x}(t_k + if) = x(t_k + if) \tag{8}$$

for i=0,... τ_f. This means that the error part of the augmented state vector resets to zero:

$$z(t_k + if) = \begin{bmatrix} x(t_k + if) \\ e(t_k + if) \end{bmatrix} = \begin{bmatrix} x(t_k^- + if) \\ 0 \end{bmatrix}. \tag{9}$$

We consider the major update times t_k, k=0,1,... They represent the beginning of a new cycle, that is, they represent the first time instant that updates are received after an open-loop period, see Fig. 3. Let $z(t_k)$ represent, in general, the augmented state after the first update takes place. The time t_0 is not necessarily equal to zero, that is, we do not require the system to start in the closed-loop interval but at any time of the cycle. It follows that:

$$z(t) = e^{\Lambda(t-t_k)} z(t_k), \quad t \in [t_k, t_k + f). \tag{10}$$

Equation (10) corresponds to the behaviour between updates in which the model state is used to compute the control input and the system follows the dynamics (7).

In particular, at time $t_k + f$ we have $z(t_k + f) = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} z(t_k)$ because of the second update. The response of the augmented system during the following period can be expressed in a similar way.

$$z(t) = e^{\Lambda(t-(t_k+f))} z(t_k + f), \quad t \in [t_k + f, t_k + 2f). \tag{11}$$

At time $t_k + 2f$ we obtain $z(t_k + 2f) = \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^2 z(t_k)$. The response of the system at every update is of similar form including the last update of the cycle which takes place at time $t_k + \tau$ and it is given by (in terms of $z(t_k)$):

$$z(t_k + \tau) = \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{\tau_f} z(t_k). \tag{12}$$

The second part of the cycle corresponds to the open loop mode when no update is transmitted for the time interval $t \in [t_k + \tau, t_{k+1})$; the response of the augmented system can be represented by:

$$z(t) = e^{\Lambda(t-(t_k+\tau))} z(t_k + \tau), \; t \in [t_k + \tau, t_{k+1}). \tag{13}$$

At time t_{k+1} we begin a new cycle and the first update of that cycle takes place at that same instant. The response of the system, including the first update, in terms of $z(t_k)$ can be written as follows:

$$z(t_{k+1}) = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{\tau_f} z(t_k). \tag{14}$$

Due to the periodicity of the open loop and closed loop as defined in this section and the periodic fast updates during the closed loop periods, the response of the augmented system to initial conditions $z(t_0) = \begin{bmatrix} x(t_0) \\ e(t_0) \end{bmatrix} = z_0$ is given by:

$$z(t_k) = \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k z_0.$$

The last expression provides the state of the system at time instants t_k, k=0,1,... The response at any time $t \in (t_k, t_{k+1})$ can be obtained simply by pre-multiplying the corresponding partial response. ■

A necessary and sufficient condition for stability of the networked system with fast-slow update rates is presented in the following theorem.

Theorem 2. *The system described by (1)-(2) with input (3) and with fast-slow intermittent update rates is globally exponentially stable around the solution* $z = \begin{bmatrix} x \\ e \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$ *if and only if the eigenvalues of*

$$\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \tag{15}$$

are within the unit circle of the complex plane.

Proof. Sufficiency. Taking the norm of the solution described as in Proposition 1 we have the following:

$$\begin{aligned} \|z(t_k)\| &= \left\| \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k z_0 \right\| \\ &\le \left\| \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k \right\| \cdot \|z_0\|. \end{aligned} \tag{16}$$

Now let's analyze the first term on the right hand side of (16). It is clear that this term will be bounded if and only if the eigenvalues of $\left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)$ lie inside the unit circle:

$$\left\| \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k \right\| \le K_1 e^{-\alpha_1 k} \tag{17}$$

with $K_1, \alpha_1 > 0$.

Since k is a function of time we can bound the right term of (17) in terms of t:

$$K_1 e^{-\alpha_1 k} < K_1 e^{-\alpha_1 \frac{t-1}{h}} = K_1 e^{\frac{\alpha_1}{h}} e^{-\frac{\alpha_1}{h} t} = K_2 e^{-\alpha t} \tag{18}$$

with $K_2, \alpha > 0$.

