

Integrating LabVIEW Capabilities for Monitoring and Supervisory Control with a B-Braun Biotech GmbH Unit for Fermentation Processing and Direct Control*

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The paper presents a control strategy and LabVIEW 6.1 computer program for the design and real-time implementation of an adaptive control system of a fed-batch fermentation process run in a Biostat[®] C fermentation unit. The methods used for modelling, parameter estimation, optimization and controller design are discussed. Algorithms for integration with the unit communication protocol through LabVIEW VIs are described and the VIs are given. The programs and control system are implemented on a standard PC, running Windows 98, and connected to the fermentation unit through a standard RS232/RS422 converter. The program is used to control a yeast production process.

INTRODUCTION

FERMENTATION IS A process that results in the formation of alcohol or organic acids on the basis of growth of bacteria, moulds or fungi on different nutritional media [1, 2]. A fermentation process is classified according to the mode that has been chosen for process operation: batch, fed-batch or continuous. A fed-batch fermentation process for the production of yeast is considered in this study [3].

From the control point of view, the fermentation processes are characterized by non-stationary process dynamics, slow response, non-linearity, sudden unexplained changes and irregularities [4]. There are insufficient methods for measuring important variables, for modelling and parameter estimation and for optimization and control calculation [5]. The fermentation processes are described by two groups of variables: biological (concentrations of substrate, biomass and product) and physiochemical (temperature, pH, DO₂, agitation). Proper changes in the physiochemical variables can bring proper changes in the biological variables through the actions of the enzymes [5]. Hence, the ability to monitor and control the physiochemical variables at their optimal operating values means an improved final yield [6].

Yeast propagation requires the control of different parameters at different stages of the fermentation process. Yeast requires aerobic conditions to grow rapidly. Oxygen starvation leads to ethanol production, with a reduction in cellular growth. An excess of nutrients also causes production of ethanol, even in the presence of sufficient oxygen [7]. Two phases can be distinguished in the process. In the first, the substrate concentration needs to be controlled to avoid the formation of by-products. Varying the feed rate overcomes the excess of nutrients and reduces ethanol production. In the second phase, due to the high solution density, oxygen transfer is a limiting factor. This is the parameter that needs to be controlled above a critical value below which the cellular metabolism changes [8].

The present paper describes part of the research work to overcome the difficulties mentioned above by control of the fermentation process through control of the physiochemical variables. An adaptive multi-layer strategy for control is developed in which the modelling, parameter estimation, process optimization and closed-loop control are designed and implemented with integrity in order to achieve maximum production of yeast at the end of the fermentation process. The adaptive control strategy was developed for the fed-batch propagation of yeast using a lab scale fermentation unit from B-Braun Biotech GmbH (Biostat[®] C

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model) [9] which is installed at the Department of Chemical Engineering in the University of Cape Town (UCT). This consists of an in-situ sterilizable culture vessel and a digital control unit capable of performing PID control of four important physiochemical variables: pH, temperature, dissolved oxygen, and agitation. Students use the unit when conducting their yearly academic experiments. Experience has shown that the following are necessary:

- some of the important process variables have to be monitored, stored and soon used;
- prediction of the process behaviour is needed through real-time simulation;
- set points and parameters of the PID controllers in the biocontroller have to be changed according to the process conditions; and
- optimal adaptive control of the process can improve productivity.

These needs require a control system that has options for data acquisition, modelling, parameter estimation, simulation, optimization and supervisory control implementation. The original unit has no such capabilities. The decision was taken to connect the Biostat unit to a PC through serial communication and to use LabVIEW [10] as the driver software for development of the whole automatic control system. The project was implemented at Peninsula Technikon in cooperation with the University of Cape Town (UCT). The LabVIEW software was selected because of its ability to solve each of the targeted problems and to be easily connected to different types of software and hardware by accepting various communication protocols.

The paper presents a control strategy and LabVIEW computer program for the design and real-time implementation of the control system. The methods used for modelling, parameter estimation, optimization and controller design are discussed. The algorithms and their integration through LabVIEW VIs are described and the VIs are given. The technology presented in the paper is based on off-the-shelf hardware components. It has been observed that, due to the latest developments in control technology globally, a lot of hardware already exists, but what is missing is the software to customize the hardware for the specific purpose. The paper addresses this. The developed software is custom specific, but with minor changes it can be adapted for other industrial applications. The developed control system is characterized by simple and cheap instrumentation, reliability and speed.

STRATEGY FOR CONTROL OF THE FED-BATCH FERMENTATION PROCESS

The requirements for design and implementation of the control of the fed-batch process are determined on the basis of the existing situation in

research laboratories and in industry. Analysis of the existing hardware and software showed a need for the following:

- simple models, convenient for calculations in real time;
- simple methods for modelling and control which do not require complex calculations and expensive hardware;
- the hardware and software system should be simple and user friendly to allow easy dialog with the operator; and
- expensive sensors for measurement of biological variables should be avoided.

