Innovation in industrial model predictive control

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The industrial application of model predictive control has been largely confined to petrochemical processes. Extension of exploitation to wider industry has been limited. Among the reasons that may be proposed for this can be highlighted a lack of precedent applications, large engineering costs and inappropriate control technologies. This article describes initiatives to address such barriers so that the benefits of MPC can be more widely available: demonstration projects on mainstream process applications; software tools to minimise engineering costs; embedding MPC within the plant regulatory control system; and a flexible approach to control technology so that solutions can be tailored to best match process situations.

Predictive Control Ltd. (PCL), a small spin-off company from the University of Manchester, was acquired by Invensys plc in 1997. There has followed a close association with Foxboro, a sister Invensys company. In the last two years, effort has been directed to advance both the software and control engineering capabilities of PCL's model predictive control (MPC) product Connoisseur[3] and to extend its industrial application base. These activities have been carried out under joint programmes, involving PCL, Foxboro and the University. This article describes aspects of these developments, as follows:

(i) Widening the scope of exploitation of MPC in industry. MPC has become a commodity technology for hydrocarbon processing. The potential for exploitation in wider industry is vast. To give indication of this potential, three recent application projects that have been carried out by Foxboro are reviewed.

(ii) Software engineering: An application of MPC can be complex, dominated not by control engineering but by issues of integration with plant data and with plant operators and engineers; by issues of integrity within a distributed control system (DCS) infrastructure and issues of reliability and maintainability. Software has been developed to cut through these issues so the commissioning engineer can focus on controller development rather than being distracted by the needs of application architecture. Such streamlining allows timescales for project execution to be cut dramatically.

(iii) More capable control technology. The control engineering capability of Connoisseur is under continuous enhancement in line with the state of the art. One recent project is to extend the MPC to be able to manage processes for which the dynamics are modelled with nonlinear radial bass function (RBF) neural networks. This offers potential to better deal with processes that have difficult nonlinear relationships[5] which for example are more prevalent in the arena of batch processing than in the continuous processing that has been the traditional arena for MPC exploitation. The capability of a prototype nonlinear controller is reviewed.

Application 1: Copper ore grinding

This application was commissioned at the ASARCO Mission Mine, Arizona, (Fig. 1) on the North Mill


Fig. 1 Panorama of the Mission Mine

Grinding Operation. A 'proof of concept' study was carried out during Spring 1998 with final commissioning completed later in that year. The North Mill processes copper ore to produce copper concentrate. The operation totals eight grinding circuits together with associated upstream ore handling and downstream flotation operations. Six of these circuits consist of a single rod mill operating in series with two ball mill and cyclone combinations (Fig. 2). A further two circuits consist of a single rod mill and ball mill connected in series.

The two major issues for control are to

- drive the line to its optimum operating point
- maintain control through variations in ore characteristics.

The MPC application has successfully addressed both issues and has demonstrated the ability to

- increase feed rate to each grinding circuit without violating operating limits on the mill such as maximum particle size, cyclone overflow density, cyclone pump current etc.
- minimise particle sizes when feed is limited by increasing recycle mass flow, giving dual benefits of increasing recovery and minimising wear on the ball mills.

Some operational problems overcome in the commissioning of the MPC application include:

- mill overloads
- varying ore characteristics
- variable process gains
- variable and complex process dynamics, including reverse response
- multiple process constraints/multiple lines
- changing equipment capacity
- changing feed availability
- difficult process measurements
- abrupt upsets.

The complete MPC solution consists of distinct components as below:

Multivariable control

A separate multivariable controller is used to control each of the eight grinding circuits. Columns in Fig. 3 represent manipulated variables (MVs) within the control scheme; rows depict controlled variables (CVs) which represent both operating objectives and process equipment constraints.

Each controller requires access to a number of process models to represent the process dynamics under different operating regimes (e.g. with varying ore hardness). The controller selects automatically the appropriate control model by determining which one provides the best fit to the prevailing conditions. The controllers also make use of online adaptation facilities to modify control models in line with longer-term drifts in operation, such as mill wear.

Steady-state optimisation

Each grinding circuit additionally incorporates a linear programme based optimisation scheme. When feed is available, the optimiser will maximise feed rate subject to equipment constraints. When feed availability is limited the optimiser is configured to minimise product particle size.

