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Research article

Control of the rotary inverted pendulum through threshold-based communication

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ABSTRACT

This paper deals with the real implementation of an event-based control structure for the classical rotary inverted pendulum. The communication between controller and plant is performed through Ethernet (TCP/IP) which leads to a Networked Control System. The bandwidth used by the control loop is reduced, compared with the one that needs a conventional control, by using a threshold-based communication. The values of the thresholds have been determined by means of simulation techniques. The results over the real plant show how this technique can reach a significant reduction of the bandwidth consumed with a negligible worsening of the performance.

1. Introduction

When dealing with a Networked Control System (NCS) the most valuable resource is the bandwidth. In this kind of control systems, the necessary communication between the control device and the controlled plant is carried out through a shared communication medium [1–7]. A potentially large number of devices are using the same medium to transmit information for different purposes: control loops, monitoring, supervising, alarms, maintenance and even transmission of information not related with control tasks (real and non-real time data).

Depending on the physical medium used to transmit the information (electrical, optical, wireless, infrared etc.) and on the distance between emitter and receiver devices, a certain bandwidth is available [8–11]. This must be understood as the amount of information that can be transmitted per time unit. The bandwidth must be shared out between all the information generators (writer devices) attached to the medium. When the number of sharing devices increases, the real bandwidth available to each *writer* decreases.

In a typical control loop there are two devices able to generate information to be sent through the shared medium: sensor and controller. There are also two information consumers (reader devices): controller and actuator. The information generated by the sensor (output samples) is consumed by the controller. The information generated by the controller (control actions) is consumed by the actuator. Two links must be implemented: sensor-to-controller (SC) and controller-to-actuator (CA). In a conventional control system each link is implemented through its own physical medium but in a NCS they are virtual links implemented through the same medium. If a physical medium offers a bandwidth B bps (bits-per-second) and L control loops are going to be closed through it, each writer has a real bandwidth of $B/(2^*L)$ bps. Of course this happens when all the writers have the same priority and the bandwidth is assigned no matter if it is needed or not. This is the policy when all the control loops are using the same sample time and the same number of samples/actions per second is transmitted. It is also possible that different writers have different needs and they get a different bandwidth. Loops with smaller sample time get a larger portion of the shared bandwidth. In this case the bandwidth is assigned to each writer depending on the control frequency and is constant during its operating life. This pre-assigned bandwidth policy is often used in industrial communication media as, for example, Profibus-DP [12–14].

But as any control engineer knows, the need for information transmission depends on the state of the controlled plant. There are periods of time in which the system is quite stable. There are neither reference changes nor perturbations and the controlled signal (i.e. the plant output) remains (almost) in the same value. Along these periods the assigned bandwidth is wasted transmitting (almost) the same sample and (almost) the same control action. To optimize the use of the precious resource an 'on-demand' policy appears to be appropriated. The main idea is to send only those sample/actions which are significant enough according to the control system behavior. The information not sent (because it has been considered negligible) leave the resource free to be used by other device. Obviously, this strategy needs a communication medium in which the bandwidth is not pre-assigned but is requested by the *writer* device. The goal is to use the minimum bandwidth to get the

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desired behavior for the controlled plant. TCP–IP follows this 'on-demand' policy and it is the communication protocol to be used in this work [15–18].

This event-triggered control strategy [19–27] differs from conventional control in the fact that the sample period is not determined only by the plant dynamics and the design specifications. The effective sample time (which determines the consumed bandwidth) is variable depending on the state of the controlled plant. When the plant is in a stable situation (the reference to be followed is not changing and there are no significant disturbances to cancel) the sample period increases (consuming less bandwidth) and when the plant is moving, the sample period decreases (consuming more bandwidth) towards the one used in conventional (constant sample time) control.

This can be compared with the variable simulation step in simulation theory [28,29]. When implementing an integration method it can be done in fixed or variable step. In fixed step the simulation step is constant during the life of the simulation. Variable step (frequently used as default in general purpose simulation tools) means that the simulation step increases or decreases depending on the computation needs to reach good quality results, according to a certain tolerance. In fixed step the number of simulation steps (and so, the computational cost) is constant and known and it is independent on the simulated system behavior. In variable step computational cost depends on the system dynamics. When simulating a system with long stable periods of time (in which the state does not change significantly) some simulation steps can be skipped (i.e. saved) to reduce the computational cost and to finish the simulation earlier. These variable step simulation based techniques are going to be applied in this work to a classical control problem. They will reduce, in a significant way, the need of bandwidth without degrading the system performance. Instead of saving computational cost the technique is used here to save bandwidth.

