AUTONOMOUS LOCAL CONTROL AND REMOTE MANAGEMENT: ALTERNATIVE FOR CRITICAL INDUSTRIAL AUTOMATED SYSTEMS

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Abstract. *In automatized industrial systems inactivity due to unplanned shortage of resource or process failures have a great influence on system performance because it generates discontinuities and instabilities. Distributed and autonomous control systems may help to cope with this kind of problems because of improved performance, but safety issues and real time constraints must be tightly addressed in these systems because of the risks involved (human, financial and environmental). Therefore an intelligent control system instantiated at the local level is proposed to allow each controller to takes critical decisions in an autonomous way. Above this, a remote system manages more complex situations beyond the capabilities of the local control system. The proposed control enables auto-adjustment in the system in order to improve its performance, to prevent and treat unexpected faults. Thus, it learns through events which have occurred in the system and environment, using Artificial Intelligence tools.*

Keywords: *autonomous control, industrial applications, distributed control, remote management, real-time systems*

1. INTRODUCTION

Stability is a fundamental requirement in the design of control systems. In addition, the system must have a suitable response time and it must be adjusted in order to also reduce its faults to a minimum acceptable value. However, precision and acceptable response time tend to have conflicting requirements, and an efficient relationship must be established between them in order to satisfy the most critical restrictions in the system.

As a consequence of the increase in the complexity of industrial systems, there are generally a high number of control meshes present in an industrial plant. Since the resources to ensure optimal performance of such meshes are limited, there is a growing need for more intelligent coordination between their various controllers so as to maintain satisfactory operation and allow a high degree of fault tolerance (Sreenivasachar et al, 1997).

Most of the complexity of a high reliability system is related to fault detection and recovery routines (Randell & Xu, 1995). Furthermore with the greater complexity of the system to control comes the need for a higher sophistication level for the controller. An alternative way to represent the dynamic behavior of these systems is the use of hybrid models. Such models reduce the complexity of the system by incorporating models of dynamic processes with different abstraction levels. It is then possible to define a basic structure and methodology for the analysis and synthesis of intelligent systems to ensure correctness, performance and stable, safe operation of the system (Antsaklis et al, 1998).

In systems that are subject to frequent unforeseen events, adopting purely conventional control functions is not always an efficient solution because the system may need to adapt in real time to internal faults or to unforeseen environmental alterations to ensure and even improve its own performance and solidity (Antsaklis et al, 1989). In this respect, this study includes a proposal of a local autonomous control system for industrial systems with critical performance and geographically distributed cells.

2. BACKGROUND

Currently, industrial automated systems can achieve high levels of complexity, making it difficult to efficient supervision by a single operator. Thus, for reasonably complex systems, it has been common to designate several operators, so that each one monitor and control specific subsystems of the system. As a result, operators have become specialists in sub-areas of the process, operating simultaneously several HMIs. However, these actions usually occur manually, requiring the presence of operators in supervision and control rooms. Besides, these actions are subject to the implications of non-automatic processes.

However, in the case of distributed systems with strong interdependency between the information exchanged or involving cooperation among them, monitoring and control tasks become difficult to perform manually, especially when seen continuity and response time constraints.

When decision and control tasks are performed by autonomous, distributed and heterogeneous systems, coordination becomes a most important aspect, because actions should be directed to the overall objectives of the system. Thus, local actions must be undertaken in order to achieve the expected results and to avoid undesirable situations by linked systems, and enabling that the whole system can evolve in agreement and safe way.

Intelligent, autonomous control systems are designed to operate without external interventions in environments subject to unforeseen events and uncertainties in the decision process. In addition, they have to carry out some control procedures apart from conventional ones. Such functions include adjustments, learning and adapting to environmental changes and to internal system faults in order to improve their performance and stability (Antsaklis et al, 1990).

In the control of industrial systems, many problems that occur are caused mainly by an inadequate decision-making and action time when facing a system instability situation. When corrective action is delayed, instability may cause a reduction in profit or even direct damages deriving, for instance, from damage caused to equipment, loss of equipment or material, or loss of production. Consequently, availability and continuity problems arise as the system has shown that it does not rely on an effective procedure to prevent or contain the problem within a useful time frame (Pacheco & Lepikson, 2009).