The proposed control strategy is based on the characteristics of the process as an object of control and on the aims of the control implementation. The strategy is based on a combination of optimal control [11] with an adaptive control approach to repetitive optimization. In this way, the controller learns about the process by acquiring data from the process and keeps on updating a control model on-line. A three-layer control structure is used to solve the problem of modelling and optimal control first, and then to implement the control action. The overall scheme for on-line implementation of the adaptive control strategy is presented in Fig. 1. The problems are solved at the beginning of every period of repetitive optimization on each layer, as follows:

- *Adaptation or model identification* (model parameter estimation). For the case under consideration, the biological variables biomass, substrate, and product concentration are described using mass balance equations. Using the same token equations, kinetic parameters are obtained as quadratic functions of the physiochemical variables on the basis of an empirical approach with experiments and a parameter estimation technique.
- *Optimization*, or the optimal settings of the process variables, is obtained by solving the problem of optimal control, together with the problem of designing direct controller parameters based on real-time model parameter estimation.
- *Direct control* is the layer of realization and implementation of the closed-loop control according to the parameter estimation from the adaptation layer and the controller parameters and the reference trajectories obtained from the optimization layer.

CONTROL SYSTEM HARDWARE

The hardware integration of the system consists of:

- *B-Braun Biostat[®] C lab scale fermentation unit from B.BRAUN International GmbH* (Fig. 2). The unit's infrastructure is based on a local control device called a biocontroller, which is

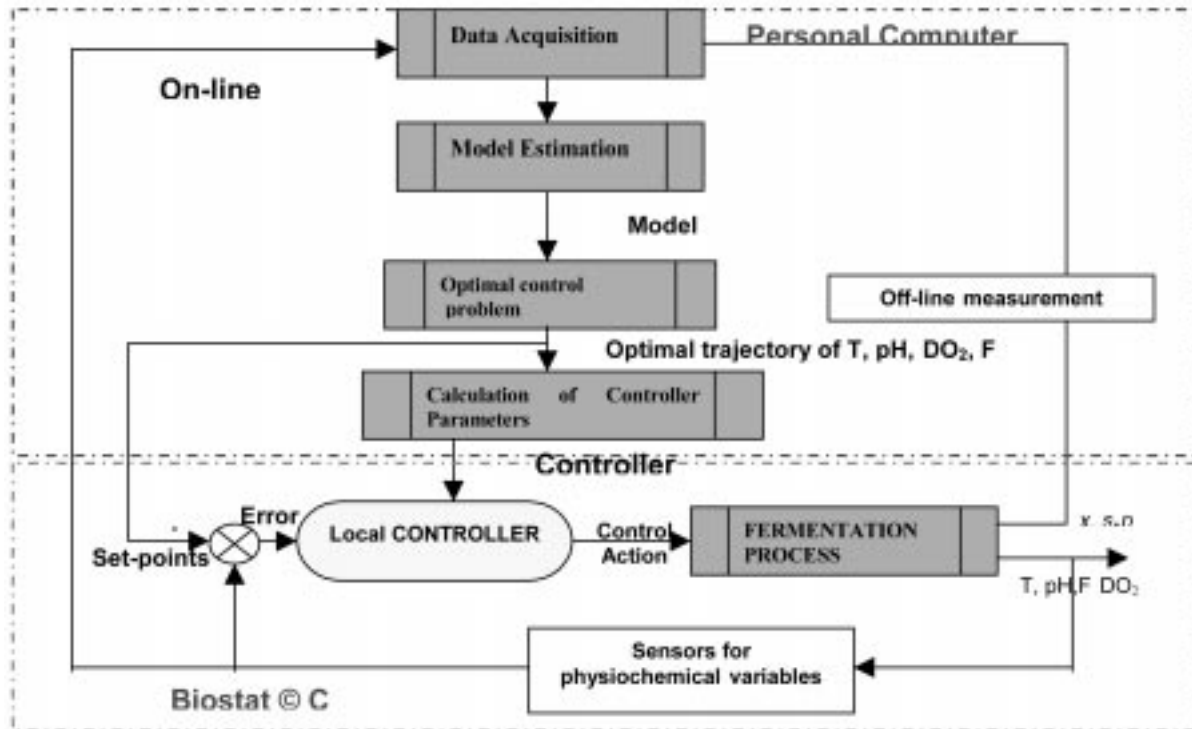


Fig. 1. Adaptive three-layer strategy for optimal control of the fermentor.

connected to a fermentor. The biocontroller has four PID digital controllers for control of the physiochemical variables, such as temperature, pH, dissolved oxygen and agitation [9]. The bioprocessing capabilities of the Biostat[®] C include batch, fed-batch and continuous processes. The ability of the biocontroller to acquire, compress and display (using liquid crystal display; LCD), and still be able to send all the acquired data through a commonly used RS232 and RS422 communication port, makes it easy for the control engineers to integrate the unit hardware and software with other control systems.

- *Personal computer (PC)*. The computation time, user interface graphics and complexity of the developed algorithms require a computer with the following minimum specifications: a Pentium IV[®] processor, 128M RAM, 10GHD, 8MB VGA graphic card, and, preferably, a 17-inch monitor for better visualization. The application was developed using the Windows 98 operation system environment and using LabVIEW 6.1 as the driver software [12]. The reason for using the Windows environment is because it was already available at UCT as an operation system and also the students are used to Windows applications.
- *IFB RS-422 Box*. The IFB RS-422 box's main function is to convert an RS-422 signal from the biocontroller into an RS-232 signal from the computer's serial interface, and vice versa. The serial interface of the computer (COM1 as default) is connected to the IFB RS-422 box using a serial cable. The side with IFB RS-422 must be

connected to the IFB RS-422 box and the other side must be connected to the computer's serial interface [13].