Plant-wide feed allocation

Based on information about the availability of fresh feed and the current operation of each grinding circuit the plant-wide feed allocation scheme distributes available feed across all operational lines in order to optimise overall equipment utilisation. The feed allocation application uses a constrained optimisation scheme based on quadratic programming (QP) technology.

Coarse ore storage bin level management

This is a rule-based scheme using fuzzy logic technology which monitors the levels of the ore storage bins that are fed from the upstream ore handling facility. The bin management scheme determines the total available ore for the feed allocation scheme.

Mill overload control

Mill overload is the 'recurring obstacle' to process optimisation. Any increases in ore hardness and size will cause an accumulation of ore in the grinding circuit

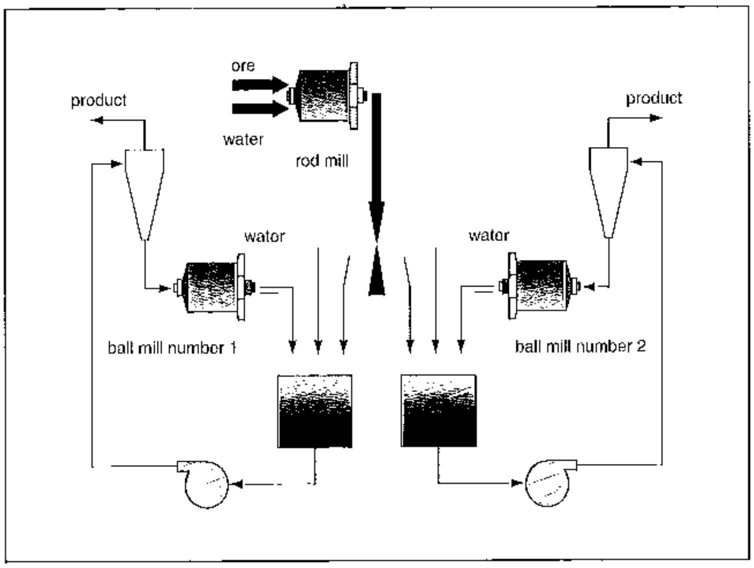
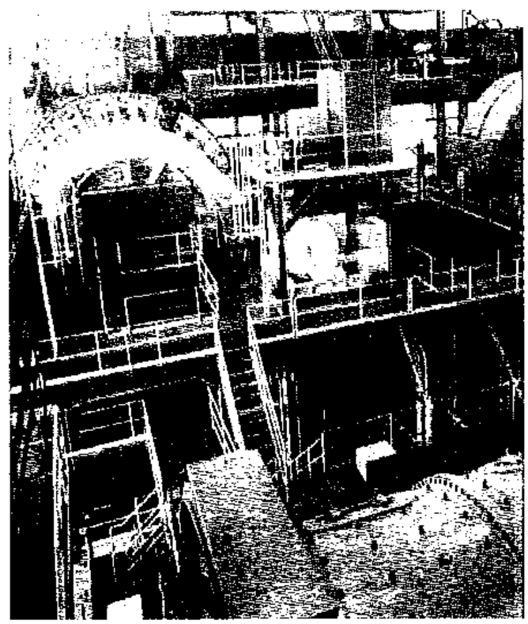


Fig. 2 The ball mill process: (left) schematic representation of a grinding circuit and (below) photo of a ball mill



and may ultimately overload the mill. This condition is detected by monitoring key process measurements including derivatives of mill current and recycle pulp mass flow. On detection of an incipient overload condition the controller must act promptly to reduce mill feedrate, or shift load between the ball mill circuits. The overload controller acts as a supervisory mechanism to the control and optimisation schemes on each grinding circuit.

Benefits

The basic regulatory system for the grinding circuit, in use before the MPC system, manipulates feed rate to control particle size. This design maximises feed rate subject to particle size specifications, which are input by the operator based on management directives or downstream flotation recovery requirements. At other times, the operator may disable particle size controls and fix the feed rate to the grinding sections. The scheme does not explicitly address equipment loading constraints or variations in ore characteristics. Each line operates independently of the others.

By contrast, the MPC scheme provides optimum operation of the grinding section of the plant under all feed conditions. When availability of feed is not the production bottleneck, the individual controllers maintain constraint control for each grinding line, maximising production rate to equipment capacity and operator-entered product size constraints.