In addition, according to Torres & Hori (2005), PID (proportional–integral–derivative) controllers lack sufficient effectiveness to ensure the high performance necessary for more demanding control systems. In such cases, the adoption of purely conventional control functions is not always satisfactory especially as the system may need to react, in real time, to internal faults or to unforeseen environmental changes in order to ensure and improve its own performance and stability.

Besides the cited losses, if an industrial production system is not controlled correctly and in time, environmental disasters as well as many other problems may arise as a consequence of inadequate operation of the controller.

However, although such problems have evaded a deterministic solution, specialists have been able to resolve them in a satisfactory manner by using their knowledge and reasoning. In this context, artificial intelligence techniques have been developed (such as fuzzy logics, artificial neural networks, knowledge representation, to name a few), to enable a computer to deal with problems by simulating some of the ways in which humans use their knowledge and reasoning to solve them (Luger, 2004).

This work proposes a control alternative for automated industrial systems so that the system can become autonomous and it can function predominantly at local level. Thus, even with a loss of connection with the remote management level, each cell will be able to manage the local control and interact with other distributed cells.

3. CASE STUDY: PETROLEUM PRODUCTION FIELDS

Petroleum wells and fields can be seen as an interesting case study of distributed manufacturing system. At present the most common topology in oil well control, when automated, is typically master-slave. Communication between local controllers located at each well occurs in hierarchical form, whereby a remote exchange periodically collect the results produced by the set of wells it monitors. This is achieved by means of PLCs (Programmable Logic Controllers) coupled to each production system which send the requested information by radio frequency. However, local controllers basically perform conventional control functions, such as on-off control and PID, which are not always sufficient.

Communication between local controllers and the exchange occurs in asynchronous form, which renders the system inflexible and often inefficient as many problems that should be detected and handled quickly are handled manually or after a long wait, when the system may already be in collapse and with irreversible impairment of the controlled system or its environment. Cases in point are emergency situations requiring a quick, immediate solution, such as oil pipe ruptures or motor overload. Today, detection by the remote exchange may not be immediate and the solution depends on the actions of local operators who besides having to work in inhospitable locations are also subject to delays in detecting the fault point as well as to the delays due to their movements on the ground (Pacheco & Lepikson, 2009).

For the system under analysis, the flow of materials produced by the well or injected in it (gas, water, etc.) is controlled. Properties such as temperature, flow, pressure and others have to be monitored as they determine the level of productivity and the operation of a well (analog control). Opening/closing valves, on/off and shut-down operations, among others, need to be managed as well (discrete control). The control devices consist of detection equipment (pressure gauges, temperature, vibration, flow, etc.), actuators (valves, motors, etc.), communication devices (asynchronous transmission by radio frequency to the central control station) and control devices (in this case, a conventional control for industrial systems as shown in Fig. 1).

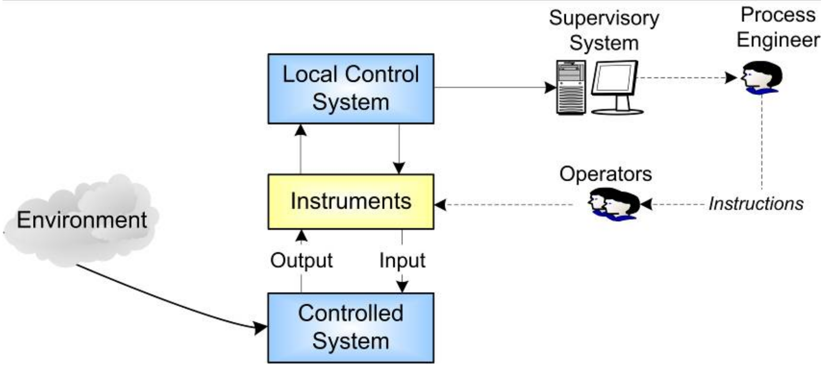

Figure 1. State-of-the-art of Remote Production Cell.

In general terms, the control of a petroleum production cell is carried out at different levels, involving activities that allow a range of events from driving production devices to analyzing and handling collected data, adjusting tags, maintaining equipments and suspending or stopping operation. However, in order for this control to be carried out efficiently, the management of these activities must also be effective, as it involves: production monitoring; corrective, preventive and predictive maintenance of equipment and devices; and adjustment of operations for each cell's production potential.

