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Event-Triggered Observer based Control of Networked Visual Servoing Control Systems

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Abstract: The present paper deals with a new continuous un-delayed state observer based trajectory tracking control of networked visual servoing control systems by using only the sampled and delayed measurements where the sampling period and delayed value are variable and unknown. This proposed event-triggered Observer based control, which is derived by using the theory of a particular hybrid systems called Piecewise Continuous Systems, has a very simple structure and can be easily implemented to the networked visual servoing control systems. Finally to show the proposed method performance, a networked visual servoing mobile cart simulation results are presented.

Keywords: Networked Visual Servoing Control Systems, Piecewise continuous systems, Event-Triggered Observer based Control

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1. INTRODUCTION

During the last few years benefiting from its accuracy, versatility and improved signal/noise ratio, Visual Servoing Control Systems (VSCS) which extract the visual information from video sequences and use them in the feedback control loop have received a considerable amount and increasing attentions. With recent advances in communications and computing technologies, video grabbing, image processing and control can be implemented on different platforms across a common communication network. This kind of setups which can be termed as Networked Visual Seroving Control Systems (NVSCS)(Wu et al. (2010,a, 2011); Wang et al. (2012); Ilas et al. (2012); Wu et al. (2013); Wang et al. (2013a)) has been been widely implemented in industrial manufacturing, building automation, remote video communicating networks, education, and aerospace exporting. An example configuration with parallel computing can be seen in Fig. 1

Compared with traditional point-to-point control systems, the benefits of an NVSCS include: it provides wide-range visual feedback and increases system autonomy, particularly when a system becomes more and more communicable, intelligent and flexible by requiring more sensors, more actuators and more complicates controllers (Bontos et al. (2012); Wu et al. (2013); Ribon. et al. (2013); Wang et al. (2013a)) . An NVSCS may employ distributed computation for image processing; it enables high-speed vision feedback and is more robust to occlusions. However despite their numerous advantages and wide applications, the communication networks (Ethernet/Internet) and vision based systems in the control loops makes the control design more complicated. The main concern is the signal processing, coding, decoding and the networks across transmission induced delay and sampled output (shown in Fig.2) which degrade inevitably the systems performance and possible cause systems instability.

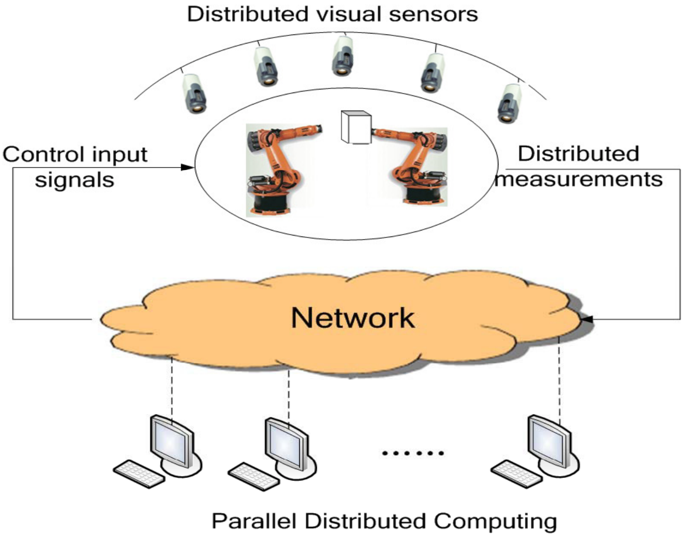

Fig. 1. NVSCS with parallel computing

The problem of ensuring stability under delays and sampling has been widely addressed (Hespanha et al. (2007); Zampieri et al. (2008); Simon et al. (2012); Wu et al.

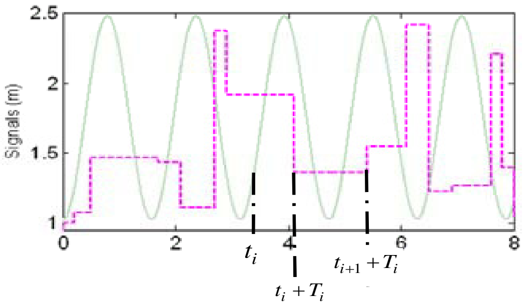

Fig. 2. Delayed and Sampled a continuous-time signal under variable period value T_i

(2013)). In the literature, there are mainly four type approaches used to resolve this kind problem:

- The first one is refereed as continuous approach means to based on the continuous-time system to design its continuous-time controller (its sampling effects in the original controlled systems have been ignored), and then discretized the derived continuous-time controller for applications; The problem is that the resulting discretized controller works only under the sampling period which is small enough to meet the closed-loop systems stability (Ahrens et al. (2009)).
- The second is referred as discretized approach which consists in the analysis of the discretized model (using lifting technology) of the system (i.e. using the discrete-time version of the Lyapunov Theorem). The main advantages of this approach are that the resulting conditions are tight and less conservative than other methods. However, it suffers from the inaccuracy of the discretized model comparing to its continuous-time model, the complexity of the conditions and the difficulty to include uncertainties in the original system (Ahrens et al. (2009); Simon et al. (2012)).
- The third is generally referred as the input delay approach which is introduced firstly in (Fridman et al. (2004)), and employed for example in (Gao et al. (2008)) among many others. This method allows for using the continuous-time Lyapunov-Krasovskii framework in order to take into account the the sampling as a particular type of delay. The main advantages of the method is the possibility to take into account time varying uncertainties both in the sampling period and in the systems parameters. However the resulting conditions are generally more conservative than the previous method.
- And the last one is referred as hybrid systems based approach (Naghshtabriz et al. (2008); Wu et al. (2013); Wang et al. (2008, 2010,b, 2012,a,b, 2013a)): such as in (Naghshtabriz et al. (2008)), the introduction of an impulsive system approach which refines the previous input delay method; and in (Wang et al. (2008, 2010,b, 2012,a,b)), the introduction of a particular type of Piecewise Continuous Observer (PCO) which is developed on a Piecewise Continuous System (PCS) and used to reconstruct the visual servoing control systems continuous un-delayed state.

Because of proving a natural and convenient unified framework for mathematical modeling of many complex physical phenomena and practical applications, hybrid systems which consist of interacting continuous and discrete dynamics under certain logic rules have gained considerable attention in science and engineering (Guan et al. (2005)). Under this scheme in this paper, a novel Event-Triggered Observer (ESO) based trajectory tracking control is proposed for the networked visual servoing output control systems with varying time sampling and delay.

Reminding that the referred proposed ETO based trajectory tracking control which is derived by using PC Systems (PCS), has a very simple structure and can be implemented easily for real-time applications. The used PCS, which is firstly proposed in (Koncar et al. (2003)) and then developed in (Chamroo et al. (2006); Wang et al. (2008, 2010,b, 2012,a,b,c, 2013)), is a particular hybrid system characterized by autonomous switchings and controlled impulses.

The remainder of the paper is organized as follows: the problem statement of the networked visual servoing control is given in Section 2. In Section 3, the design preliminaries of PCS are introduced. Then in Section 4 based on PCS, an ETO based trajectory tracking control is developed. The networked visual servoing mobile cart simulation results are illustrated in Section 5 which is finally followed by some conclusion remarks in Section 6.

2. NVSCS PROBLEM STATEMENT

From the analyzing of NVSCS, we deal with the case when the only available plant information is delivered from the plant output via a digital camera sensor introducing a delay with variable value $T_i, i = 0, 1, 2, ...$ which corresponds to the random time needed to code, decode, process and communicate the information (see Fig.3).

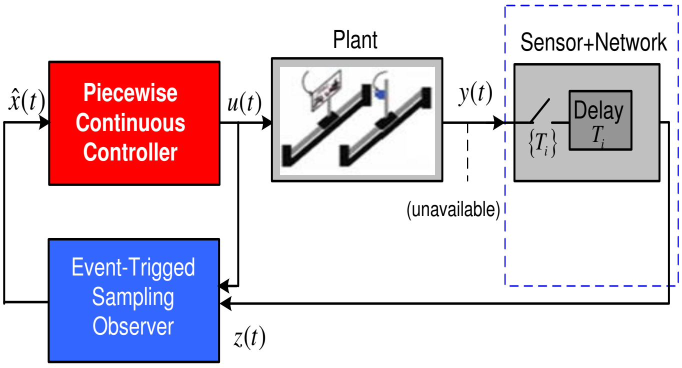

Fig. 3. ETO based trajectory tracking control architecture

Moreover to prevent out of memory in micro-processor or network congestion problem, the camera takes an image whenever the processing of the previous image is finished in our case, its sampling interval is equal to the referred computational and transmission delay T_i. For the considered NVSCS, the total delay T_i contains mainly three parts: the image processing delay, the transmission delay and the camera sampling interval. In this paper, we only consider the situation where the sensor and the controller are communicating through a communication network, while the controller and the actuator are connected directly. Thus, the information from controller to the actuator will be free of delay.

For the preliminary study of a NVSCS with sampling and delays, we consider a linearized system of a more general manipulator dynamics as

$$M(q)\ddot{q} + C(q,\dot{q}) = \Gamma \tag{1}$$

with a Jacobian transpose controller $\Gamma = J^T K x$ and $x^T = [q^T, \dot{q}^T]$. Its corresponding closed-loop formulation of position-based visual servoing systems can be denoted as follows

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \dot{q} \\ D \end{bmatrix} \tag{2}$$

where $D = M^{-1}(q)(J^T(q)Kx(t) - C(q,\dot{q}))$, q is the joint displacements, $M(q)$ denotes the manipulator inertia matrix, $C(q, \dot{q} = \Gamma)$ represents the centripetal and Coriolis torques, and $J(q)$ is the robot Jacobian. And its corresponding linearized model at the origin $q \equiv 0$ can be rewritten as

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{d}{dq}D & \dfrac{d}{d\dot{q}}D \end{bmatrix} \tag{3}$$

For reasons of simplification, it can be described as follows

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \\ z(t) = y^*(t - T_i) \end{cases} \tag{4}$$

where $A \in \Re^{n\times n}$, $B \in \Re^{n\times r}$ and $C \in \Re^{m\times n}$ are constant matrices and $*$ represents sampling operation with variable period T_i. For simplified notation, $z(t)$ in (4) can be denoted as $y(t_{i-1})$ or more simply as y_{i-1}.