MAIN PROGRAM SOFTWARE MODULES

The main program for full automatic control of the fed-batch fermentation process consists of modules enabling design or real-time implementation. The program is written using the graphical programming language G of LabVIEW together with the interface protocols of the B-Braun Biostat controller and MS Access database of Microsoft. The main program organizes the work of all the

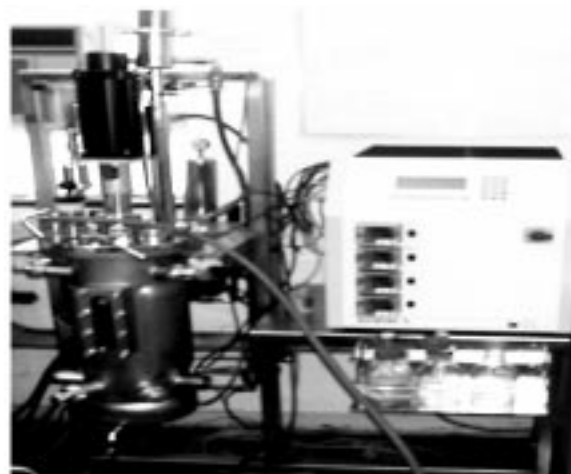


Fig. 2. B-Braun Biostat[®] C biocontroller.

modules. Its front panel is shown in Fig. 3. It has the ability to:

- initialize the biocontroller at any time whilst the program is running ('Initialize' button);
- acquire and log data during the experimental period in the local MS Access database, to query that data from the database using a date and time index and export the data into an MS Excel spreadsheet for further analysis and plotting ('Reports' button);
- acquire and log the off-line measured variables in an MS Excel spreadsheet using the keyboard ('OFF-line Variables' button);
- simulate in real time and estimate model parameters ('Parameter estimator' button);
- calculate the optimal trajectories of physiochemical variables from a given moment in time until the end of the process ('Optimization' button);
- recalculate the PID controller parameters using the built-in LabVIEW PID auto-tuning toolkit ('Auto tuner' button);
- send control loops settings (i.e. set point, minimum and maximum values of variables and controller parameters) to the biocontroller using a user-friendly pop-up window ('Control Loops Settings' button); and
- help, in order to explain the program functions ('Help' button).

The software of the control system has three main modules corresponding to the three main tasks for adaptive control implementation: Data Acquisition (DAQ) for monitoring; Optimization for repetitive calculation of model parameters, optimal trajectories of the variables and local controller parameters; Set up of the biocontroller parameters to fulfil the designed control system aims. All these modules are implemented on the basis of integration of the B-Braun protocol for

serial communication with the LabVIEW 6.1 functions for serial communication and calculation from the three built-in libraries: Serial Compatibility VIs, File I/O VIs, Gmath VIs.

PC-LABVIEW/BIOSTAT COMMUNICATION PROTOCOL INTEGRATION

The communication between the host computer and the biocontroller (substation) is based on the master-slave principle i.e. (the data transmission can only be started by the host computer provided the Remote (REM) key on the biocontroller is ON). Communication between the substations themselves (multi-drop connection) is not possible. The host computer can control the data transmission to a substation via commands. Commands are available for: DR—requests to process data from the subsystem; DS—sends process data to the subsystem; and SU—subsystem initialization. An address field in the command telegram selects a specific substation. For each substation the address can be manually set. The elements of the communication are:

- *Substation Initialization.* The DCU button on the biocontroller is used to initialize it at any time while the process is running, no matter what the status of the REM (on the biocontroller) key and the operating mode (recipe process, sterilization). Prior to the first data request, the host computer must initialize the corresponding substation (SU command) [14]. The initialization command sends parameters to the substation and thus adapts the data transmission to the requirements. Without initialization, the substation sends an error telegram after receiving a Data Request (DR) command.

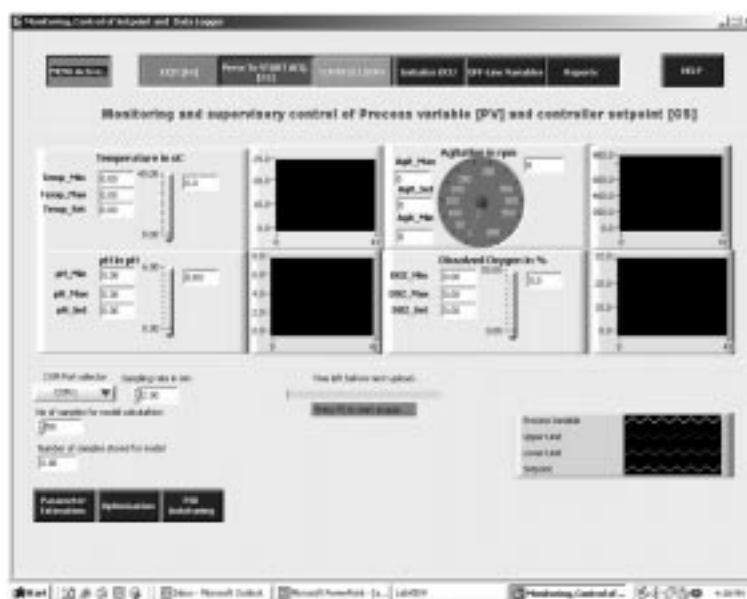


Fig. 3. Main program window.