Such a decision is in fact hindered by the delay in obtaining and handling information, as well as by the delay in determining effective action. Consequently, operational continuity and reliability problems may ensue from the above problems.

4. PROPOSAL

A controller is an important module responsible for ensuring the performance of a manufacturing system because it can compensate for inefficiencies in the controlled systems. An alternative to improve production process performance is distributing the decision-making process among local controllers, thus transferring part of the system intelligence, which was previously centralized, to each production cell.

The proposed system consists of an intelligent control at local and remote level so as to enable the local controller in each physical system to take autonomous complex decisions. Remote management system would step in to help in situations in which a local action is not sufficiently adequate. The proposed architecture for autonomous control is represented in Fig. 2.

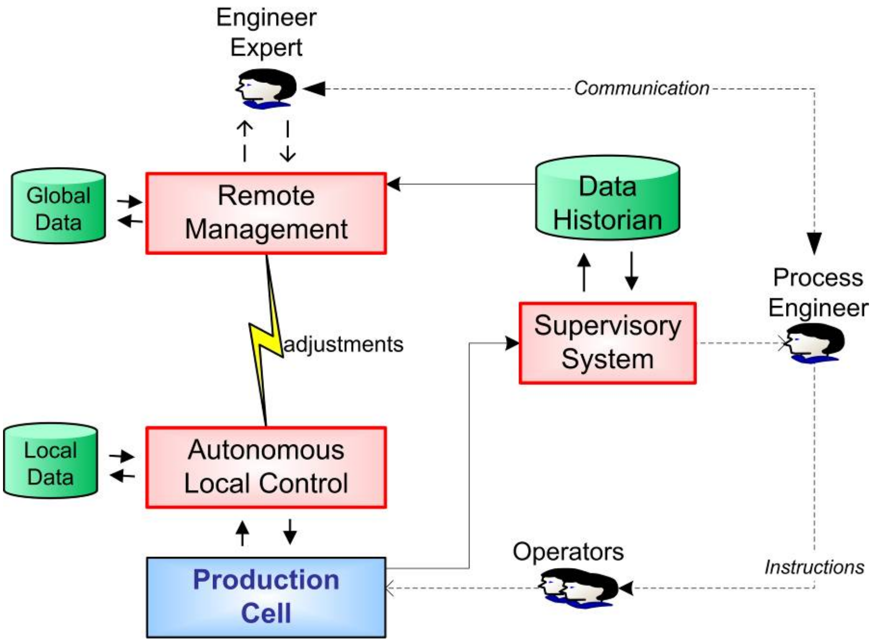

Figure 2. Proposed Autonomous and Distributed Manufacturing System.

Local intelligence must assure that decisions can be carried out objectively, without ambiguous interpretations, and without continuous interference from experts and engineers making adjustments. This intelligence is implemented by an intelligence module connected to process control. It can be embedded, for example coupled in a PLC, with the capability to process a neural-fuzzy algorithm, and store a knowledge-base.

However, if these functions are provided, they are generally found in large and often expensive industrial controllers. An alternative is to connect an external device that supports these capabilities on the existing process controller. This device should be able to perform read and write operations in the control layer.

One of the advantages of separating the intelligence layer in an external device is that if some maintenance or modifications to the intelligence layer is required, the connection within the two layers can be temporarily disconnected. Thus, maintenance can be performed without stopping or restarting the service, and with no interference in conventional control routines.

During maintenance within layers, the process would be controlled in accordance with the procedures of conventional control (e.g. on-off and PID). Any complex decisions will be subject to human intervention.

The intelligence module should analyze the information received from the controller network and its activities during the conventional control, proceeding with adjustments, warnings or shutdown, whichever is necessary.

For remote control, the decision may occur due to instructions from the remote management system, which analyzes the historical series and interacts with each local controller, adjusting parameters, modifying operational and control algorithms or updating the goal functions of the local system.

The control must allow the system to self adjust in order to correct faults and perform preventive adjustments before any malfunction event occurs. To do this, it must learn with events that occur within the system and in the environment around it.

Checking activities must occur continually (so as to foresee and perform adjustments for possible faults before they occur, thus preserving stability and information distribution in the system) as well as in cases of unexpected faults (so as to correct and thus preserve operational continuity of the system).