Assuming that the proposed controller design algorithm proposed here for linear system (4) can be applied to nonlinear visual servoing systems with more DoF locally by linearizing the system at equilibrium states or by the computed torque feed-forward approach.

3. PRELIMINARIES OF PIECEWISE CONTINUOUS SYSTEMS

The used PCS are characterized by two input spaces and two time spaces. The first time space is the discrete time space $S = \{t_i = \sum_{j=0}^{i} T_j;\ i = 0,1,2,\ldots;\ j = 0,1,2,\ldots,i\}$ called switching space, where T_i are the switching periods with variable values and used to designate the sampled and delayed variable periode in the NVSCS. The second one is the continuous time space $\Phi_t = \{\Im - S\}$ where $\Im = \{t \in [0,\infty)\}$. Each input corresponds to one specific time space. At each switching instant, the plant is controlled from the first switching input and between two switching instants, the plant is controlled from the second continuous input. Two successive switching instants t_i and t_{i+1} delimit an interval denoted $\Phi_i = \{\Phi_t | \forall t \in]t_i, t_{i+1}[\}$.

For $t_i, i = 0,1,2,...$, a Linear PCS (LPCS) is described as:

$$\begin{cases} x_s(t_i^+) = B_{s2}v_s(t_i), \forall i \in S \\ \dot{x}_s(t) = A_s x(t) + B_{s1}u(t), \forall t \in \Phi_t \\ y_s(t) = C_s x_s(t), \forall t \in \Im. \end{cases} \tag{5}$$

where $x_s(t) \in \Re^n$ is the PC system state, $y_s(t) \in \Re^m$ is the system output and $v_s(t) \in \Re^p$, $u_s(t) \in \Re^r$ are switching and continuous inputs respectively, and $A_s \in \Re^{n\times n}$, $B_{s1} \in \Re^{n\times r}$, $B_{s2} \in \Re^{n\times\sigma}$, $C_s \in \Re^{m\times n}$ are constant matrices. At switching instants the system state changes according to the first equation of (5) and the continuous-time state evolution is described by the second linear differential equation of (5). Fig. 4 illustrates respectively the LPCS structure and symbolic representation. The system (5) will be further denoted as $\Sigma(S, A_s, B_{s1}, B_{s2}, C_s)$.

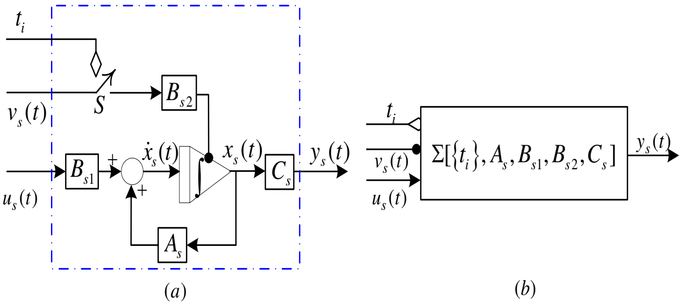

Fig. 4. Linear piecewise continuous systems

Integrating the referred second equation in $\Phi_i = \{\Phi_t | \forall t \in]t_i, t_{i+1}[\}$ and taking into account $x_s(t_i^+) = B_{s2}v_s(t_i)$, one obtains

$$x_s(t) = e^{A_s(t-t_i)}B_{s2}v_s(t_i) + \int_{t_i}^{t} e^{A_s(t-\tau)}B_{s1}u_s(\tau)\,d\tau. \tag{6}$$

The left limit $x_s(t_i^-)$ of $x_s(t)$ at $t = t_i$ is deduced from (6) in the Φ_{i-1} interval:

$$x_s(t_i^-) = e^{A_s T_{i-1}}B_{s2}v_s\big(t_{i-1}\big) + \int_{t_{i-1}}^{t_i} e^{A_s(t_i-\tau)}B_{s1}u_s(\tau)\,d\tau.$$

Thus from the above equation and the first equation of (5), in the general case, one obtains the following equation

$$x_s(t_i^-) \neq x_s(t_i^+). \tag{7}$$

An example of a first order system state evolution with $B_{s2} = 1$ is shown in Fig. 5.