- **Break-Generation via the Host Computer.** Before sending a command to the substation, a break condition must be generated on the interface in order to switch the connected substation to the Receive mode. The latter is achieved with the break function from the serial compatibility submenu of LabVIEW. The duration of the break (which depends on the baud rate) should be approximately the same as the transmission time for two characters. After resetting the break, a 2-ms delay time is recommended before sending characters.
- **Remote Mode.** The substation has the ability to switch between two modes of operation (i.e. Local and Remote modes). This is achieved by using the Remote key from the substation menu. Only the Remote mode allows a control via the host computer (i.e. the substation only accepts the set parameters of the host in the Remote mode). Except for the initialization command and the setting of the real time and the process time, all commands with which parameters in the substation can be changed will be responded to by an error telegram if the substation is not in the Remote mode. If the host computer sets the process parameters in the Remote mode, all other functions, direct access included (Shut down, Acknowledge, etc.), can be realized at any time. A change from Remote to Local is only active (delay possible) when a running data transmission/processing of one block is finished.
- **Reserved Control Characters.** The following characters are required for data transmission control: *—Start character host telegram; #—Start character substation telegram; :—Delimiter for data fields; @—End mark for each telegram; /—Delimiter for date and time and for initialization formats; ,—Delimiter between integer fields of date and time;
- **Telegram Format.** The connection between the PC and the biocontroller has to use the Biostat built-in protocol. Its structure is: SC ADR: COMMAND: SEQ: STAT: MSG-FIELD: CS EM, where SC is a Start character, ADR is a Unit address, SEQ is a Sequence, STAT is a

Status of sender, CS is a Check Sum, and EM is an End Mark. Depending on the data group, however, the message field can change in its structure. The status field always indicates the actual status of the telegram sender. MSG—FIELD (Message Field) has the following structure: DES: NO: VAL: NO: VAL: DES, where DES is Designation (PV—process variable, CS—control signal), NO is Channel Number, and VAL is Value.

Example: Sending commands: *1:DS:0:0:CS:3:625.0:CM:3:1:PA:3:0.0:666.6:1:0:0.0:2859@ means that the Controller Set point No.3 on pH has to be 7.5, the Controller Mode No.3 on Auto and Alarm parameter PA No.3 Limits Low=0/High=8pH, Mode=Enable, 2xReserve. Acknowledgement telegram is: #1:DS:0:17:619@

- **Response Telegrams of Substations.** The contacted substation responds within the timeout limit (500 ms) with the required response telegram (specification see below) or with an error telegram if all the following conditions are fulfilled: Command telegram begins with * and ends with @; Sent Check Sum = calculated Check Sum; Received address = set address.
- **End of Data Transmission.** The data transmission is only finished if all the data blocks of one substation telegram are correctly sent to the host. A new response telegram is only sent to the substation if the last data block has been sent to the host and if the host computer has then sent a new data request command with the sequence 0.
- **Check Sum.** The Check Sum is used by the biocontroller to validate the data that it is receiving from the host computer. The Check Sum is formed by addition of all ASCII values from the start sign (* or #) up to and including the delimiter (:) directly in front of the Check Sum. The calculated value cannot exceed the value of 32385 and is variable depending on the message length. The Check Sum error correction is used. This implies that the Check Sum must be calculated before data are sent to the control unit. The latter is achieved with the specially

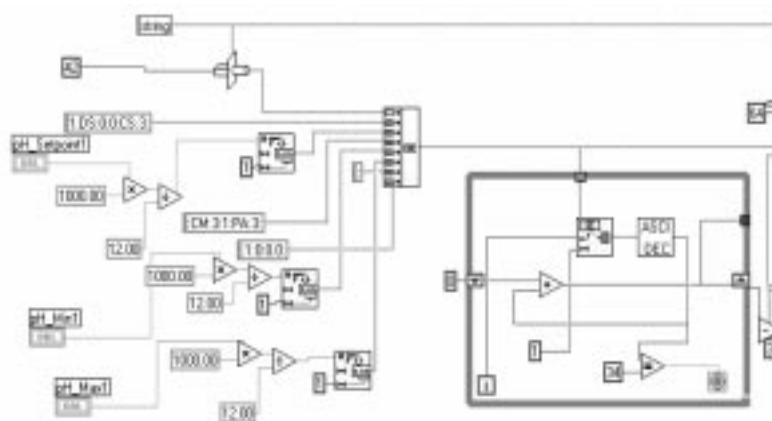


Fig. 4. Check Sum calculation module.

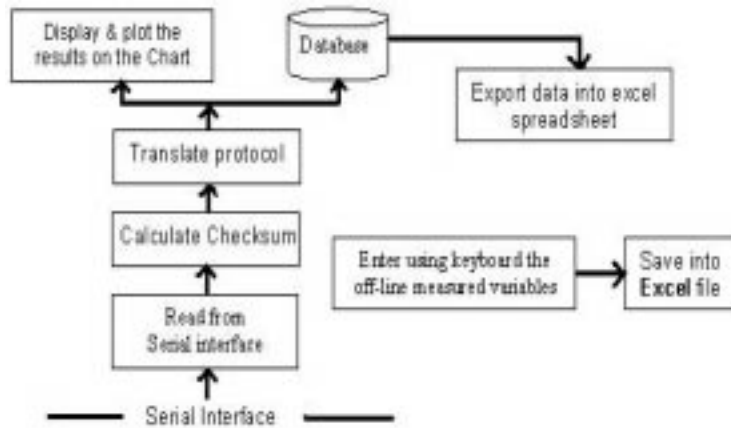


Fig. 5. Schematic of DAQ program.

developed Check Sum calculator module. The ASCII string from the serial telegram functions is passed to the Check Sum calculator. It calculates the Check Sum of the string coming and going to the biocontroller and returns an error on the data format if it exists. A program of the Check Sum calculation is given in Fig. 4.