Even if there is a connection loss with the remote management, each local system should continue operation based in its local knowledge base for decision-taking. In addition, if local data is not sufficient to support a critical action, the cell keeps working in cooperation or in negotiation with its related cells, sending possible fault or instability occurrences to each other in order to adopt the necessary actions based in a node level decision-making (Fig. 3).

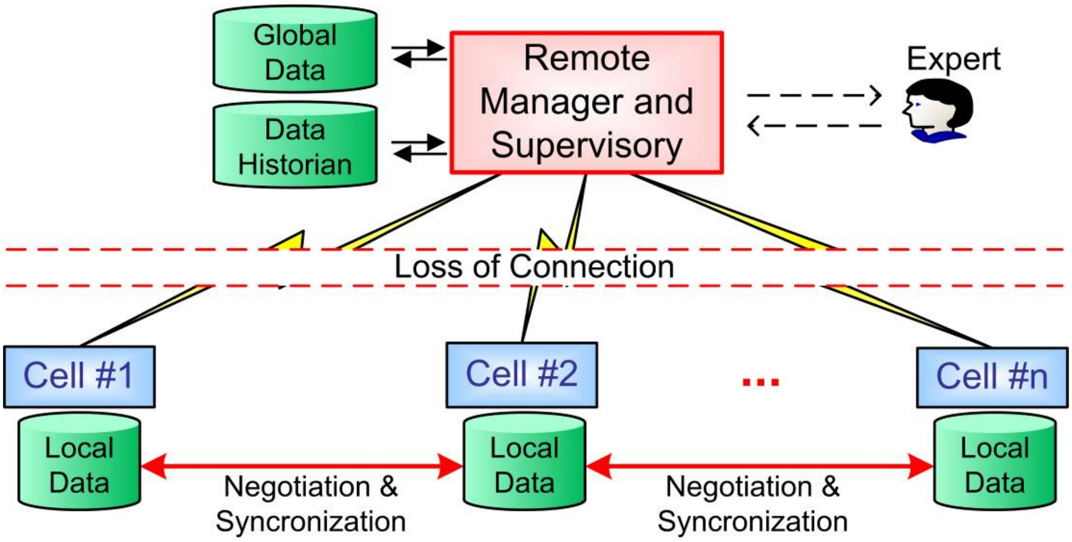

Figure 3. Operation mode in loss of connection

Each local system (cell) must have a list with the addresses of the other interconnected local systems and equipment/devices that have any type of influence on its local performance/operation, for prevention in case of external faults, to be efficient and to avoid its interference into other local system performance and operation. To accomplish this, every local controller must operate according to designed routines for safe autonomous and integrated operations.

An example of interaction among cells is a case in which a variable of a cell varies beyond acceptable limits (upper or lower). In this case, the cell can start to investigate whether the instability is isolated or impacts other cells. If it is isolated, the sequence of investigation occurs only with local data. Otherwise, another investigation is carried out based on information from all involved cells.

In addition, any controller with favorable conditions must coordinate the production rhythm of controlled system, in order to maintain the desired average for the field, without harming the overall performance of the system.

Local intelligence must allow decisions to be taken without the need for a constant exchange of messages with Remote Management System. Local action must occur in such a way that when the remote manager perceives the instability, local measures will already have been taken and the system will already be working safely. In addition, the network must be able to reorganize itself automatically: if a cell fails, the network must remain stable, even when more than one cell is missing.

Similarly, when a new cell is added or an inactive cell resumes operations, it must be automatically recognized and managed. Thus, once aspects of self-organization and safety (such as access control, data cryptography, etc.) are observed and handled, the control mesh can be constituted in a fault-tolerant system.

The main duties of supervisory systems are: (i) supervising the actions of each process as well as the general plant status; (ii) providing routines and test functions for equipment and building remote control strategies for instability that are not handled locally; (iii) have a global overview of plant processes and signal the cells that show any abnormality. In addition, the remote management system carries out analyses and remote adjustments in autonomous controllers.

4.1. Model Abstraction Levels

The structure of the proposed system draws on the CBD (Component-Based Development) paradigm, which emphasizes the design of parts or components interacting through well defined interfaces that can be implemented independently of each other. This division of tasks allows different components of the same software system to be developed or be maintained by different teams at distinct times (Brown & Wallnau, 1998).

Fig. 4 provides an overview of the environment with its basic interaction levels.

