Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Multi-Agent Control System of a Kraft Recovery Boiler

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Abstract: In this paper the authors have undertaken an attempt to implement the Multi-agent technology on controlling a recovery boiler, aiming to manage and integrate production, quality and security to the process. The operation of the recovery boiler has two well defined objectives, each one with its operational constraints: (1) steam production, an important asset in the pulp and paper process, and, (2) reduction of inorganic reagents to recover sulfate and sodium carbonates, the necessary chemicals in the Kraft pulp production. Each one of these functions, is an independent system inside the recovery boiler, however they have their performances connected to each other by common variables present in the process. This is exactly the definition of an agent system, in other words, a definition of a Multi-Agent System (MAS), for which there is not an optimization, but the search for the best possible outcome. Agents' engineering aspects are addressed by adopting the domain independent software standard, formulated by FIPA. Jade core Java classes are used as a FIPA specification implementation. A dynamic model of a Kraft Recovery Boiler was built on a Matlab-Simulink platform.

1. INTRODUCTION

Engineers have been introducing better support for procedures of monitoring complex conditions through the application of intelligent decentralized systems, implementing a variety of artificial intelligent techniques. Nowadays it is vastly known that these problems that are consequence of the functional complexity of monitoring conditioning can be solved trough architectures, built by many intelligent distributed modules, which interact dynamically, known as intelligent agents. Technology based on agents have been creating excitement over the last years because of its promise of being a new paradigm that can be used to define modelling and implementing concepts for control systems. For instance, Maturana and Norrie (1996) presented a multi-agent mediator arquitecture for distribuited manufacturing; Heikkila et al. (1999). suggested a manage architecture for manufacturing control; Law et al. (2001) proposed a viable reference architecture for a multi-agent supported holonic manufacturing system. Tad and Wong (2005) presented a multi-agent system for the control of manufacturing systems, whereby a prototype multi-agent-base control has been developed for a flexible assembly cell and Zhou et al. (2007) presented a design methodology of autonomous and cooperative flexible manufacturing system (FMS) control systems based on the later agent standards of the foundation intelligent physical agent (FIPA). In this paper we present the methodology to design and develop an agent-based network-distributed control system for a chemical process,

This methodology was implemented in a Kraft Recovery Boiler dynamic model. Due to the complex tasks involved in controlling the Recovery Boiler it appears to be a process which may profit from a Multi-Agent Control System. The basic strategy for recovery boiler control is steady and stable operation. Process variations cause unstable recovery boiler operation. Unstable process parameters can limit the boiler operator's flexibility for control. When there are fluctuations in process parameters, boiler operators must make accommodations for the worst case. On the other hand, stabilizing furnace operation makes it possible to tightly control process variables and perform nearer to the optimum levels at all times. Incremental performance improvements can be realized by implementing an agent-based intelligent control system. The main reason is that the agents can always objectively take a decision on the basis of a large number of pieces of information. This is not easy for an operator who will have difficulties in being up to date with all relevant information in a critical situation.

The following section will introduce agent technologies and agent specification standards used in this project. Sections three and four will describe control agent platform architecture and specialized agents descriptions and behaviours. Section five will discuss the developed metadata used to describe control systems and processes planned to be integrated into the global control environment. Finally, we conclude with a brief discussion of our future plans.

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10.3182/20080706-5-KR-1001.3616

2. PRESENTATION OF BASIS CONCEPTS.

2.1 Software Agents

An agent system is a set of distributed entities, each one with some capabilities that could potentially modify the its surrounded environment, and committed to a social goal, that is, a target objective for the whole agent community.

Sycara (1998) defines the characteristic of a distributed problem based on Multi-Agents as,

- each agent has incomplete information or capability to solve the problem, and thus has a limited viewpoint;
- there is no system global control,
- data are decentralized and,,
- computation is asynchronous

Thus, a distributed problem – and specially a control problem – that is suitable to be solved by a Multi-Agent approach must be some or all of the characteristics above.

Another important characteristic of an agent society is if it is open, which is, if agents are free to join or leave the society, or closed, where the number of agents is fixed. Such characteristic could change significantly the complexity of the problem to be solved, what could not justify the application of this approach.