When feed is limited by upstream conditions, the system optimises performance of all the grinding lines by limiting overall production to operator set limits, while allocating feed to equalise particle size at the smallest possible value. The feed allocation scheme oversees the co-ordinated operations of all grinding lines, allocating feed for maximum downstream recovery during these periods. Under all conditions, process constraints arising from mill loading, ore hardness, water supply limitations etc. are respected.

Application 2: Utility boiler optimisation

This project was conducted on Unit 3 of The Lower Colorado River Authority's, Sim Gideon Power Plant in Texas. The unit is a 340 MW, natural gas, tangentially fired, single furnace, Combustion Engineering boiler. The objective was to use the MPC software, interfaced to an existing Foxboro I/A control system, to improve the unit efficiency (heat rate – Btu/kWh) without detrimental effect to greenhouse gas emissions from the boiler. A

	mill feed rate	feed splitter	mill number 1 water	mill number 2 water
number 1 particle size	X	X	X	
number 2 particle size	X	X		X
number 1 feed mass flow	X	X	X	
number 2 cyclone feed mass flow	X	X		X
number 1 cyclone overflow density	X	X	X	
number 2 cyclone overflow density	X	X		X
number 1 cyclone feed density	X	X	X	
number 2 cyclone feed density	X	X		X
number 1 pump current	X	X	X	
number 2 pump current	X	X		X
number 1 cyclone feed flow	X	X	X	
number 2 cyclone feed flow	X	X		X

Fig. 3 Cause and effect matrix for single grinding circuit

secondary objective was to reduce NO_x emissions. Reduction in unit heat rate naturally leads to reduced CO_2 emissions per MW of generation.

The control solution was designed to reduce overall unit heat rate by reducing air flows (excess oxygen) within the boiler and by maintaining superheat and reheat temperatures at their required operating target. To avoid compromising existing control of the boiler the MPC scheme was designed to manipulate bias parameters to existing regulatory schemes. Fig. 4 shows the cause and effect matrix. The application was

	O_2 bias	auxiliary air bias	fuel air bias	A level bias	B level bias
RH temp	X	X	X	X	X
SSH desup spray valve	X	X	X	X	X
NSH desup spray valve	X	X	X	X	X
auxiliary air demand	X	X	X	X	X
FD fan demand	X	X	X		
fuel air demand			X		
stack NO_x	X	X	X	X	X
stack CO	X	X	X	X	X
unit heat rate	X	X	X	X	X

Fig. 4 Cause and effect matrix for utility boiler

commissioned over a seven week period which consisted of three weeks of plant step tests, two weeks spent on data analysis and controller design and a further two weeks at site installing the controller and training the unit operators.

Benefits

To verify the effect that the optimiser had on the process a separate verification test plan was produced to simulate the normal unit load profile for a typical day. The same test of 10 hour duration was conducted twice on consecutive days: with and without the optimiser in service. The results showed

- 35% reduction in unit heat rate over all load conditions and transitions
- 55% improvement during steady load
- reduced NO_x emissions.

Application 3: Lime kiln optimisation

A lime kiln is an important unit operation in the production of pulp for paper manufacture, supplying reburned lime to the recausticising operation. It is the largest single energy consumer in the mill. The main objective of lime kiln operation is to produce uniform quality lime. Additional operating objectives include minimising fuel consumption and complying with environmental regulations. Given the long process delays and interaction inherent to the lime kiln, these objectives can be extremely difficult to achieve under traditional kiln operation.

The kiln is operated over a wide range of production rates. In addition, the lime mud feed is cut off for approximately 5 minutes in every 4–8 hours in order to clean the mud filters. These process disturbances can result in a significant variation in lime quality as well as increasing the risk of damage to the kiln refractory due to overheating.

Fig. 5 shows a block diagram of the overall control scheme. The lime kiln controller maintains the required kiln temperature profile by manipulating the kiln firing rate and air flows. Excess oxygen and kiln emissions provide additional constraints to the operation.

Lime quality is determined by the amount of residual carbonate in the reburned lime product and is measured by the process operator every 2–4 hours. To enable closed-loop control of this variable an inferential model of lime quality was developed using a neural network. Lime quality is a strong function of the temperature profile of the kiln. To maintain closed-loop control of this nonlinear variable a simple fuzzy rule based control scheme is utilised. This scheme sets the required kiln operating temperature based on inferred lime quality and current lime discharge temperature.