We can conclude from (16) and using (18) that:

$$\begin{aligned} \|z(t)\| &= \left\| \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)^k z_0 \right\| \\ &\le K_2 e^{-\alpha t} \cdot \|z_0\|. \end{aligned} \tag{19}$$

Necessity. We will now proof the necessity part of the theorem by contradiction. Assume the system is stable and that $M = \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda(h-\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{f\Lambda} \right)^{t_f} \right)$ has at least one eigenvalue outside the unit circle. Since the system is stable, a periodic sample of the response should be stable as well. In other words the sequence product of a periodic sample of the response should converge to zero with time. We will take the sample at times t_k. We can express the solution t_k as:

$$z(t_k) = M^k z_0 . \tag{20}$$

We also know that M has at least one eigenvalue outside the unit circle. This means that $z(t_k)$ will in general grow with k. In other words we cannot ensure $z(t_k)$ will converge to zero for general initial condition z_0.

$$\|z(t_k)\| \to \infty \qquad \text{as} \qquad k \to \infty \tag{21}$$

this clearly means the system cannot be stable, and thus we have a contradiction. ■

IV. Output Feedback Control with Intermittent Feedback

In this section we extend the approach discussed in the previous section to consider the case when only output measurements can be obtained but not the whole state vector. We consider systems of the form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du. \end{aligned} \tag{22}$$

The nominal model corresponding to system (22) is given by:

$$\begin{aligned} \dot{\hat{x}} &= \hat{A}\hat{x} + \hat{B}u \\ y &= \hat{C}\hat{x} + \hat{D}u. \end{aligned} \tag{23}$$

The approach we follow in this section is to implement a state observer at the sensor node. The observer is given by:

$$\dot{\bar{x}} = (\hat{A} - L\hat{C})\bar{x} + \begin{bmatrix} \hat{B} - L\hat{D} & L \end{bmatrix} \begin{bmatrix} u \\ y \end{bmatrix}. \tag{24}$$

The parameters used by the observer are the available model parameters and it is assumed that the observer has continuous access to the output of the system since it is implemented at the sensor node. In order for the observer to obtain access to the system's input, a copy of the model is also implemented at the sensor node and the state of that model is updated at the same updated instants as the model in the controller node.

The state of the model is now updated using the observer state. Define the observer-model state error

$$\bar{e} = \bar{x} - \hat{x} \tag{25}$$

and the error matrices $\tilde{A} = A - \hat{A}$, $\tilde{B} = B - \hat{B}$, $\tilde{C} = C - \hat{C}$, $\tilde{D} = D - \hat{D}$.

Proposition 3. *The system described by (22)-(24) and input (3) with initial conditions* $z(t_0) = \begin{bmatrix} x(t_0) \\ \bar{x}(t_0) \\ \bar{e}(t_0) \end{bmatrix} = z_0$, $t_0 = 0$, *has the following response:*

$$z(t_k) = \left(\begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{\Lambda_o(h-\tau)} \left(\begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{f\Lambda_o} \right)^{t_f} \right)^k z_0 \tag{26}$$

where $\Lambda_o = \begin{bmatrix} A & BK & -BK \\ LC & \hat{A}-L\hat{C}+\hat{B}K+L\tilde{D}K & -\hat{B}K-L\tilde{D}K \\ LC & L\tilde{D}K-L\hat{C} & \hat{A}-L\tilde{D}K \end{bmatrix}$ $z(t) = \begin{bmatrix} x(t) \\ \overline{x}(t) \\ \overline{e}(t) \end{bmatrix}$

and $h = t_{k+1} - t_k$. ■

Theorem 4. *The system described by (22)-(24) with input (3) and with fast-slow intermittent update rates is globally exponentially stable around the solution* $z = \begin{bmatrix} x \\ \overline{x} \\ \overline{e} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ *if and only if the eigenvalues of*

$$\begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{\Lambda_o(h-\tau)} \left(\begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & 0 \end{bmatrix} e^{f\Lambda_o} \right)^{t_f} \tag{27}$$

are within the unit circle of the complex plane. ■

V. Example

Example 1. Consider the following open-loop unstable continuous-time system:

$$A = \begin{bmatrix} -0.76 & 2.23 \\ 1.87 & -2.56 \end{bmatrix}, B = \begin{bmatrix} 1.14 \\ 0 \end{bmatrix}. \tag{28}$$