DESCRIPTION OF THE DAQ PROGRAM

The DAQ module provides the operator with the ability to monitor and exercise supervisory control of the biocontroller. The main LabVIEW functions that are used in the program are the serial port functions. The latter include [15]: serial port initialize; serial port break; serial port configuration; serial port read; serial port write, etc., and the Gmath toolbox. The schematic of the DAQ program is given on Fig. 5. The main parts of the program are:

- *Serial port read and serial port write LabVIEW serial functions* are used to read and write data to and from the serial interface. The input to these functions is the port number and the requested

byte count. The output is an ASCII string of data. The requested byte count is the number of bytes received or sent to the serial port specified in the port number input.

- *Biostat protocol translation.* A sub-VI called Strip_protocol.vi has been developed to translate the protocol from the serial port of the Biostat. The sub-VI receives an ASCII string of data from the serial functions described above and translates it into full process variable values that the operator can understand.
- *Database.* The output of the Strip_protocol.vi is sent to the MS Access database, to process model VIs for updating and to the display interface. The developed sub-VI for inserting data into the database uses the Open Database Connectivity (ODBC) and SQL command to access data to and from the MS Access database (Fig. 6).
- *Export data into MS Excel spreadsheet.* The data stored in the local database can be accessed from the database using the developed sub Reports.vi, Fig. 7. The sub-VI allows the user to go back and access old data using a date and time index. A utility to sort the data according to the operator interest is incorporated in the program.

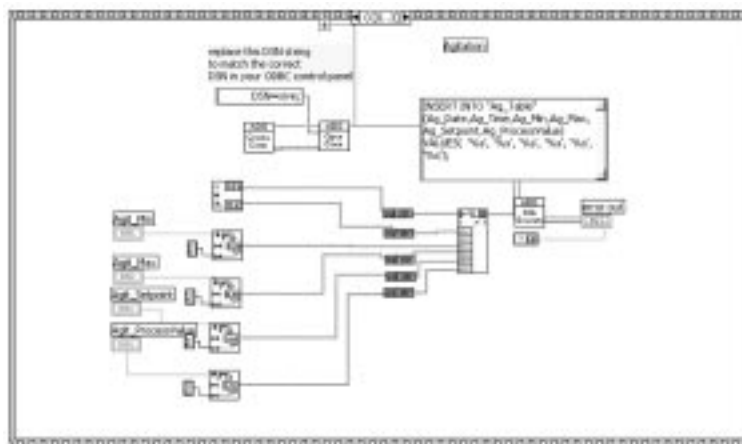


Fig. 6. Insert into database block diagram.



Fig. 7. Reports window.

The operator can specify a date using the format dd/mm/yyyy. The time format is hh:mm PM/AM. The operator can select the process variable to query and select the way the output data are to be sorted in MS Excel. On clicking the button 'Export Data into Excel', a window pops up for the operator to specify the filename 'XXXX.xls', where 'XXXX' is the chosen name of the file generated from the export function.

- *Input data from the keyboard for the biological variables.* The results from the variables being measured off-line in the laboratory are introduced into the PC by the keyboard and are logged in the spreadsheet file for further analysis. From the menu, clicking the 'Off-line variables' button brings up the window that allows the operator to enter the variable details. The entered data is then sent to the spreadsheet file using the 'Send' button. A function has been incorporated into the program to allow the user to enter the off-line measured variables on the database.
- *Help.* The help window pops up on clicking the 'Help' button on the far right of the main program window (Fig. 3). The other help utility is to press H whilst holding down the 'Ctrl' key, then move the cursor to the button the help is needed for.

TASKS OF LAYERS FOR ADAPTATION AND OPTIMIZATION, REPETITIVE CALCULATION OF MODEL PARAMETERS, OPTIMAL PROCESS TRAJECTORIES AND LOCAL CONTROLLER PARAMETERS

Process model simulation

The following variables are selected in the study to characterize the fed-batch fermentation process as an object of control:

- Inputs used as control signals: Base/acid flow rate, On/off heating energy, Flow rate of oxygen for the physiochemical variables, and Flow rate of substrate, Temperature, pH, DO₂ concentration for the biological variables.
- Outputs and state space variables: Concentration of biomass, Concentration of substrate, Concentration of product, Volume of the reactor.
- The model of the process is obtained using mass balances [16] in the fermentation tank for each of the biological variables and the tank volume. The equations are:

$$\dot{x}(t) = x(t)(\mu(t) - k_d - D(t)), x(0) = x_0 \quad (1)$$

$$\dot{s}(t) = D(t)(s_i(t) - s(t)) - x(t) \left(\frac{2\mu(t)}{Y_{x/s}} + m_s \right), s(0) = s_0 \quad (2)$$