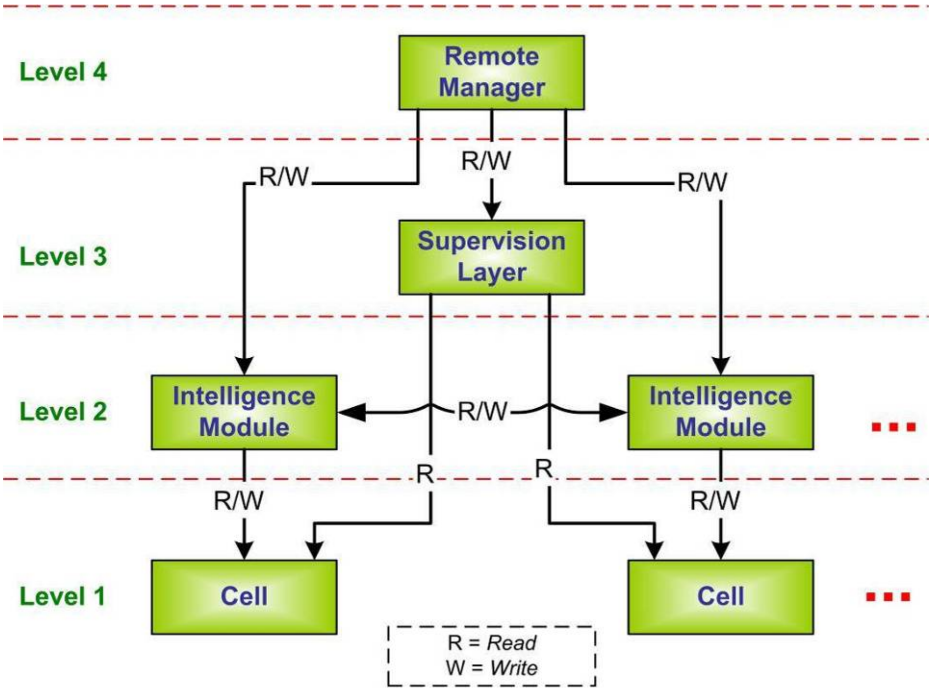

Figure 4. Basic Interaction Levels

At the first level there are industrial cells, each represented by an industrial process controlled by PLC's, controllers or other intelligent devices that perform traditional control such as PID.

At the second level there are the autonomous controllers, represented by intelligence modules coupled to cells, which perform the function of an expert in decision making in situations involving uncertainty or imprecision.

Each intelligence module should be able to perform read and write operations in the control layer of process, to adjust parameters and set points, or to force a specific action in an occurred situation in order to prevent the cell from leading to failure mode. In addition, the related intelligence modules should communicate with each other, making parameter adjustments in order to improve intelligent control.

The third level is the supervision layer where there are supervisory systems that allow engineers and operators to view the information and operational scenarios of the plant, and to parameterize data as well.

The fourth level has a remote manager, which incorporates supervisory functions and allows an expert process to view and adjust second and third levels. Furthermore, the remote manager can adjust intelligence modules from distributed cells and assume their function, if the intelligent module is not able to converge towards a final result. It also performs intelligence module optimization.

There may be a need to monitor and control over long-distances, be it because of the geographical distribution of controlled systems in inhospitable or distant areas, maintenance difficulties, the need for rationalizing and expediting decision making, or the need for decentralization of decisions, to name a few. Thus, remote management systems associated to an autonomous local control are extremely useful, because they offer increasing performance and reliability in managing these activities and they contribute to their development.

4.2. Local Layer Control

The autonomous local control proposed is structured in two hierarchical layers: reactive layer and intelligence layer (Fig. 5). The reactive layer and the controlled system compose the first level of the model abstraction, in the Fig. 4, and the intelligence layer composes the second level.