The kraft recovery boiler operation is a control problem with two strong coupled processes. It could hardly be called a society, if an association is make between independent processes and agent entities. However, even if the problem is tightly coupled, the solution could be loosely coupled, what suits a Multi-Agent approach as defined by Fasli (2004).

The justification for such approach is that if double control is to be applied each one, the steam control and the redactor of reagents could interact as a loosely coupled system where these two agents cooperate to avoid degeneration of the system.

It has also the advantage of skip from the demand of an analytical solution for a centralized control. Besides an equilibrium solution would come out from the cooperative action of these two systems.

Thus, we have to face a fixed task assignment control system, composed by two agents, that are expect to converge to a stable control solution by the negotiation of its cooperative capabilities. The coordination of such control actions is the real challenge and the motivation of the present work by Malone and Crowston (1994).

In what follows we try to justify this approach and will show a first attempt to treat the kraft recovery boiler as a Multi-Agent system, envisaging good results,

Before discussing the approach and the partial results we will describe the Multi-Agent environment used in this work and its available features. Next we will describe the agent environment and the methodology of the experiment, and then the first results obtained.

2.2 FIPA

Foundation for Intelligent Physical Agents (FIPA) is the most promising standardization effort in the software agent world. The FIPA agent reference model was chosen to provide the normative framework within which agents can be deployed and operate. FIPA specification establishes the logical reference model for the creation, registration, location, communication, migration and retirement of agents.

First of all, they describe the reference model of an agent platform, as shown in Fig. 1. Basically, it identifies the roles of some key agents necessary for the management of the platform, and specifies the agent management content language and ontology.

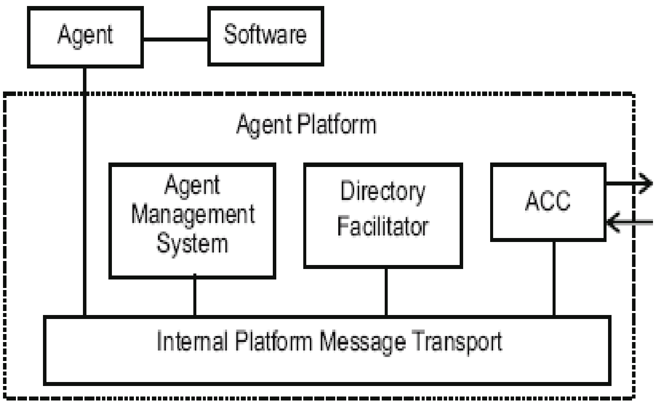

Fig. 1. FIPA reference model of an agent platform

Three key mandatory roles are identified in an agent platform. The agent management system (AMS) is the agent that exerts supervisory control over access to use of the platform; it is responsible for authentication of resident agents and control of registrations. The agent communication channel (ACC) is the agent that provides the path for basic contact between agents inside and outside the platform; it is the default communication method that offers a reliable, orderly and accurate message routine service; it must also support Internet inter-orb protocol (IIOP) for interoperability between different agent platforms. The directory facilitator (DF) is the agent that provides a yellow page service to the agent platform. Notice that no restriction is given to the actual technology used for the platform implementation. FIPA also specifies the agent communication language (ACL). Agent communication is based on message passing, where agents communicate by formulating and sending individual messages to each other. The FIPA ACL specifies a standard message language by setting out the encoding, semantics and pragmatics of the messages. Other parts of the FIPA standard specify other aspects, in particular the agent-software integration, agent mobility and security, ontology service, and the human-agent communication. However, they have not yet been considered in the JADE implementation.

2.3 JADE Agent platform.

JADE is a software framework to aid the development of agent applications in compliance with the FIPA 2000 specifications for interoperable intelligent agent systems, (Bellifemine *et al*., 2001).. The JADE system can be described from two different points of view. On the one hand, JADE is a runtime system for FIPA compliant multi-agent systems, supporting application agents whenever they need to exploit some feature covered by the FIPA standard specification (message passing, agent life-cycle management, etc.). On the other hand, JADE is a Java framework for developing FIPA-compliant agent applications, making FIPA standard assets available to the programmer through object oriented abstractions. The JADE communication architecture tries to offer flexible and efficient messaging, transparently choosing the best transport available and leveraging state-of-the-art distributed object technology embedded within the Java runtime environment.