The lime kiln optimisation scheme was commissioned over a four week period which included one week of plan step tests, one week of data analysis and controller design and a further two weeks at site installing the controller and training the unit operators.[1,2]

Benefits

The following benefits are obtained from the lime kiln optimisation scheme:

- reduced variability of lime quality
- reduced fuel consumption
- reduced risk of kiln damage due to high temperatures (kiln refractory and feed equipment damage)
- overall improvement in kiln stability (rejection of disturbances due to mud filter rewash)
- potential for increased production where equipment capacity is limited
- reduced airflow reduces emissions due to dust losses and improves overall efficiency through reduced exit gas temperatures.

Software engineering

MPC has become essential to enable companies in the process industry to attain ever higher performance objectives. Historically MPC evolved in the petrochemical industry where large-scale control problems had led to complex PID control structures. The amount of computation involved in MPC directed most implementations towards a high-end workstation integrated into the process DCS through a local network. However, MPC products are now in their third generation and, as control algorithms become more efficient and computing power is soaring, it is common to see MPC solutions installed on a low-cost PC platform.

Unfortunately by locating the MPC software on a separate computer, connected to the process over a network, the fault tolerance of the system as a whole is degraded. Mature MPC products have the ability to deal with lost sensors and actuators, but problems with the network or computer can take the controller unpredictably off-line. There is also an issue of operator retraining, a costly but necessary task when a new system is introduced. The use of an MPC product brings new information and user interfaces to the operator's console.

Integration

MPC products generally provide a number of tools to aid commissioning of a process. However, it is not the cost of equipment and software that generally dictate the cost of commissioning, it is engineering time. It is therefore important that an engineer spend as much time on the process as possible doing control engineering, rather than system configuration and maintenance.

Configuration of both hardware and software is a time consuming but necessary task that exists in every new application. The DCS must be interrogated to extract a list of available sensors and measurements, these are then used to co-ordinate a process response test in order to collect data for modelling. Once a control scheme has been developed, the DCS user interface must be configured to give the operators access to the key parameters and information necessary to operate the new control scheme. These are both examples of configuration tasks that are essential, but detract from the job of engineering an effective control strategy for the process.

A set of tools has been developed which closely integrates the Foxboro I/A system (the DCS) and the Connoisseur product suite (the parent product). Known as the integration product this consists of the parent product software, an extended set of DCS application objects, the API server, and a set of configuration utilities (see Fig. 6). The net result is a hardware and software control system which is easier to use, wastes less engineering time, and outperforms traditional control strategies.

The integration product supports the automatic configuration of the MPC signal database. The DCS is scanned for all relevant process signals for a defined process area, as this avoids the possibility of missing important information during data collection. The MPC is automatically configured with the appropriate MVs to