The nominal model dynamics are given by:

$$\hat{A} = \begin{bmatrix} 1 & 2 \\ 2 & -3 \end{bmatrix}, \hat{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{29}$$

The control gain is obtained based on the available model parameters:

$$K = \begin{bmatrix} -5.4621 & -11.1658 \end{bmatrix}. \tag{30}$$

Suppose that the closed loop time τ, when updates are received at a faster rate, and the update period f are given

$$\tau = 0.4\,\text{sec}$$
$$f = 0.1\,\text{sec}.$$

We want to find the range of values for h that result in stability. Fig. 4 shows the eigenvalue of matrix (15) with maximum magnitude for different values of $h \geq \tau$. The plot shows that stability is obtained for choices of h greater than 0.4 seconds to about 1.83 seconds.

The response of the system for different choices of h is presented in Fig. 5 – Fig. 7. In Fig. 5, h=1 second was chosen and the system is stable as expected. In Fig. 6 the selected period is h= 1.83 seconds and the system is stable with large oscillations. The eigenvalue with maximum magnitude is very close to one in this case. Fig. 7, in contrast, shows the response of an unstable system since h=1.84 seconds is used and the eigenvalue of (15) with maximum magnitude is 1.006.

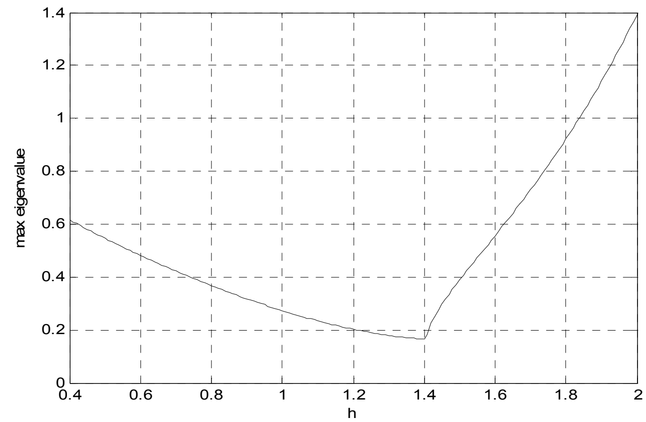

Fig. 4. Maximum eigenvalue of matrix (15) for different values of h.

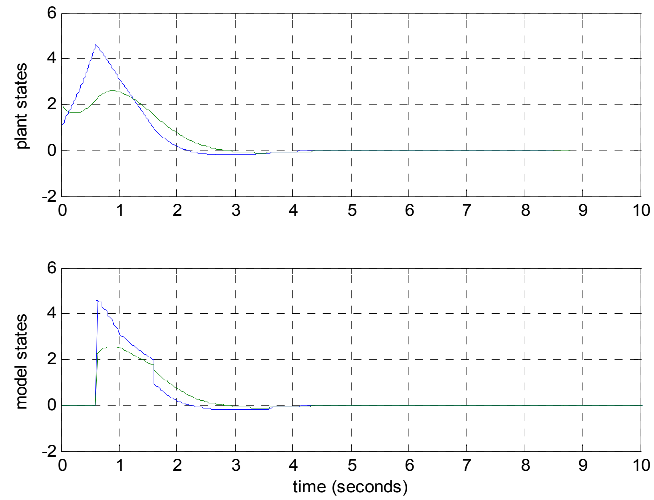

Fig. 5. System response with h=1 sec.

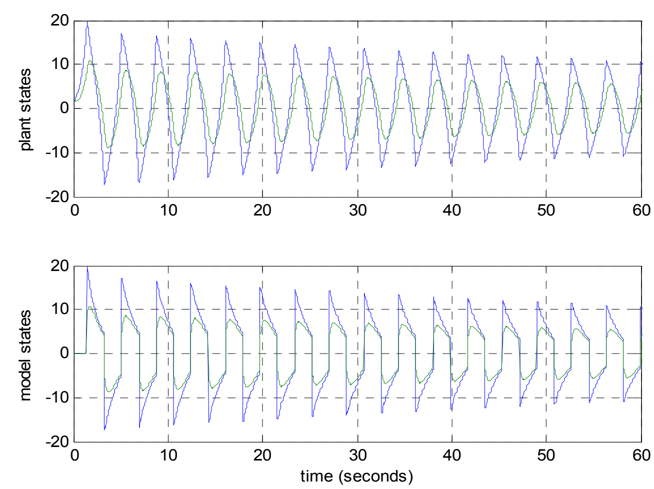

Fig. 6. System response with h=1.83 sec. Maximum eigenvalue equal to 0.985.