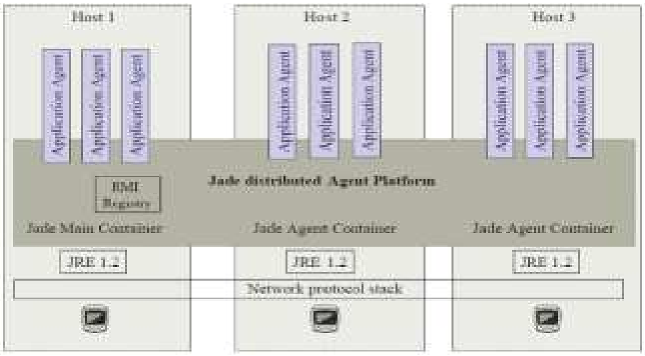

Fig. 2. JADE Agent Plataform

3. KRAFT RECOVERY BOILER

The Kraft process is used in production of paper pulp and involves the use of caustic sodium hydroxide and sodium sulfide to extract the lignin from wood chips in large pressure vessels called digesters. The spent, extracted pulping liquor, called black liquor, is concentrated by evaporation and burned in the recovery boiler to recover the inorganic chemicals for reuse in the pulping process.

A recovery boiler is both an ordinary steam boiler with tubes in the walls, bottom and top of the furnace that delivers the steam required by the mill and a chemical reactor where sodium sulphate is reduced to sodium sulphide. An unique characteristic of such boilers is the use of char bed in the lower furnace. The boiler has three critical functions. First, it uses the chemical energy in the organic portion of the liquor to generate steam for the mill; second, it plays a major role in the sulphate process as a chemical reactor; and third, it destroys dissolved organic matter and thus eliminates one type of environmental discharge.

The objectives of the recovery boiler are:

1. Production of Smelt (sodium sulphide and sodium carbonate): The efficiency of the smelt generation is measured by the reduction ratio, which is the fraction of the total sulphur in the smelt which is present as sodium sulphide.
2. Production of steam: The combustion of the organic solids releases large quantities of heat which can be recovered in the steam generating part of the recovery furnace. High steam production efficiency requires complete combustion and clean heat transfer surfaces.
3. Prevention of the emission of particulate and gaseous matter: Particulate emissions are made up of a fine dust of salt cake and sodium carbonate carried by the flue gases. The gaseous emissions are carbon monoxide, sulphur dioxide, hydrogen sulphide and various other foul smelling sulphur components. The composition of the flue gas can be controlled to some extent by manipulating some of the furnace input variables.
4. Safety: If free water or too dilute liquor comes into contact with molten smelt, violent explosions can occur. To minimize the possibility of such explosions, close monitoring of the spray liquor density is required.

4. CONTROLING A RECOVERY BOILER USING A MULTIAGENT SYSTEM

4.1 Control strategy

Optimum chemical recovery, low emission levels, and maximum steam production per ton is accomplished by maintaining a satisfactory char bed on the furnace wall and on the floor, a good air flow and maintaining a steady tapping of smelt to the dissolving tank. To reach these conditions we choose to manipulate two important variables:

- <u>Temperature of the black liquor</u>: To keep a satisfactory char bed the usual method is by varying the temperature of the black liquor going to the spray nozzles. The drop size distribution is extremely sensitive to the liquor temperature as a few degrees will change a coarse spray to a fine mist. At the same time as an increase in the liquor temperature immediately increases the rate of combustion in the secondary zone, less water will reach the char bed surface, and less heat is required for evaporation, the char bed will start to heat up, and more combustible material will be released. The net result is more combustion. As the air flow is kept constant, the oxygen deficiency in the primary zone is higher and the reduction is better. The liquor temperature is accurately controlled and responds very quickly to set point changes as the steam is injected directly into the liquor.
- <u>Liquor Flow</u>: Manipulating the liquor flow we have a control over the steam production because the flow of combustible solids is directly affected. Increasing the liquor flow first cools the char bed and causes the char bed level to increase slightly. As the primary flow is increased by the air control system, the rate of combustion is increased, and the net disturbance in the char bed is slight.

5. SIMULATION MODEL

The implemented simulation model is shown in Fig 3. It is composed for three components: The recovery boiler dynamic simulation, the agent's platform and the communication middleware.