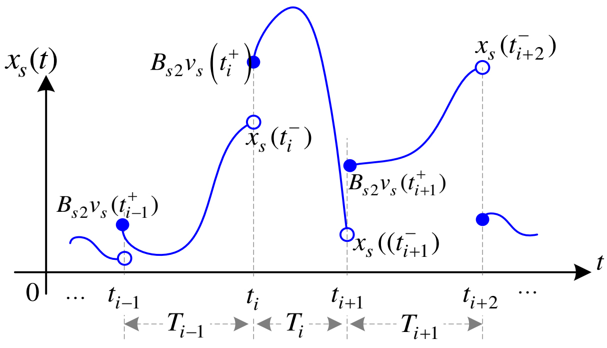

Fig. 5. Linear piecewise continuous systems state revolution with variable switching instants of t_i

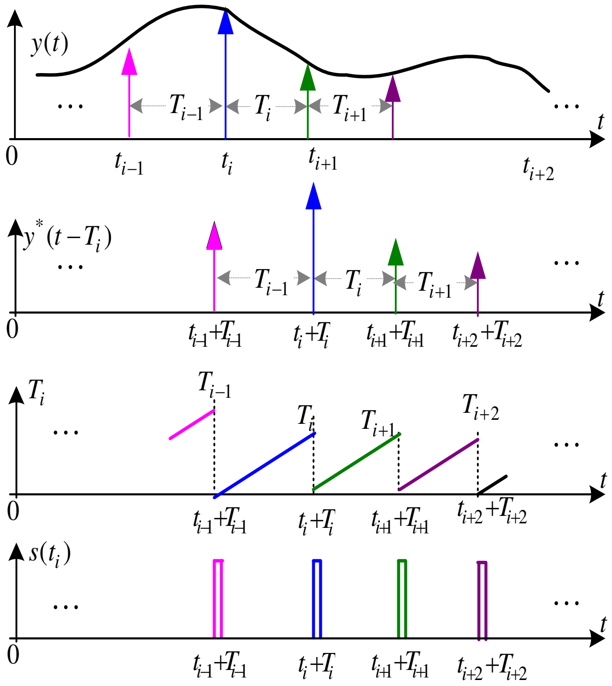

Fig. 6. Timing diagram of a networked visual serving control system, T_i denotes the time delays of image processing and data transmission. T_i is also considered as switching period whose values are variable in PCS. And the signal $s(t_i)$ represents the generated variable period (T_i) square wave with negligible width comparing to the value of T_i.

Based on the PCS theory, a PC controller requiring a linear plant model was firstly developed in (Koncar et al. (2003)). Then, a new class of PC controllers which allows controlling the plant without knowledge of its model was developped in (Wang et al. (2009)). This new type controller can be easily implemented and makes possible to realize robust output trajectory tracking of a real-time mechanical X-Y robot. In this paper, we focus on the observer based trajectory tracking by using the presenting PCS.

4. EVENT-TRIGGERED OBSERVER (ETO) BASED TRAJECTORY TRACKING CONTROL

In this section, a novel ETO based trajectory tracking control which is derived by using PCS is introduced. The entire ETO based tracking control has a very simple structure and can be implemented easily for the NVSCS.

4.1 NVSCS event-triggered sampling time

The timing diagram of a NVSCS is shown in Fig. 6, where T_i is the time sampling period and delays of image processing and data transmission. It is important to note that T_i is also considered as switching period whose values are variable in PCS. At instants $t_i = \sum_{j=0}^{i} T_j$, the current captured image starts to be processed, then the extracted image features through the communication network are fed into a host PC which is connected directly to the controlled system (ex. a mobile cart). As soon as the host PC receives the information, a new image is acquired and processed. At each instant $t_i + T_i$, a square wave signal which is denoted as $s(T_i)$ with variable period of T_i, can be generated and shown in Fig. 6. Reminding that the square wave width is considered negligibly by comparing to the value of T_i. Moreover, it is important to note that the square wave signal's rising edge can be considered as an event-triggered signal and used as a reset switching signals for PCS in ETO based trajectory tracking control.

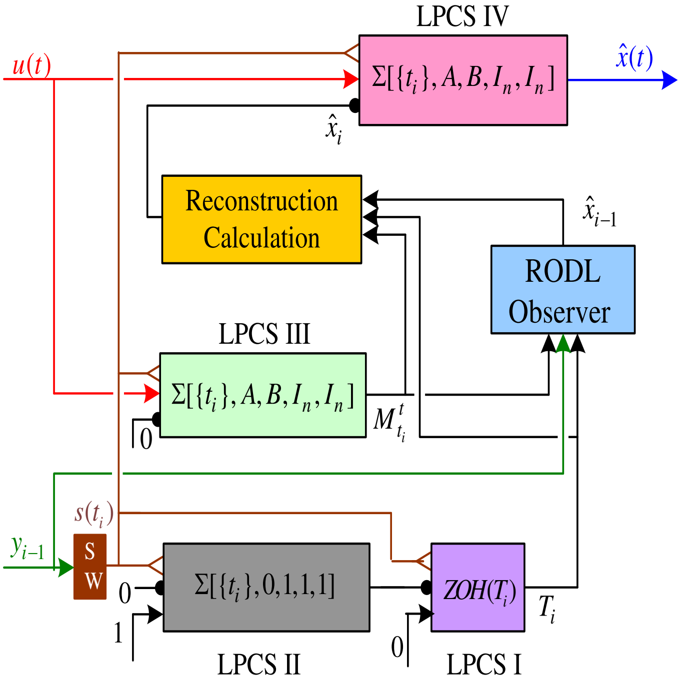

Fig. 7. Event-triggered Observer architecture

4.2 Event-triggered Observer Design

With the variable sampled and delayed measurement y_{i-1}, the aim of the ETO is to reconstitute the continuous-time un-delayed state $x(t) = [y(t)^T \ w(t)^T]^T$, where $w(t) \in \Re^{n-m}$ represents unmeasurable state. The proposed observer whose architecture is illustrated in Fig. 7 consists mainly on four LPCS, a Reduced-Order Discret Luenberger (RODL) observer and a simple reconstruction calculation bloc.