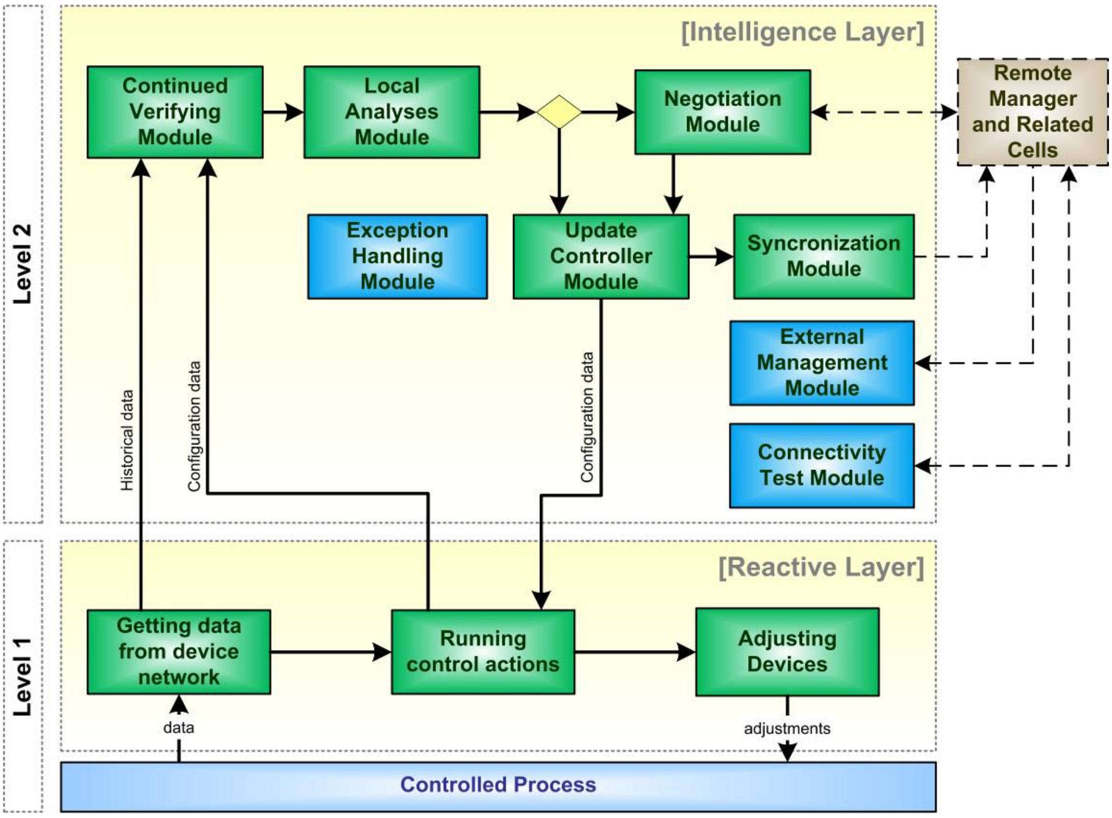

Figure 5. Reactive and Intelligence Local Layers

The reactive layer has a hybrid interface for communication between the production system (instrumentation level) and the intelligent control layer, dealing simultaneously with both continuous and discrete events. Thus, it functions as an interface between the physical system and intelligent control. It is connected to shop-floor devices (sensors, actuators, etc.) and it basically carries out the conventional control actions in the system: valve opening and flow control, PID control, motor drive, etc.

As it receives current values data, the reactive layer maps the discrete flow for each analogical signal device to be applied in the process, providing the set of required rules and adjustments to maintain the production system.

The intelligence layer analyzes the historical data obtained from the Reactive Layer and verifies its consistence with the configuration data. Then, it implements a module that provides a neural-fuzzy control and coordinates the analysis and processing of the data received from the other cells in order to improve general system performance and to handle faults that were not effectively processed with data from a single cell.

The intelligence layer consists of five principal and three additional modules: Continued Verifying Module (CVM), Local Analysis Module (LAM), Negotiation Module (NEM), Synchronization Module (SYM), Update Controller Module (UCM), Exception Handling Module (EHM), Connectivity Test Module (CTM) and External Management Module (EMM).

The CVM verifies the variables that are controlled by the Reactive Level, besides objective-functions and times response, and analyzes its operational limits. If measured values (*mv*) show no signs or exceeding the control limits – upper (CTR_{MAX}) or lower (CTR_{MIN}) – these deviations are interpreted as a possible failure on Reactive Level, or situations which in fact are not treatable by it (unforeseen events, insufficient data, etc.), since the adjustment exceeded its powers of acting and can result in error states (Table 1).

Table 1 – Rules to identify a failure event.

