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Maximization of biohydrogen production using an output feedback controller

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Summary of key findings

For a glucose-fed bio-hydrogen producing bioreactor, we have fitted the model parameters of a known model using experimental data obtained from a pilot laboratory-scale bioreactor. We use this fitted model to design an output-feedback controller based on the super-twisting algorithm, which uses only the on-line measurements of the hydrogen production rate and maximizes this variable by manipulating the hydraulic residence time. Simulation results are very encouraging, even under a time-varying influent substrate concentration.

Background and relevance

Hydrogen (H2) is a potential energy resource replacement to fossil fuels because of its low generation of pollutants and high energy density. One of the most promising technologies for bio-H2 production is dark fermentation, where microorganisms produce it by degrading complex sugars and carbohydrates, generating acids and solvents that can be used in further processes downstream. It has the advantage of simple operation, high bio-H2 production rate, and that it can be applied to a great variety of organic solid and liquid wastes, such as wastewater (Wang and Wan 2009).

The key for producing bio-H2 from liquid waste streams is finding the correct operational conditions, since this influences the main metabolic pathway of the microorganisms and thus the process efficiency and the product gas quality. For example, the organic loading rate (OLR) apparently has an optimum value that leads to maximum bio-H2 production (Hafez et al. 2010). In a continuous stirred tank reactor (CSTR) configuration this translates into finding the optimal hydraulic residence time (HRT) for a given inflow substrate concentration. However, usually the optimal OLR is close to the one that overloads the system. Furthermore, since the OLR is a combination of the HRT and the inflow substrate concentration, which is usually unknown but within certain bounds, it is difficult to assess on-line which HRT yields the optimal hydrogen production rate (HPR).

In this contribution we propose a simple, yet mathematically sound, controller that maximizes on-line in a practical way the HPR by feeding back the measured value of the quantity to be maximized, i.e. the HPR. This controller was tested successfully with numerical simulations under realistic scenarios using a mathematical model of a CSTR (Aceves-Lara et al. 2010) that was previously calibrated with experimental data from a laboratory bioreactor.

Methods

It is difficult to design feedback controllers for bioreactors because of two reasons: the lack of reliable on-line sensors and actuators for many process variables and the high uncertainty in the underlying mathematical models. For example, complex models with many internal variables and an even larger set of parameters usually describe anaerobic processes such as dark fermentation, e.g. the ADM1 model and its variants. However, to capture the main behaviour, simpler models may be used. For bio-H2 production, we have considered a model that has proven useful for feedback controller design (Aceves-Lara et al. 2010). However, our proposed controller is based on even simpler assumptions: that the system can be modelled locally by a single differential equation for the substrate dynamics and an output function of the substrate concentration that predicts the HPR. This output function has a single well-defined, but unknown maximum.

The approach may sound too simplistic given the complexity of the process, but it is effective. In fact, the key is considering that the model parameters are time-varying and that the prediction horizon is not large. Using a simple model representation, we propose the use of a modification of a second order sliding mode controller, which is robust against uncertainties of the model. This is a so-called super-twisting controller (STC) (Moreno 2011), which is used to regulate a signal to a given set-point, with finite-time convergence despite uncertainties and some non-modelled dynamics. The controller proposed builds on the STC concept and adapts it for output-feedback extremum-seeking control. Its objective is to bring trajectories to the maximum of the output function, but measuring only the output signal (in our case the HPR). It must be combined with a state machine to estimate both the set-point (the maximum HPR achievable) and a signum function that is needed for the STC.

It is assumed that for each inflow substrate concentration there exists an unknown optimal HRT that maximizes the HPR. The controller starts by gradually decreasing the HRT until a maximum in the HPR signal is detected. This triggers a change in a controller parameter, so now the HRT is gradually increased after a small positive discontinuity. This will lead the HPR signal to pass again through a maximum, which again is detected, triggering a change in the same controller parameter that will again decrease gradually the HRT, and so on. Thus, the HRT will be oscillating between two values that bound the optimum. At each detection of a maximum, the set-point is recalibrated, so the controller can accommodate for changing conditions. In fact, if the inflow substrate concentration changes slowly (a reasonable assumption), the controller is able to cope with it, finding the corresponding optimal HRT automatically.

Results

To test the controller design concept, we considered the model proposed by Aceves-Lara et al. (2010) as virtual plant. Previously, we had calibrated the model and found the corresponding parameters for an experimental setup in our laboratory. This is a 1.2 L CSTR bioreactor with 0.9 L of reaction volume equipped with a bio-controller (Applikon Biotechnology), which regulates the temperature at 35°C, the stirring velocity at 100 rpm, the pH at 5.5, and the volume is kept constant. The reactor is fully instrumented with a variable velocity pump (Masterflex) for remotely establishing the HRT, a hydrogen on-line analyser (HY-optima model 7000, H2scan) and a biogas flowmeter (ADM 2000, Agilent Technologies), all connected to a personal computer for data acquisition and manipulation. Collected data under different combinations of HRT and OLR were used to calibrate the parameters of the model.