Reminding that the following used matrices A, B and C are defined identically in (4).

First step: using the LPCS I, LPCS II and the square wave generator

At each event-triggered sampling instant t_i, the host PC receives the values y_{i-1} and generate a Square Wave (SW) signal with the notation of $s(t_i)$. Then by using the LPCS (I and II) to generate the variable delayed and sample period of T_i .

The used LPCS I $\Sigma\big(\{t_i\}, 0, 0, I_n, I_n\big)$ with the inputs of $u_s(t) = u(t)$ and $v_s(t) = 0$ is used to generate a generalized Zero-Order-Holder whose variable period is T_i Koncar et al. (2003); then combined with the LPCS II $\Sigma\big(\{t_i\}, 0, 1, 1, 1\big)$ with the inputs of $u_s(t) = 1$ and $v_s(t) = 0$, the variable delayed and sampled period T_i can be memorized and generated by the host PC.

Second step: using the LPCS III

Using the LPCS III of $\Sigma\big(\{t_i\}, A, B, I_n, I_n\big)$, with the inputs of $u_s(t) = u(t)$ and $v_s(t) = 0$, one has

$$M_{t_{i-1}}^{t} = \int_{t_{i-1}}^{t} e^{A(t-\tau)} Bu(\tau)\, d\tau = \begin{bmatrix} m1_{t_{i-1}}^{t} \\ m2_{t_{i-1}}^{t} \end{bmatrix}, \tag{8}$$

with $m1 \in \Re^{m}$ and $m2 \in \Re^{n-m}$.

Sampling the output of the first LPCS by using a T_i period Zero-Order-Hold (ZOH), one obtains

$$M_{t_{i-1}}^{t_i} = \begin{bmatrix} m1_{t_{i-1}}^{t_i} \\ m2_{t_{i-1}}^{t_i} \end{bmatrix} = \int_{t_{i-1}}^{t_i} e^{A(t_i-\tau)} Bu(\tau)\, d\tau. \tag{9}$$

Third step: using a RODL Observer

In the Φ_{i-1} interval, the delayed and sampled state x_{i-1} is estimated by using a RODL observer defined as follows:

$$\begin{cases} \theta_i = F_i\theta_{i-1} + G_i y_{i-1} + (m2_{t_{i-1}}^{t_i} - L_i m1_{t_{i-1}}^{t_i}) \\ \theta_{i-1} = \hat{w}_{i-1} - L_i y_{i-1} \end{cases} \tag{10}$$

where $\theta \in \Re^{n-m}$ represents the RODL observer state, and the matrices $F_i \in \Re^{(n-m)\times(n-m)}$, $G_i \in \Re^{(n-m)\times m}$ are defined as

$$\begin{cases} F_i = f_{22}(T_i) - L_i f_{12}(T_i) \\ G_i = (f_{22}(T_i) - L_i f_{12}(T_i))L_i + (f_{21}(T_i) - L_i f_{11}(T_i)) \end{cases} \tag{11}$$

and the corresponding matrix of $f_{11}(T_i) \in \Re^{m\times m}$, $f_{12}(T_i) \in \Re^{m\times(n-m)}$, $f_{21}(T_i) \in \Re^{(n-m)\times m}$ and $f_{22}(T_i) \in \Re^{(n-m)\times(n-m)}$ are variable constant matrices defined from the following equation

$$A_d(T_i) = e^{AT_i} = \begin{bmatrix} f_{11}(T_i) & f_{12}(T_i) \\ f_{21}(T_i) & f_{22}(T_i) \end{bmatrix}.$$

And the observation matrix $L \in \Re^{(n-m)\times m}$ can be selected as

$$L_i = f_{22}(T_i) f_{12}^{T}(T_i) \big(f_{12}(T_i) f_{12}^{T}(T_i)\big)^{-1}. \tag{12}$$

Because the system (4) is observable, the RODL observer gain is always existing and can be selected to maximize its convergence speed.