$$\dot{p}(t) = Y_{p/x}\mu(t)x(t) + Dp(k), p(0) = p_0 \quad (3)$$

$$\dot{V}(t) = F(t), V(0) = V_0 \quad (4)$$

$$D(t) = \frac{F(t)}{V(t)}, \quad \mu(t) = \left(1 - \frac{p(t)}{p^*} \right) \frac{\mu_m(t)s(t)}{K_s + s(t)} \quad (5)$$

where F is the feed rate for the nutrient substrate in [m³/s], s_i is the substrate concentration input, V is the culture volume in the reactor vessel [m³], x is the biomass, s is the substrate, and p is the product concentration, in the fermentor [mg/l]. At the initial moment s_i(0) = s_i = constant in [mg/l], V(0) = V₀ in [l], x(0) = x₀, s(0) = s₀, p(0) = 0 [mg/l], D is the dilution rate [1/s], μ is the specific growth rate, k_d is the death rate constant, m_s is the maintenance coefficient, Y_{p/x} is the product yield coefficient, Y_{x/s} is the yield coefficient for the growth of biomass, μ_m is the maximum specific growth rate [s⁻¹], K_s is the Monod constant, or the substrate saturation constant, p* is the product concentration after which the biomass is inhibited,

and n is an empirical constant. Once the values of the kinetic parameters μ_m , K_s , $Y_{x/s}$ and $Y_{p/s}$ have been determined, the model can be used to estimate the cell biomass, substrate and product concentration as a function of time. The main problem with the fermentation process is that model parameters are difficult to calculate because they change with time depending on the variation of the physiochemical variables. The complex relationship between physiochemical and biological variables are reflected in the values of the equation kinetic parameters, which can be represented as functions of the physiochemical variables:

$$\begin{aligned}
 \mu_{\max} &= a_1 + a_2T + a_3T^2 + a_4pH + a_5pH^2 \\
 &\quad + a_6DO_2 + a_7DO_2^2 \\
 k_s &= b_1 + b_2T + b_3T^2 + b_4pH + b_5pH^2 \\
 &\quad + b_6DO_2 + b_7DO_2^2 \\
 Y_{x/s} &= c_1 + c_2T + c_3T^2 + c_4pH + c_5pH^2 \\
 &\quad + c_6DO_2 + c_7DO_2^2 \\
 Y_{p/x} &= d_1 + d_2T + d_3T^2 + d_4pH + d_5pH^2 \\
 &\quad + d_6DO_2 + d_7DO_2^2
 \end{aligned} \tag{6}$$

where the values of a_1 – a_7 , b_1 – b_7 , c_1 – c_7 , and d_1 – d_7 are not known and cannot be determined theoretically. As a result of the latter, these coefficients are determined on the basis of experimental data and the application of the least mean square approach for the parameter estimation. In equations (1)–(5) the value of the coefficients k_d and m_s were determined previously by experiments. Usually they are very small, $k_d=0.01$ [hr⁻¹], $m_s=0.03$ [g of substrate/g.cells.hr]. The mass balance equations (1) to (5) together with the equations (6) represent the model that is used in the common control system for parameter estimation, process optimization and direct control. Input variables for this model are the physiochemical variables T , pH , DO_2 , flow rate F , while output variables are the biological variables x , s , p , and the volume V .

Model simulation is performed in real time. The control and simulation software for Gmath is used to realize the yeast model. This software provides routines for modelling, analysing and simulating dynamic systems and handles real-world control problems, simulation tasks, or a combination of both. This support tool is useful while developing a control system that is partly simulated and partly realized. The developed model resembles the latter, hence the software is selected to realize the control system. The data from the on-line measurements through the serial port are read using the serial LabVIEW function. The data are stored in a file Table.dat at an interval specified by the operator. The data from the file is used to recalculate the new values for μ_m , K_s , $Y_{x/s}$, and $Y_{p/s}$. The new values of

the parameters from the latter are passed into the biological model for calculation of the concentrations x , s , p , and the volume V according to the discrete version of the model (1) to (6).

Model parameter estimation

The problem for model parameter estimation can be formulated mathematically in the following way: Find the values for the parameters a_i , b_i , c_i , d_i , $i = 1, 7$, in such a way that the error between the measured values of the outputs of the process $\bar{x}(k), \bar{s}(k), \bar{p}(k), \bar{V}(k), k = 0, K-1$ and the output of the model equations (1) to (6) $x(k), s(k), p(k), V(k), k = 0, K-1$, expressed by the criterion:

$$\begin{aligned}
 J &= \sum_{k=0}^{K-1} \|e(k)\|^2 \\
 &= \sum_{k=0}^{K-1} \|\bar{z}(k) - z(k)\|^2 \mapsto \min, z = x, s, p, V, \tag{7}
 \end{aligned}$$

is minimized under the model equations (1) to (6), where the number of points of measurement in the time interval $0, t_f$ is K . The criterion gives the best strategy for fitting the trajectories of the model to the measured trajectories. It has many advantages, as it gives a unique model trajectory for a given set of data [17]. The problem for parameter estimation is solved by a numeric gradient method. It uses the result from the VI for a model simulation. The front panel of the module for parameter estimation is given in Fig. 8. The number of the calculated model parameters is 28. The recursive least squares techniques for parameter estimation is selected, as it is suitable for operation in a noisy practical environment, and it has minimum storage requirements and does not need computational time for matrix inversion. The use of LabVIEW functions and VIs makes the implementation of the algorithm in real time easy. The results are the values of the model parameters used for optimal control and PID parameter-tuning problem solutions.