After calibrating the controller parameters, we tested the designed controller under simulation for several scenarios, including some with time-varying inflow substrate concentrations (Glu_{in}). Figure 1 shows a run for a period of 30 d, where the inflow glucose concentration varies randomly between 13 and 27 g/L, periodically and smoothly. The upper-right subfigure shows the input/output steady-state map for this system; for each constant Glu_{in} the curve that describes the HPR (q_{H2}) in steady state as a function of a constant HRT is plotted. For too low HRT's a biomass washout eventually occurs, but it is also evident that for each constant Glu_{in} there exists an optimal (constant) HRT that maximizes the HPR in steady state. This is indicated by the blue curve, which is again explicitly plotted in the lower-right subfigure. If we knew this curve beforehand and we could measure $Glu_{in}(t)$, a good (open-loop) control strategy would be to change the HRT accordingly. In the subfigures on the left the outcome of this (unrealistic) procedure is shown with the blue dashed curves. In contrast, the red solid curves show the time evolution with the proposed control strategy (from top to bottom): the glucose concentration in the CSTR, the HPR, and the HRT. The top-left subfigure also shows the $Glu_{in}(t)$ signal as a green curve.

The q_{H2}(t) signal obtained with the proposed controller follows closely the one that would be obtained if we knew the I/O steady-state map and could measure the inflow substrate concentration. The HRT oscillates around the optimal value, which was found automatically by the controller.

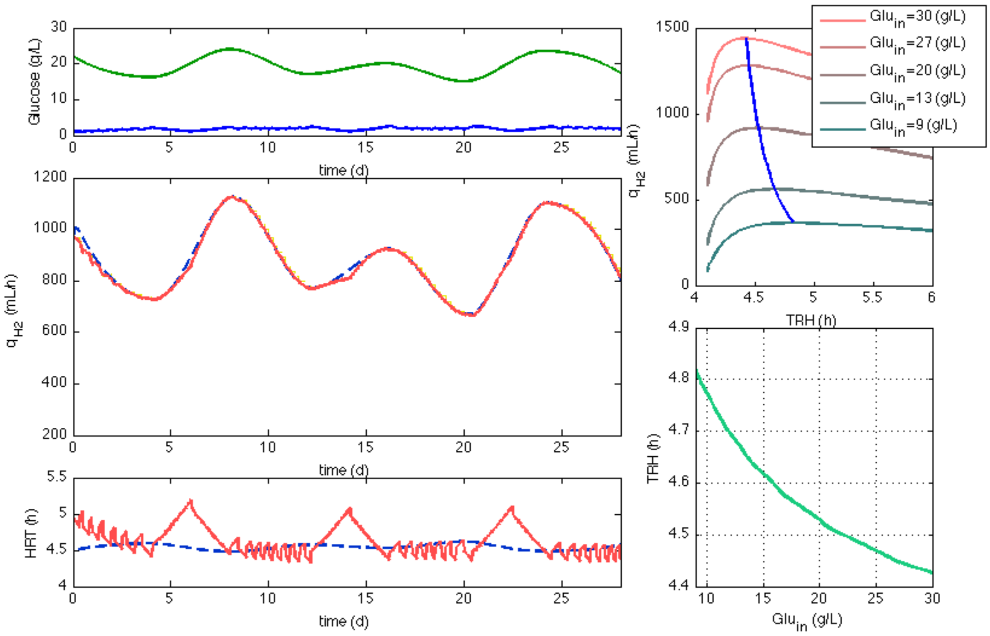

Figure 1. Simulation results for the proposed output-feedback controller. Top-left: time-varying glucose concentration in the influent (green) and inside the bioreactor (blue). Middle-left: H2 flow rate (red) and theoretical maximum (blue dashed). Bottom-left: controlled HRT (red) and theoretical value for maximization in steady state. Top-right: I/O map for the bioreactor for different inflow concentrations. Bottom-right: optimal HRT for steady-state maximization.

Discussion

We have proposed a simple yet effective controller for maximizing the hydrogen production in a CSTR. This is an initial investigation and the model used as virtual plant is a simplification of a very complex process. Furthermore, we have considered not wastewater, but a synthetic preparation with glucose as unique and readily available carbon source and thus the hydrolysis process is not considered. Nevertheless, we believe that due to its simplicity, the proposed controller may be a feasible alternative to maximize the HPR.

Acknowledgement

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