By using the second equation of (10) to obtain the estimation w_{i-1}, one gets the sampled delayed state estimation

$$\hat{x}_{i-1} = \left[\, (y_{i-1})^{T} \;\; (\hat{w}_{i-1})^{T} \,\right]^{T}. \tag{13}$$

Fourth step: using a reconstruction calculation bloc

For the sampled undelayed state x_i, one uses the following reconstruction calculation:

$$\hat{x}_i = A_d(T_i)\hat{x}_{i-1} + M_{t_{i-1}}^{t_i} \tag{14}$$

Fifth step: using the LPCS IV

Using the LPCS II of $\Sigma\big(\{iT_i\}, A, B, I_n, I_n\big)$, with the same inputs of $u_s(t) = u(t)$ and $v_s(t) = \hat{x}_i$, one reconstitutes finally the continuous-time undelayed state:

$$\hat{x}(t) = e^{A(t-t_i)}\hat{x}_i + \int_{t_i}^{t} e^{A(t-\tau)} Bu(\tau)\, d\tau. \tag{15}$$

The proposed ETO uses only the sampling and delayed measurements y_{i-1}. The advantages of this proposed ETO are that whose initial conditions can be re-trigged at each rising edges of the square wave signal $s(t_i)$ which represent the effects of receiving the measurements at host PC side and its estimation error can not be cumulated by making use of PCS. Reminding that the stability demonstration of this proposed ETO can be done in the same way as (Wang et al. (2012b)) where the considered delay and sampling period are constants, while here are variable and unknown in advance.

4.3 ETO based event-triggered sampling trajectory tracking control

With the proposed ETO, we supposed that the state of the controlled plant is available. The main focus here is to use the PCS theory to design a new Piecewise Continuous Controller (PCC) which enables event-triggered sampling trajectory tracking of desired references.

An initial PCC with constant sampling period was developed in (Koncar et al. (2003); Wang et al. (2008)). For a general PCC whose sampling periods are event-triggered based and variable can be defined as follows

$$\begin{cases} \lambda(t_i^{+}) = B_{c2}\psi(t_i), \forall k \in S \\ \dot{\lambda}(t) = A_c\lambda(t) + B_{c1}\varphi(t), \forall t \in \Phi_t \\ u(t) = C_c\lambda(t), \forall t \in \Im. \end{cases} \tag{16}$$

A simplified PCC can be obtained choosing $B_{c1} = 0$ and C_c diagonal matrix with positive diagonal elements. Thus the only parameter defining the controller behavior between two event-triggered sampling instants is the matrix A_c which is chosen to ensure the stability of the entire PCC.

In this case the tuning of PCC consists of determining B_{c2} and $\psi(t)$ in order to achieve a sampled tracking of a desired state trajectory $x_d(t)$ by the plant state $x(t)$ with one event-triggered sampling period of delay:

$$x_{i+1} = x_{d,i}, \quad i = 0, 1, 2, \ldots \tag{17}$$

If we undertake the same idea presented in Wang et al. (2008), the state event-triggered sampling trajectory tracking for such plants can be ensured by a general simplified PCC with:

$$\begin{cases} B_{c2} = M^{-1} \\ \psi(t) = x_d(t) - A_d x(t) \end{cases}$$

where $A_d = e^{AT_i}$ and $M = A_d \int_{t_i}^{t_{i+1}} e^{A(t-\tau)} BC_c e^{A_c\tau}\, d\tau$.

PCC can be further simplified for sampled tracking of a desired output trajectory $y_d(t)$:

$$y_{i+1} = y_{d,i}, \quad i = 0, 1, 2, \ldots \tag{18}$$

by enabling event-triggered sampling at high frequencies $(T_i \to 0^+)$. In this case one obtains

$$\lambda_i^+ = I_m^- \lambda_i^- + e_i \tag{19}$$

where

$$\begin{cases} I_m^- = I_m - CBC_c T_i - \varsigma(T_i^2) \\ e_i = y_{d,i} - y_i \end{cases}$$

Equation (19) can be interpreted algorithmically as an iterative evaluation of λ_i^+ at each calculation step:

$$\lambda_i^+ \leftarrow I_m^- \lambda_i^- + e_i. \tag{20}$$

The evolution of the controller state for $T_i \to 0^+$ being negligible, PCC can be regarded as a zero order hold. Furthermore, if switching occurs at each calculation step of the computer, PCC can be realized by a simple circuit as shown in Fig. 2.

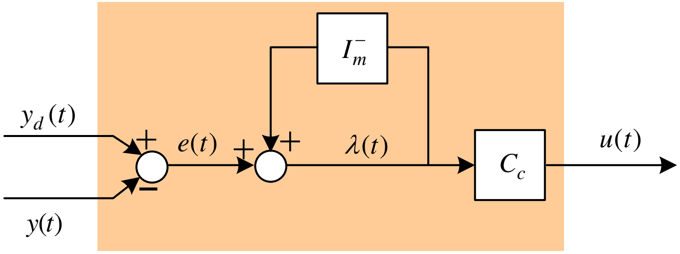

Fig. 8. Derived Piecewise Continuous Controller

In practice I_m^- can be chosen as a diagonal matrix $I_m^- = diag(i_1^-, i_2^-, \ldots, i_m^-)$ with $\|i_k^-\| < 1,\ k = 1, 2, \ldots, m$.