Optimal control calculation

The optimal operation of the process is based on some criteria for the production of biomass and product, and some constraints over minimum and maximum values of the variables. In this study, it is based on maximizing the production of yeast. The problem is how to influence the process in order to achieve this aim. The possibilities for influence are given by the input substrate flow rate, temperature, pH and DO_2 concentration, which are considered as control variables. Then the problem for optimal control is to find the trajectories of the feed flow rate, temperature, pH and dissolved oxygen concentration $F(k), T(k), pH(k), DO_2(k), k = 0, K-1$ in such a way that the concentration of biomass at the end of the process

$$J = x(K) \rightarrow \max \tag{8}$$

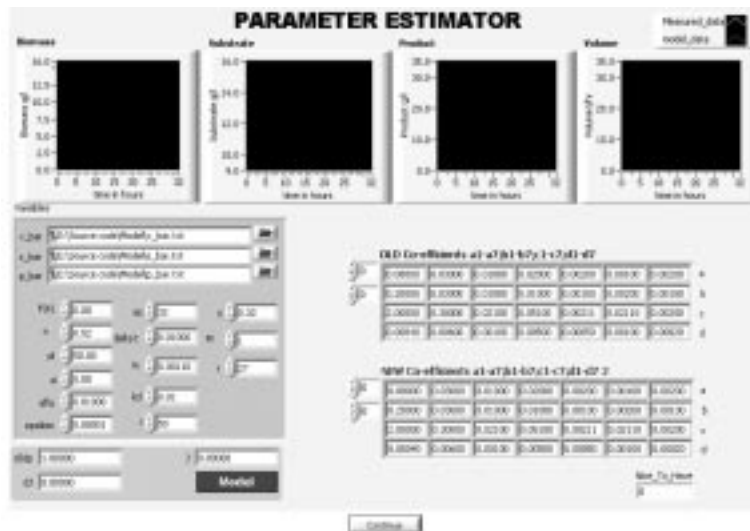


Fig. 8. Parameter estimation front panel.

is maximized under the model equations (1) to (6) and some constraints over the minimum and maximum values of the variables. The problem for optimal control is characterized with a non-quadratic criterion, a non-linear model and constraints over the variables trajectories. The variable $F(k)$ enters the model equations in a linear way but at the same time it does not appear in the criterion function. This means that the optimal control problem according to this variable is a singular one and its solution is more complicated. To overcome this difficulty, the problem is solved on the basis of an augmented functional of Lagrange, which introduces quadratic terms of the model equations into the ordinary function of Lagrange. A decomposition method in the time domain is developed to solve the augmented problem. The calculations are performed in a two-level computing structure [18, 19]. The

optimization module's front panel is shown in Fig. 9. The results are the optimal trajectories of the physiochemical and biological variables from the current moment of solution until the end of the fed-batch process. The optimal trajectories of the control variables F , T , pH and DO_2 are used as reference trajectories for the PID controller tuning.

PID auto-tuning

The PID controllers built in the biocontroller have to be tuned according to the requirements of the process in real time. The developed application has an option that allows the operator to recalculate the controller parameters for a PID controller. The latter is available through the 'PID' button, as seen on the main program display (Fig. 3). In order to calculate the PID controller parameters, the optimal trajectories of the physiochemical variables pH , temperature and dissolved oxygen

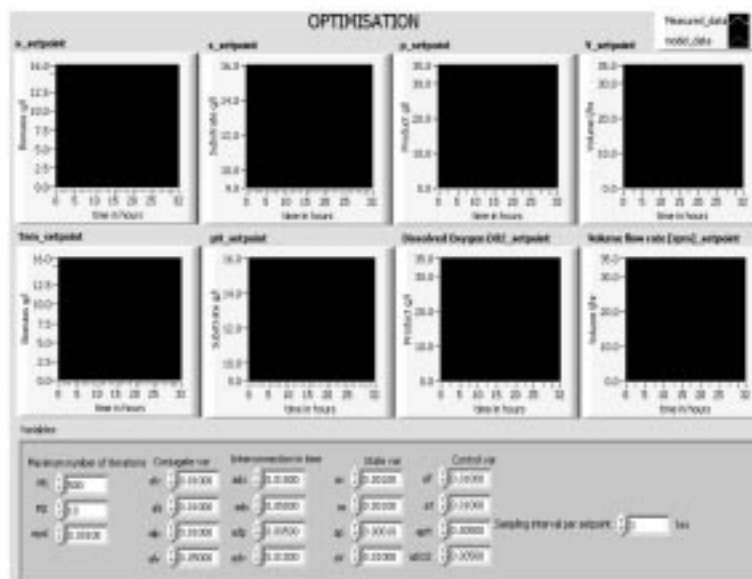


Fig. 9. Optimal control front panel.