Example 2. The results in this paper offer necessary and sufficient conditions for stability in terms of different parameters including the parameters of the system which are unknown. In this example we use the results in Theorem 2 to estimate the admissible uncertainties for given model parameters, i.e. those uncertainties that result in a stable model-based control system.

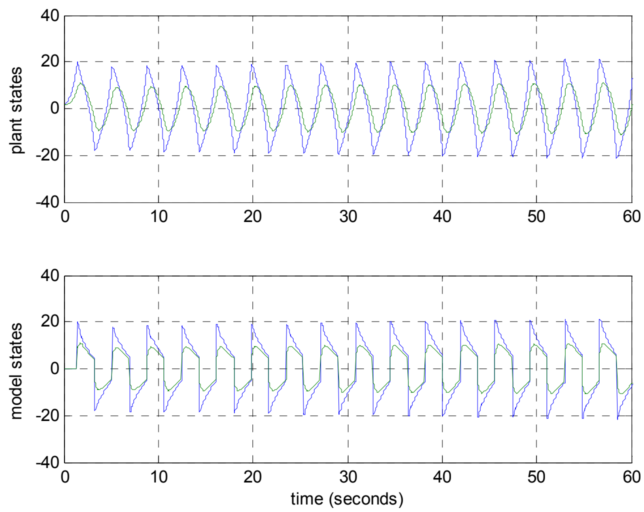

Fig. 7. System response with h=1.84 sec. Maximum eigenvalue=1.006.

The example considers a first order system for simplicity but the same type of search can be followed for systems of higher order by searching over an increased number of scalar parameters corresponding to the elements of the real system matrices. Let the model parameters be given by: $\hat{A}=1, \hat{B}=1$ and let us fixed the network parameters: h=2 sec, τ=0.5 sec, f=0.1 sec. Fig. 8 shows the eigenvalue of (15) with maximum magnitude for different values of A and B, the real parameters. The figure shows which combinations of plant parameters result in a stable control system for the given selection of model and network parameters.

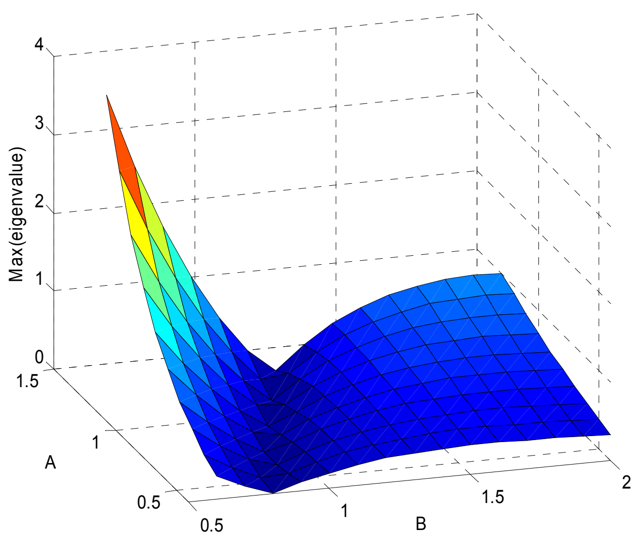

Fig. 8. Maximum eigenvalue of matrix (15) for different values of A and B.

VI. Conclusion

Necessary and sufficient conditions for stability of MB-NCS with intermittent feedback have been presented in this paper. In contrast to previous work we do not require continuous network communication during finite periods of time. The approach in this paper is based on the implementation of different communication periods that are used to update the state of the model. This work preserves the advantages of the open-loop and closed-loop modes of operation concerning the efficient use of network bandwidth while providing a simple and practical approach for transmission of measurements during the closed-loop periods. In this paper we considered model uncertainties and the absence of feedback measurements for possibly long periods of time. Future work will consider other important aspects of network communication such as network induced delays.

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