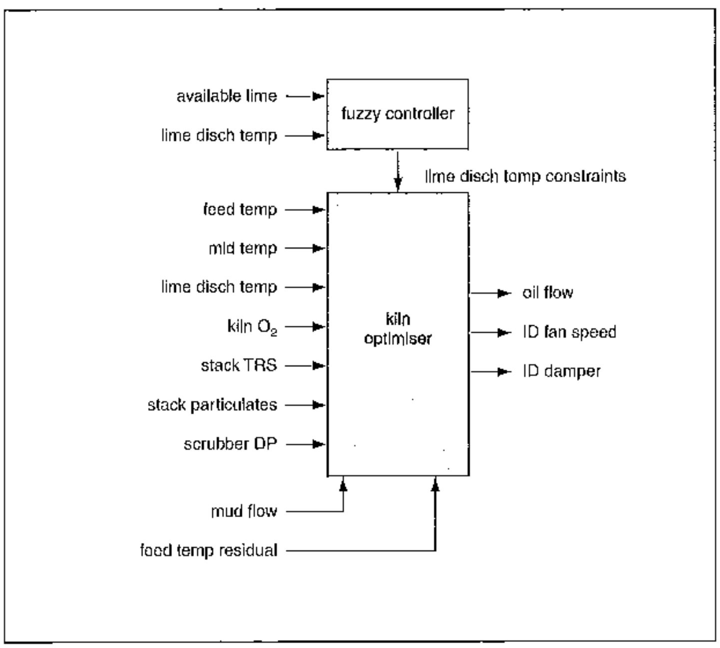


Fig. 5 Kiln optimiser block diagram

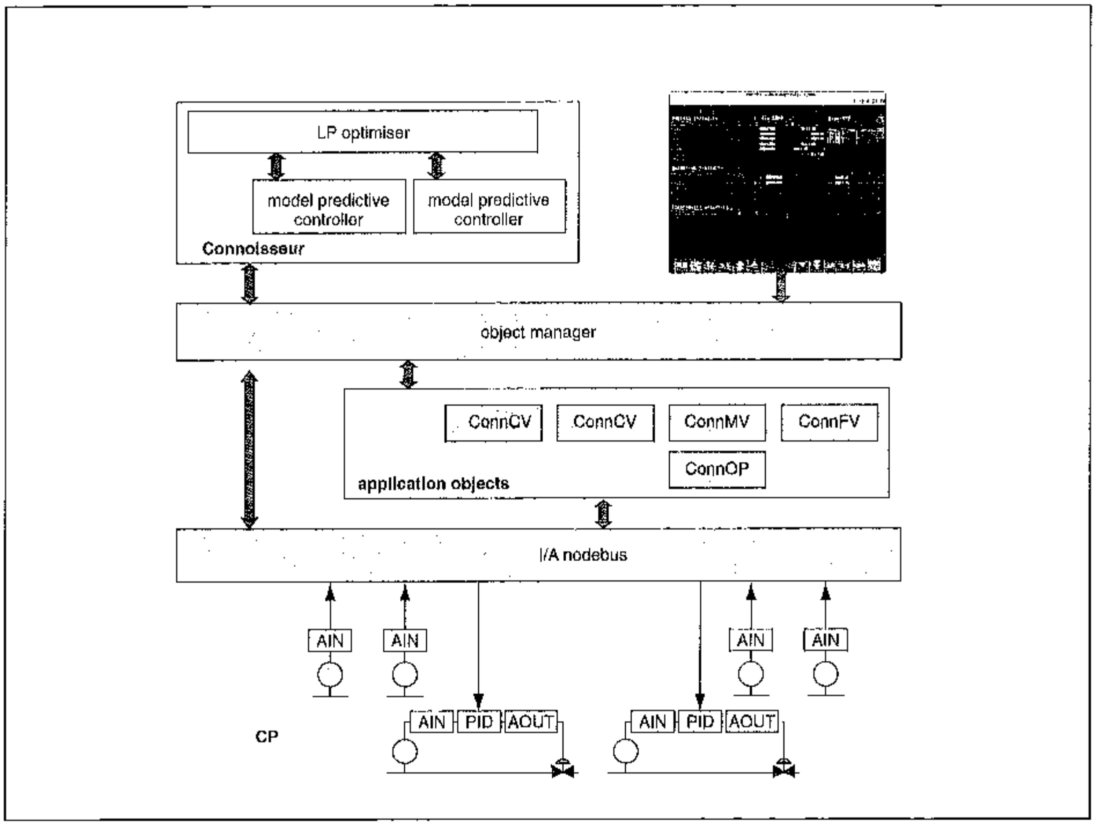


Fig. 6 Integrated I/A architecture

generate plant test sequences (e.g. PRBS).

After data collection the engineer is then free to develop the appropriate models and controllers from the test run on the process. The resultant control scheme can be validated using the relevant MPC simulation facilities before deployment.

The DCS utilises an object-oriented database to which external applications can write information via the API server. The MPC package is thus able to write information into and read information back out of the DCS. The DCS control system uses data within the object databases to control the process. The integration product utilities support the automatic configuration of the object database, the operator displays, and all the signal information required to support the application, including sensor validation status, MV read-back, wind-up status etc.

The integration product uses the standard DCS control features that allow secure supervisory control of the DCS control blocks. This allows access to features such as back-calculated setpoint values to allow bumpless initialisation together with explicit wind-up indication. The automatic time-out detection and fallback actions that are available are used to provide safe and secure control in all situations.

The utilities can also generate a standard DCS display for use on the operator consoles on the process. This provides seamless integration between the operator and the MPC software. All information required for execution of MPC is displayed in an environment that is familiar to the operator, reducing the need for training with the new technology. The MPC design system is still available, so that an engineer can tweak the controller at source.

The integration product reduces engineering time required to commission a new application through reduction of configuration time of both hardware and software, and allows engineers to concentrate on the control problem. It also allows for a standard implementation to be reproduced on subsequent applications with minimal configuration effort.