Fig. 10. Auto-tuning window.

obtained as solutions of the optimal control problem are sampled additionally inside the period of repetitive optimization. The value of the corresponding variable is averaged inside the sampling interval and then sent as a set point to the algorithm for controller tuning. The recalculated controller parameters can be compared with the previous parameters. If the operator is satisfied, the recalculated parameters can be entered manually or automatically into the biocontroller using the keypad user interface. This operation cannot be done automatically in the case being considered, as the biocontroller model Biostat[®] C does not allow the sending of controller parameters from the host computer. The auto-tuning algorithm is developed using the LabVIEW PID auto-tuner. A pop-up window (Fig. 10) appears after clicking on the buttons allowing the operator to 'Select', 'View', 'Specify cycle time' and 'Tune' the selected PID process variable and controller. The set points (SP) are obtained from the optimal control problem solution; the process value (PV) is received through the serial port for a cycle time specified by the operator. Self-tuning of the PID controller simplifies the necessary tuning procedures and executes them automatically. It observes the process' reaction to a sent disturbance and sets the tuning parameters accordingly. The LabVIEW toolbox uses Ziegler and Nichols' heuristic methods for tuning a PID controller [12].

The algorithms for simulation, parameter estimation and optimization were programmed and run in parallel with a Matlab/Simulink environment. The implementation of the programs is quicker in Matlab/Simulink, mainly because of its functions for integration. The corresponding continuous LabVIEW functions require the values of the derivative for the whole period of integration. The discrete 'Unit-delay' LabVIEW function allows the same use as a corresponding Simulink function and can be used in every sampling period, which is why it is used in the application. The problem is that this function is slow and the time for parameter estimation and optimal control

problems calculation is longer than with Matlab/Simulink. The calculation time in LabVIEW is less than two minutes and, because the fermentation processes are slow, the results can be used in real time. Future work on the programs will include changing the realization of the functions of integration.

SET-UP OF THE BIOCONTROLLER CLOSED-LOOP PARAMETERS TO FULFIL THE AIMS OF THE DESIGNED CONTROL SYSTEM

The direct control closed-loop parameters for the given process variable are: minimum, maximum and set point values and PID controller parameters. Minimum and maximum values can be changed by the operator according to the stage of the process. The set points are determined using the optimal trajectories of the physiochemical variables after solving the optimal control problem at the beginning of every period of a repetitive optimization. The optimal values of the PID parameters are determined by the auto-tuning VI. The control-loop settings window (Fig. 11) pops up on clicking the 'Control loops' button on the main menu. The main function of this window is to send the control-loop setting to the biocontroller. The controller parameters do not appear in the window, as the type of biocontroller under consideration does not have the capability to accept them through the serial communication. These parameters are adjusted manually using the biocontroller's buttons. The control-loop settings VI is built using the Biostat command protocol. The biocontroller has an option to execute the sent control-loop parameters immediately or to execute them later. The operator can specify the mode the process should start with. If the check box is ticked 'On', after pressing the 'Send' button the controller will immediately try to reach the specified set point. If the check box is *not* checked, the controller will not try to reach the specified set point, but

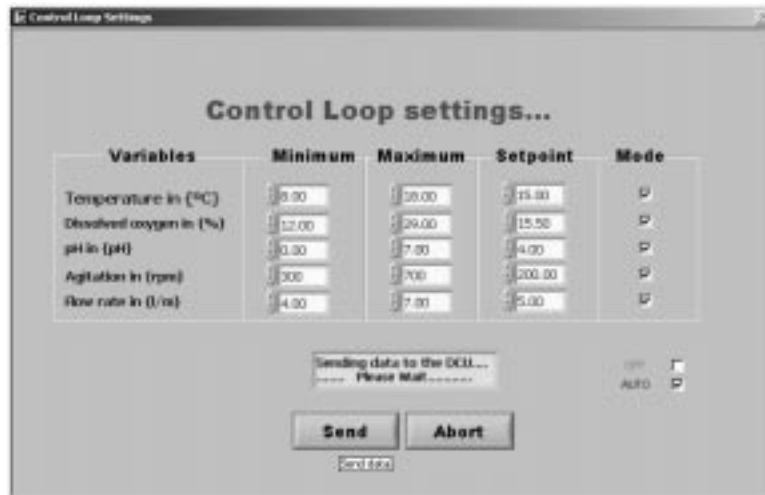


Fig. 11. Control-loop settings window.

will run from the old set point values. After inserting the values in the fields, data will be sent to the biocontroller when the 'Send' button is pressed. When the 'Send' button is pressed, the indicator pops up and displays the sending progress. The 'Abort' button discards the changes made to the data fields and the process will then run from the previous control settings.

CONCLUSIONS

The strategy that has been developed and the LabVIEW program are used to address the problem of real-time control of the fermentation processes. The ability of the developed program to store and display the process data and to vary some of the fermentation set points with simple commands makes the control system very effective. The software that has been developed integrates LabVIEW's ability to monitor and supervise control with the fermentation unit's facility for data acquisition, serial communication and direct PID control. The developed system automates the operation of the lab scale fermentation unit for the production of yeast using a lab scale fermentation unit from B-Braun Biotech GmbH (Biostat[®] C model). It can be used as a basis for further development of methods and programs for process

modelling and optimization in real time. It is safe, stable and practical and can be used in any industry where there is significant need for monitoring and optimization of the fermentation processes. The positive characteristics of the method's algorithms and programs are as follows:

- The model incorporates the physiochemical variables in the biological mass balance equations. In this way the influence of the enzymes over the biological variables is utilized and possibilities are created for process optimization.
- The process can be optimized in both physiochemical and biological variables.
- The physiochemical variables can be used as control inputs to reach the process optimization.
- The data acquisition system allows for analysis and simulation of the process.
- The optimal control of the process is achieved without using expensive on-line sensors for measurement of the biological variables, which is why this system is applicable to the existing hardware and software control and measurement systems in industry.

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