Rule	Possible Failure
$mv = shutdown$	True
$mv > CTR_{MAX}$	True
$mv \geq CTR_{MIN}$ and $mv \leq CTR_{MAX}$	False
$mv < CTR_{MIN}$	True

Thus, if these deviations are not caused by overshoots or undershoots, the failure reason should be identified to be corrected or reported. The variables related to possible failures are sent to the LAM, which is responsible for this identification.

The LAM deals with nonlinearities and uncertainties in the process, and it should be able to identify or propose new actions based on its perception of the input information. It represents the knowledge of experts on a particular subject and interpolates decisions from entries containing vague, imprecise or uncertain concepts. It provides the characteristics of human reasoning and subsidizes the decision-making process. After possible causes of failure or conflict identification, it guides recovery actions in order to fix them. The LAM seeks to correct failures and improve system performance, making adjustments and corrections so that the variables evolve consistently.

If the LAM can not converge to a final action (with an acceptable degree of precision that is defined by experts) in time to prevent a variable from exceeding operation limits, the cell is disabled in a safe mode until a specific action to be supported by related cells (cooperative or dependent) or by remote manager. This communication within related cells is provided by the NEM and by the SYM, which allows that KB's are adjusted, which means operational limits, roles, local and global objective-functions, setpoints, operational restrictions, among others.

The LAM should identify instability situations or adjustments beyond the competence of a local solution. If it is detected that it cannot reverse or correct a fault, it disables the cell operation in a safe mode which means to update the local KB and to send the settings to UCM, which updates and adjusts the Reactive Layer

After updating, the SYM propagates the events to the related cells and to Remote Manager so that adjustments or deadlocks can be investigated along with them.

The EMM manages events generated by Remote Manager and related cells, like KB's updating and negotiation of adjustment in global variables. The CTM periodically performs connectivity test with Remote Manager and related cells, in order to anticipate the identification of plant disconnections. If the continuation of activities can lead to operational failures, the EHM is activated and performs the treatment of exceptions identified.

However, it is not the objective of this proposed solution to solve all operational problems but to minimize them. Thus, there may be situations where a cell is disconnected from the Remote Manager and, even after possible interactions with other cells, it can not achieve a solution to some problem. In this case, the affected cell can interrupt local operation, avoiding greater impacts, until specialists or operating engineers investigate and resolve the instability.

The main benefit offered by an Intelligence Layer is prior detection of unexpected situations or situations not detectable by a conventional controller, which will negatively impact cell or the whole system's performance. Furthermore, it identifies ways in which the system can reach optimal performance.

An Intelligence Layer puts together the characteristics Fuzzy Systems and Artificial Neural Networks using the potential of the two paradigms to incorporate empirical knowledge and to adapt their parameters by means of specific algorithms for each situation.

The Intelligence Layer seeks to identify possible instabilities untreated by the Reactive Layer, correcting errors and resolving impasses for the controlled system to obtain satisfactory results and, if possible, optimize performance.

4.3. Remote Manager

An intelligent processor is also embedded in the remote level (Fig. 6) to analyze process data which are historically recorded in a historian database. Historical data for each analyzed process variable feed the remote intelligent processor that, based on status change of variables for each combination of events that occurred over time, determines relevant adjustments and corrections in order to achieve evolution of the variables toward a consistent tendency. This has to be done for all interesting variables and it should generate automatic updating of autonomous controllers (intelligence module). This level corresponds to the third and fourth levels from the model abstraction.

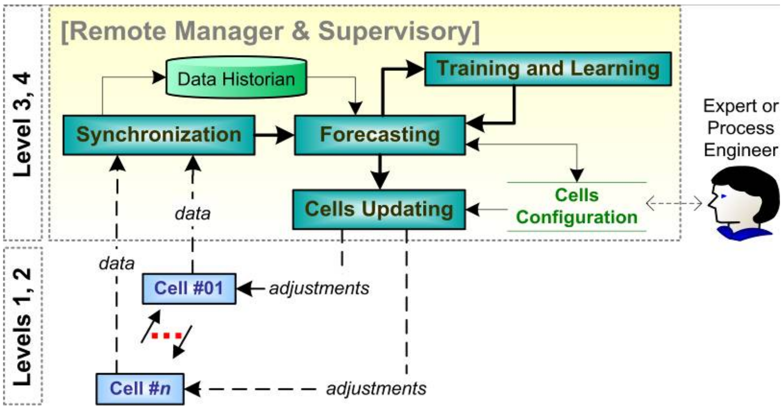

Figure 6. Remote Manager Level

In this manner, the knowledge base is trained based on a greater volume of data, and it is transferred to local knowledge bases enhancing autonomous controllers and ensuring its efficiency in case of loss of connection.