Embedded MPC

An embedded MPC product has been developed which enables the deployment of MPC within a control processor (CP) on the Foxboro I/A system. This product is foremost a deployment option for MPC, and the parent MPC product is still required to test the process for data collection, identify model structures and coefficients and design an appropriate controller. The resulting controller can then be downloaded into the CP on the process (see Fig. 7). The MPC product can then be detached from the plant, and MPC executed from the CP.

In this workflow construct, the 'heavy lifting' of analysis and identification is performed outside the DCS to generate the application 'configuration' with the run-time entity in the most secure level of the DCS hierarchy.

The MPC application is downloaded into two new block types in the CP, retaining the standard block operation, displays and alarms of the CP. This is considered an evolution of the block processing capabilities of the DCS, and will ease transition and training of operators (Fig. 8). The MPC application is treated as a supervisory control entity and utilises the DCS's secure supervisory control (SSC) to ease integration into existing CP based control schemes. The MPC application is run as a low-priority task in the CP, so that any issues with the application will not affect the regulatory control system integrity.

A significant concern from a product maintenance perspective was creating a means of keeping the embedded MPC product current. This issue was solved by creating a common mode stream for the parent and the embedded MPC products. The respective products literally share a common code base, ensuring identical control behaviour, and bringing advances in the control engineering of the parent product over to the embedded MPC product. The particular MPC algorithm has brought excellent unmeasured load rejection performance to the DCS.

The embedded MPC product addresses a number of key issues associated with MPC, and in doing so widens the potential applications base for users. The product is offered on a true fault-tolerant platform, offering DCS levels of availability, and removing the need for a separate workstation and network.

The embedded MPC product has been integrated into the CP block family with considerable attention being paid to the look and feel. The intention is to provide an advanced control capability whilst retaining the user friendly look and feel of the DCS. This should result in the expanded use of the technology but without the attendant high training and maintenance costs.

Prototype for industrial nonlinear MPC

This section describes development to employ the multivariable and constraint management concepts of MPC in a nonlinear context.

Linear MPC

Within Connoisseur, one approach to linear MPC is to employ QP to minimise a cost function compounded from predicted MV absolute and incremental moves and CV errors.[3] This QP is configured to deal only with MV hard constraints. CV constraint violations (soft constraints) are dealt with by using closed-loop simulation to estimate process behaviour over a defined prediction horizon. If violations are predicted, the control objectives are altered, subject to defined priorities that permit sensible management of degrees of freedom, to prevent the anticipated violations from arising. In comparison with solving the soft constraints within the full QP address, this