In variable step simulation the decision of changing the simulation step (i.e. computing or not each step) is based on an estimation of the simulation error. Two different integration methods are used and the results are compared. If the difference is below a certain tolerance it is assumed that the simulation is performing well and the step is increased, saving computational cost. In the control strategy proposed in this paper the condition to change the effective sampling period (i.e. transmitting or not each sample/action) is slightly different. If the difference between one sample/action and the previous one is below a certain threshold, the sample is not transmitted, saving bandwidth for other devices. This threshold must be chosen not too small to get a significant reduction on the used bandwidth and not too large to avoid a significant worsening of the system performance. And this is the main challenge: to choose the appropriated threshold to get a good bandwidth/performance ratio.

The threshold is the parameter to decide if the difference between one sample/action and the previously transmitted one is negligible or not. This parameter must be pre-arranged to an appropriated value. It can be done experimentally working with the real plant to be controlled or with a reliable enough mathematical model. Only constant thresholds are used in this work, that is intended to be continued using variable thresholds. In variable threshold it will be dynamically adapted during the life of the control system in a similar way as it is modified the size of the step in variable step simulation.

The fact that not all the samples/actions are going to be transmitted, according to its difference with the previous one, leads to an event sampling control system. The transmission of one sample/action is not caused by an external event but by an event which depends on the plant state which is, in fact, modified by the event itself.

The aim of this work is to prove that the previously described threshold-based control strategy can be applied to a real plant with a significant gain on the bandwidth consumption. In conventional control the easy way to save bandwidth is to increase the sampling period (i.e. to decrease the control frequency). This is simple and efficient but only useful when the sampling time requirements of the controlled plant are low. When controlling a plant with small time constants, the lower bound of the control frequency is easily achieved. In this case, decreasing the control frequency will lead to performance degradation and instability. The proposed strategy only makes sense if it is better than the conventional solution so, it must be tested in rough conditions, in the limits of the control frequency. The plant to be controlled will be the rotary inverted pendulum (RIP) for several reasons:

- RIP is a classical control problem frequently used as a benchmark to measure the goodness of control structures.
- RIP is an unstable and non-minimum phase plant, with a small time constant, which becomes easily unstable when the control frequency is decreased.
- RIP is a multivariable plant with (at least) three signals to transmit (two output signals and one control action). The bandwidth gain will be larger when more information is transmitted between controller and plant.
- RIP is available at our laboratory and the proposed control strategy can be implemented in real conditions not only over the simulation model.

The paper is organized as follows. Section 2 shows the behavior of the control in ideal conditions; conventional control and small enough control frequency to reach the desired behavior. Section 3 shows the bandwidth saving when using threshold-based communications. Section 4 presents conclusions of this paper and future work.

2. Conventional control of the rotary inverted pendulum

The well-known rotational inverted pendulum (RIP), also named Furuta pendulum, has a DC motor that moves an arm attached to its shaft. At the end of this arm there is a joint in which it is attached the pendulum [30–35]. The goal is to keep the pendulum in its unstable equilibrium upwards position, while a certain reference signal is followed by the motor arm. In this work, the RIP developed by Quanser Consulting Inc. is going to be used. Fig. 1 shows the plant, in the upwards position.

The results in this section have been obtained with the real RIP when using a conventional control, without bandwidth limitations. This will be the nominal behavior to compare with the one that will be achieved when reducing the amount of information transmitted between the plant and the control structure.

RIP is a continuous underactuated plant with one input, the control action applied to the DC motor carrying the pendulum ($u(t)$, measured in volts) and two outputs:

- $\theta(t)$: Angular position of the motor shaft around the vertical axis.
- $\alpha(t)$: Angular position of the pendulum rod around the motor shaft axis.

The theoretical multivariable model includes the first derivative of these signals (velocity) but is not going to be considered as the real plant does not have sensors to measure them. Fig. 2 shows a schematic representation (top and front view) of RIP.

The aim of this work is to prove, over a real plant, that threshold-based communication can reduce the amount of information between controller and plant without a significant worsening of the system behavior. No new controller is going to be designed to reduce the bandwidth. The controller will be the one developed to operate in a conventional control structure without