5. REAL TIME SYSTEM BASED CONTROL APPLICATION

5.1 Networked Visual Servoing Mobile Cart System

The considered controlled plant here is a mobile cart which moves along a horizontal and straight line segment. The cart is powered by an electric motor by means of a notched belt. The motor is of a brushless type. It is driven in ±10 V by a dSpace computer input/output card via a power amplifier. Supplied with 240 V (mono), it can offer a nominal couple of 3.0 Nm with a power of 200 W. The aim of experiment is to realize a netwoked visual servoing position control of the cart. Thus, the sensor is an "artificial vision" system that observes an infrared LED fixed on the cart, as shown in Fig. 9.

This networked visual servoing system is constituted of a motionless digital infrared CCD camera connected to a computer allowing image processing. And the camera is positioned above the cart and observes its motion. Thus, after a location operation, the artificial vision system outputs the position of the cart which is sent across the communication network to the host PC under a variable sampling and delayed value of T_i. Thus this referred networked visual servoing mobile cart system can be modeled as

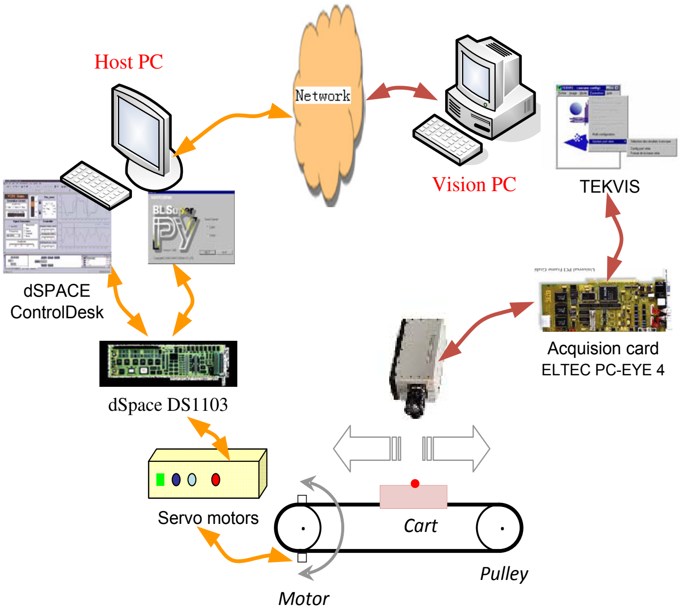

Fig. 9. Networked visual servoing mobile cart system

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{1}{\tau} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ \dfrac{k}{\tau} \end{bmatrix} u(t) \\ y(t) = [\,1 \;\; 0\,]\, x(t) \\ z(t) = y^*(t - T_i) \end{cases} \tag{21}$$

where $x(t) = [\,p_x(t)\ v_x(t)\,]^T$ is the plant state which is composed of the cart position $p_x(t) \in \Re$ and the speed $v_x(t) \in \Re$, $\tau = 8.3$ ms, $k = 2.9$ m·s/V are the system time constant and overall gain, $y(t)$ is the system output, and $z(t)$ represents the visual servoing system measurements.

5.2 Numerical Simulation Results

To show the proposed ETO based DPCC trajectory tracking performance, we implement it to the referred NVSCS. In these numerical results of networked visual servoing mobile-cart, we have tested firstly a desired position reference of $p_d(t) = -0.17t^3 + 2.5t^2 - 10t + 10$ for trajectory tracking test, and then secondly a piecewise constant position reference. These two tests are realized under different variable sampling period.

For the first case, its corresponding figures are illustrated in Fig. 10-13, and for the second case, its corresponding figures are illustrated in Fig. 14-17. From these simulation results of position regulation and trajectory tracking, it is clear to note that under variable sampling and delayed period T_i, the proposed ETO based trajectory tracking control can follow exactly the desired position reference either under the polynomial reference or piecewise continuous constant , and the proposed ETO can reconstitute quickly the networked visual servoing mobile cart system position and speed information by using only the sampled and delayed outputs y_{i-1}.

6. CONCLUSION

According to the design procedure, the proposed event-triggered Observer (ETO) based trajectory tracking con-