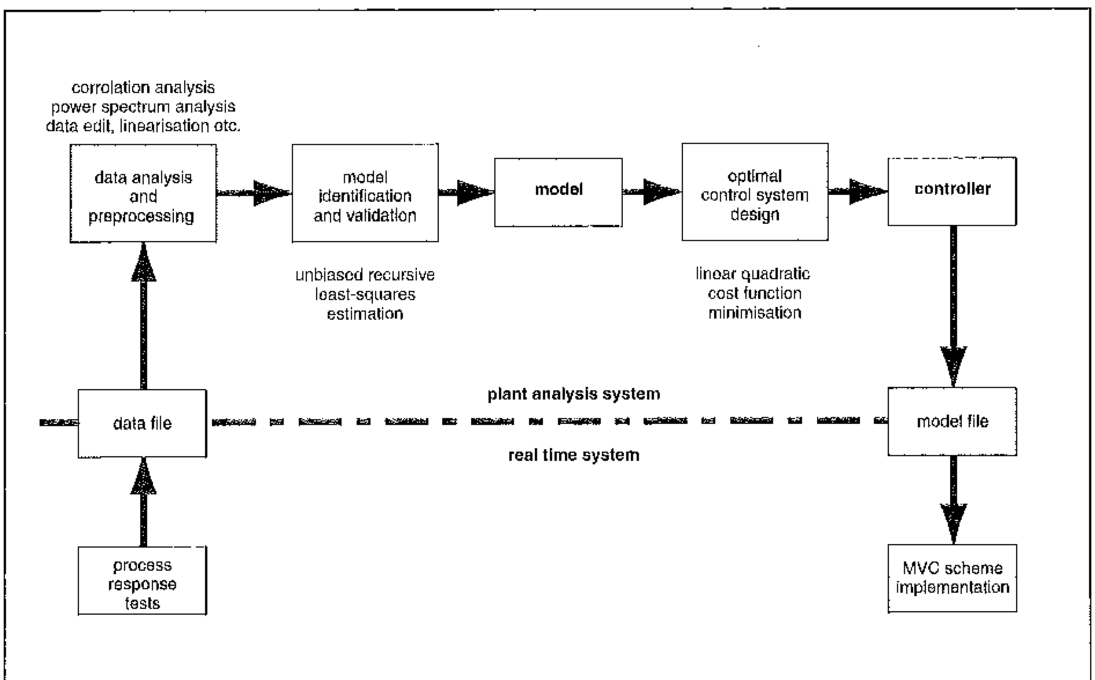
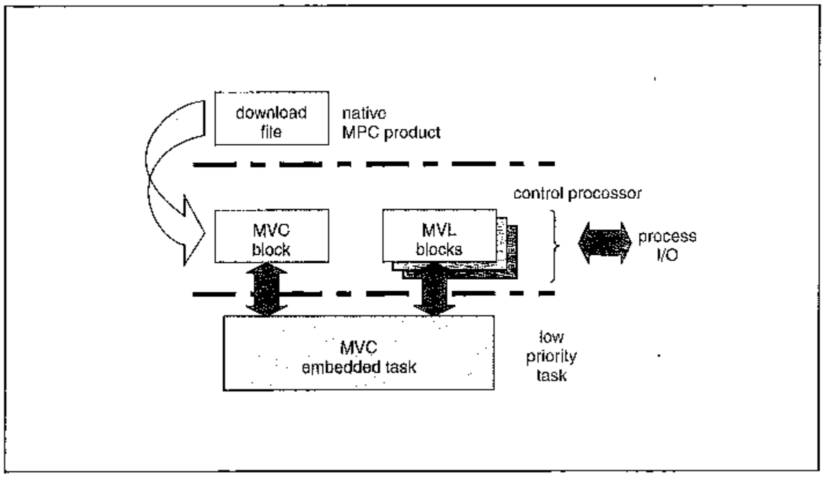


Fig. 7 Embedded MPC workflow

Fig. 8 Embedded MPC concept



approach is computationally more efficient, avoids issues of unfeasibility and provides better control engineering balance between the management of setpoints and of soft constraints.

Implementation of nonlinear MPC

For nonlinear MPC, in place of a linear ARX model, the system is instead modelled using an RBF neural network.[7,8]

The resulting MPC cost function thus incorporates a general nonlinear component from predictions of CV errors. The minimisation of this function is achieved using successive quadratic programming (SQP).[6] This approach to nonlinear control involves repetitive evaluations of the nonlinear model as the solution progresses.[4,5]

The proposed methodology offers a flexible method of implementing nonlinear control for a wide range of processes with little more effort than for the linear case.

SQP is a constrained nonlinear optimisation technique which is suited for use in nonlinear MPC applications. SQP relies on gradient information, including a Hessian matrix that may be known in advance or updated online from an initial estimate.

Each iteration of the SQP procedure involves two distinct stages. Firstly a QP problem is solved to yield the direction in which the solution should move. As the use of a quadratic solution is only approximate for a general nonlinear function, a step length must then be computed such that the combined move guarantees to reduce the objective function in some optimal way.

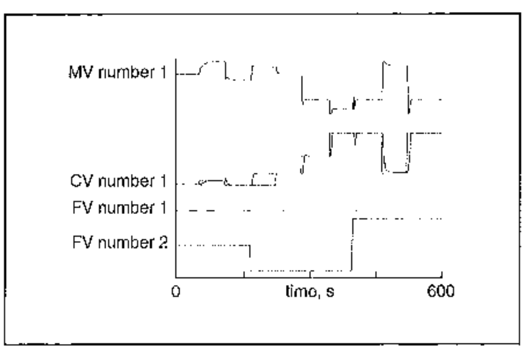


Fig. 9 Simulated pH control

The starting point of the solution is initialised to the current values of the MVs (i.e. a 'do nothing' strategy) and the solution is found in terms of the absolute MV values. The Hessian matrix is initially set to an identity matrix and updated online using the BFGS Algorithm.[6] This approach ensures a positive-definite Hessian matrix at every iteration and thus the continuing solution of the QP problem, plus quadratic convergence as the final solution is approached. This updating approach is necessary for nonlinear control since the Hessian matrix cannot be estimated from the RBF model as it can from a linear ARX model. However, the guarantee of positive definiteness makes it arguable that the updated Hessian approach is optimal even in situations for which the Hessian matrix may be evaluated exactly.