In addition to proposing a safer and more efficient management of local cells by the remote manager, the suggestion put forth here also enables a reduction in network overhead, since many decisions that would have been taken exclusively in a centralized manner are transferred to each local production process.

The proposed autonomous cells makes the control of critical processes flexible so that the cells of production can carry out their functions efficiently, even in cases of unpredictability, ambiguities or uncertainties in the process. Besides this, it can learn over time with the assistance of the remote management, so it can handle increasingly complex tasks.

The autonomous actions (locally and remotely) must occur wherever possible so that when the expert or engineer identifies process instability, security measures have already been taken, and the autonomous cell continues operating safely or can be safely disabled, avoiding error propagation in all system. In addition, the expert or the process engineer can make remote complementary adjustments or send instructions about local actions to be done by operators (Fig. 7).

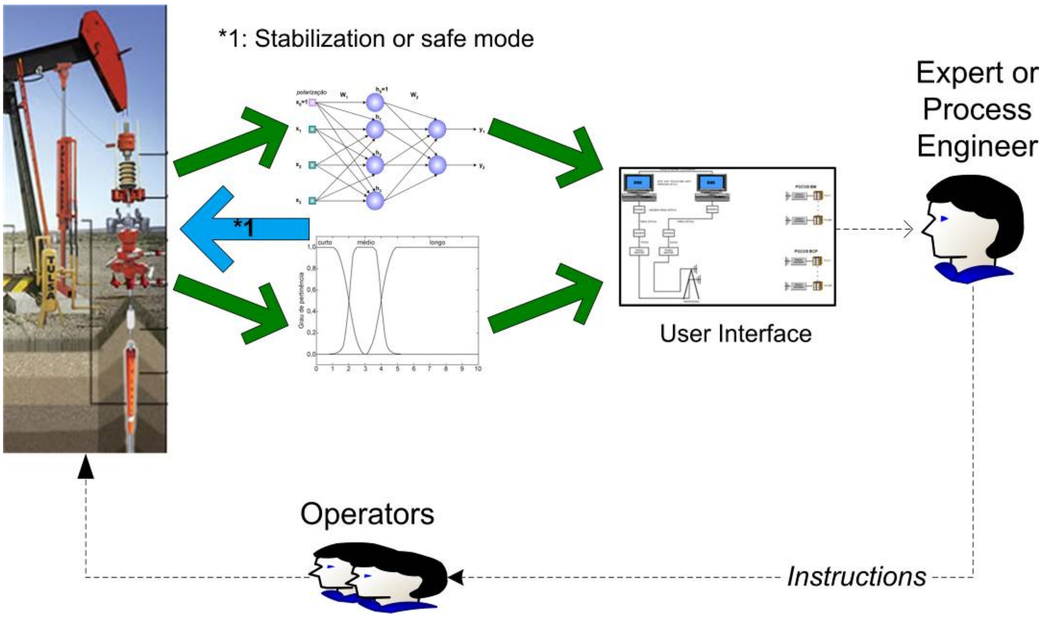

Figure 7. System overview in safe operation or safely disabled.

5. CONSIDERATIONS

It is hoped that the application of this proposal will improve the control systems performance for critical industrial processes based in distributed cells. To this end, a control system is proposed that aims to handle aspects of reliability, availability, continuity and response time inherent to such systems efficiently.

Dividing the architecture into layers allows the system to be analyzed and manipulated with varying levels of abstractions, enabling its maintenance and evolution. This is made easier by the division of important system aspects in independent, integrable modules, each of which can be analyzed and handled individually. In addition, this allows more complex functions to be handled efficiently and enables subsequent adjustments to be carried out in any given module or layer without invalidating or impairing the other modules or layers.

This paper studies aspects related to real-time systems with applications in industrial control systems and it aims to contribute both to industrial as well as academic communities by opening the way for subsequent research, such as to construct or propose a device that supports the intelligence module, research into aspects related to communication, information security and fault tolerance, among others. Each of these could constitute a separate endeavor in view of the complexity of the issues at hand. Next steps include validating this proposal in a real industrial environment in view of its subsequent use in a production environment.

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