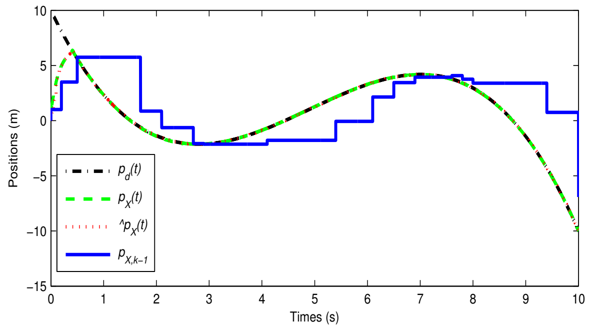

Fig. 10. First case: position signals

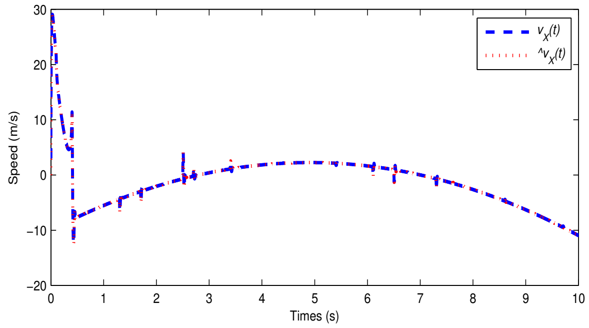

Fig. 11. First case: Speed signals

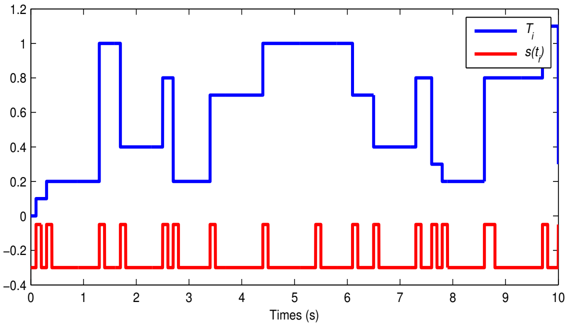

Fig. 12. First case: T_i and $s(t)$

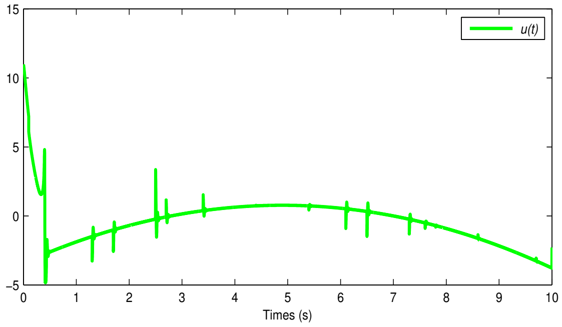

Fig. 13. First case: control input

trol which is based on the Piecewise Continuous Systems (PCS) is effective and robust for the Networked Visual Servoing Control Systems (NVSCS). It requires only the variable sampling period and delayed measurements $z(t) = y_{i-1}$. With the application of the ETO, the NVSCS's continuous un-delayed state $x(t)$ can be reconstituted.

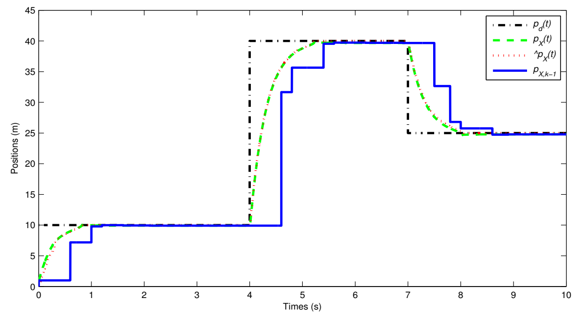

Fig. 14. Second case: position signals

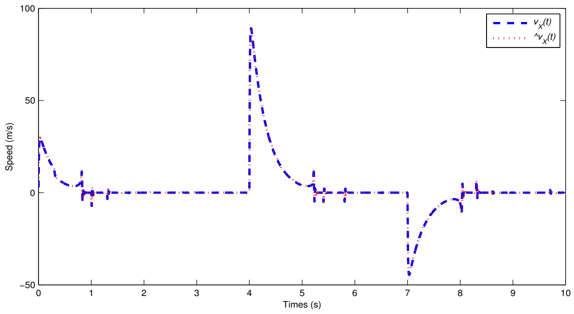

Fig. 15. Second case: Speed signals

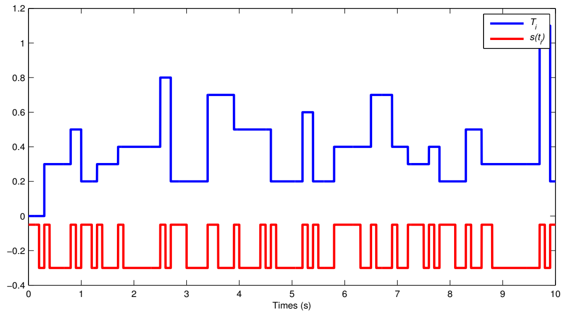

Fig. 16. Second case: T_i and $s(t)$

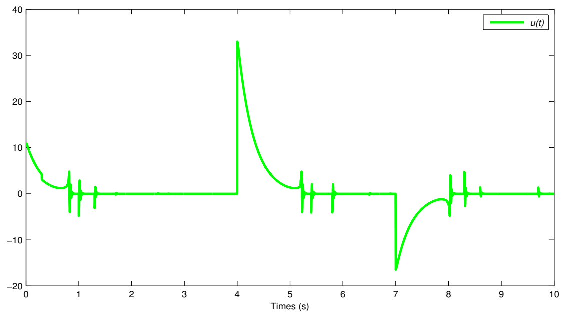

Fig. 17. Second case: control input

With the proposed PCS based ETO and PC controller, Compared to classical sampled-data controls which uses a sampled state or output feedback, the application of control scheme can facilite easily the realization of the trajectory tracking and the improvement of system dynamical performances.

It is important to remind that the estimation error $e(t)$ of the ETO is not cumulated by making use of the the PCS which can help to re-initialize the observer at each event-triggered sampling instant. Moreover, the proposed ETO based trajectory tracking scheme has a simple structure easily to be implemented on the computer technology based systems.

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