At each iteration, the QP problem is formed in terms of the constraints, constraint gradients and the gradients of the cost function, to yield a direction of movement. In the second stage, a one-dimensional minimisation approach is employed to find the distance that the solution should move to optimally reduce the cost function. For this 1D problem, an additional merit function is defined from the MPC cost function and the constraints, and this is minimised in order to guarantee a valid solution for the MVs.

The formulation of the MPC solution avoids the need to handle nonlinear soft constraints within the SQP. This simplifies coding and eliminates errors of linear constraint approximation, thus making exploitation more straightforward.

Case study in nonlinear MPC

Initial evaluations of the performance of the SQP have been made by assessing the capability of the SQP to match the control performance of straightforward QP in application to linear systems (for which the Hessian is computed directly from the linear model). Results show that solution time for the SQP is at least a factor of 10 greater than for the QP for a problem that involves 10 variables. The SQP solution takes some 20 iterations for the successive updates of the Hessian matrix to converge. The results do demonstrate the capability of SQP to generate equivalent controller performance provided that there is time between controller updates to complete computations.

To demonstrate the functionality of the prototype SQP controller, the SQP approach is used to control a nonlinear system, modelled by an RBF, and for which traditional linear MPC is unsatisfactory.

The study relates to an effluent treatment plant for which product pH is to be controlled via manipulation of reagent flow. Two FVs are included, the effluent flow and effluent pH, respectively.

If linear MPC is employed, using an approximate linear ARX model, the response to changes in pH setpoint is strongly dependent on the operating regime of the process. The response is overdamped in some regions and highly oscillatory elsewhere, and overall represents an unsatisfactory solution.

The nonlinear relationship between pH level and reagent flow is such that the pH responds readily to changes in the reagent flow around the middle of its range but is relatively unresponsive to changes in flow as the upper and lower limits of the pH range are reached. The cause and effect relationships of this system have been modelled with an RBF network and this nonlinear relationship has been processed by the SQP to effect control.

Fig. 9 shows the nonlinear controller in operation. The top trace is the MV (reagent flow) varying full scale. The second trace is the CV (pH) varying between 0 and 9. The total data span is 27 minutes with control updating every second. The bottom two traces are the FVs. The responses to setpoint and FV changes are seen to be consistent across the operating regime, due to the use of a realistic nonlinear model within the MPC formulation. Close inspection of Fig. 9 shows the CV and setpoint parting company occasionally. Most of these occurrences correspond to high MV saturation. The remainder correspond to situations where the process gain is essentially zero because of the influence of nonlinearity. It is interesting to note that under such a situation the MV is not subject to integral wind up, which would arise for classical regulatory control.

Conclusions

The application studies emphasise the need for flexibility in approach. None of these solutions was attainable by the exploitation of MPC alone. It proves necessary to augment the standard technology with various enhancements (e.g. adaptive modelling with grinding circuits, purpose calculations with boiler optimisation, rule-based control with the lime kiln), to achieve final acceptability. Such flexibility is the key to successful industry wide exploitation of MPC.

The described software engineering programme is ongoing and there is much yet to be achieved. It is a constant battle to maintain pace with operating systems such as Windows NT and development systems such as Java (both of which figure strongly in the products referred to above). The embedded MPC module is currently of restricted scope because of limitations in the power of the DCS hardware. The DCS will be updated in the coming months which will enable the CP to support more comprehensive solutions, perhaps even to be able to absorb the nonlinear aspects!

It is early days for nonlinear MPC. It is one thing to establish and prove an engineering prototype. It is quite another to consolidate that prototype to operate robustly in day-to-day exploitation. Most MPC applications do not require a nonlinear approach. A key issue is to determine process situations that require a nonlinear solution so that such solutions do not propagate in applications that can be dealt with quite adequately by the straightforward linear address.

Acknowledgments

The authors gratefully acknowledge:

A. Morrow, C. Burns and D. Labbe (The Foxboro Company)

A. P. Burrows and A. G. Mitchel (PCL)

T. Kinney and N. Divittorio (Invensys Intelligent Automation)

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