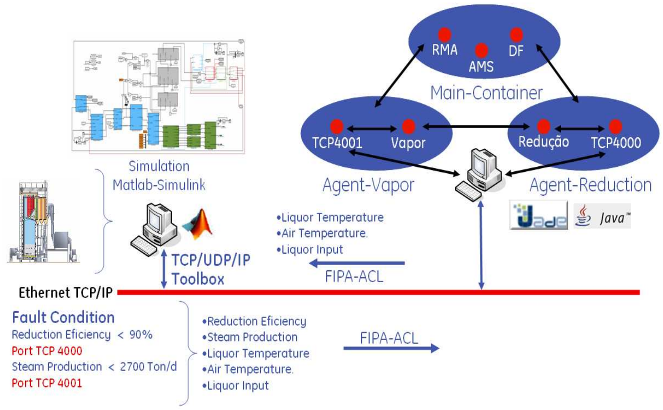

Fig 3. Recovery Boiler MAS Control proposed Architecture.

5.1 Kraft Recovery Boiler Dynamic Simulation

A Simulink implementation of a mathematical model of a Kraft Recovery Boiler. A Mathematical process model serves at least two useful purposes in the testing of a control system. Primarily it is a concise description of all relevant information about the process. Secondly, as one very rarely has access to a process for extensive experimentation. The recovery boiler implemented in this project is an adaptation of the Babcock and Wilcox recovery unit model done by Karnienny et al. (1979). Since this model there has been very intensive research on nearly every aspect of recovery boiler operation which made it obvious that an update was needed. Most of these studies were found at the reference textbook on recovery boiler by Adams et al. (1997).

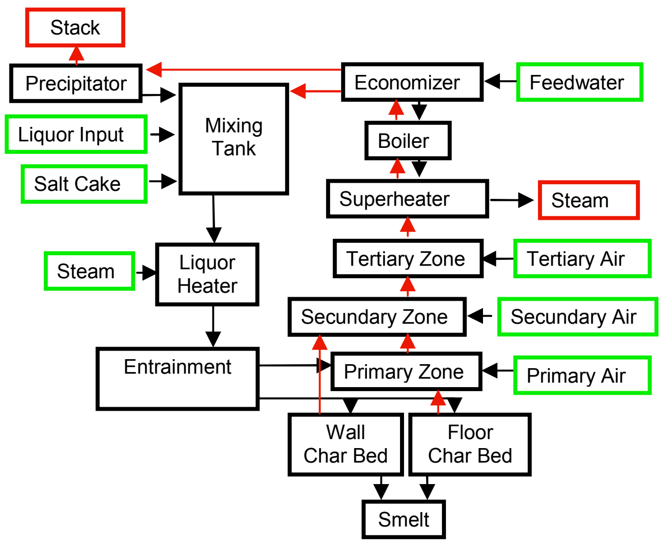

Fig. 4. Material and energy balance diagram

5.2 MAS Platform.

An implementation of the MAS platform in JAVA Agent Development Framework (JADE). The agent platform has two containers with two types of agents, TCP Agents that provides the communication bridge between the control agent and the recovery boiler simulation (TCP4000 and TCP4001) and Control Agents that represents the action control (Reduction agent and Vapor agent).

The interaction between agents happens when a fault situation occurs, when the efficiency of the smelt is less than 90% and when the Production of steam is less than 2700 ton/day. When a fault condition occur a TCP Agent receive the fault from the simulation and send a FIPA Request message to the Control Agent reporting the status. When the Control Agent receive REQUEST message, it stars the negotiation process with the other Control Agent. Based on the requirements of the process, we needed and auction or negotiation protocol. FIPA standardizes some of these interaction protocols and we decided to use the Contract Net Interaction Protocol.

The contract-Net Protocol was proposed and described in FIPA (2006). The representation of this protocol is shown in figure 5. In the Contract-Net Interacion protocol, one agent (the Initiator) wishes to have some task performed by one or more agents (the Responders) and it establishes the preferences of the negotiation. For a given request, the Participants may send a proposal or the may refuse. Then, the negotiation continues with the Participants who send a proposal. Once the initiator receives the proposals, they are evaluated and the best ones are selected. The initiator informs the agent(s) that they were selected for the task with and accepted message (those not selected will receive a notice of rejection). Once the initiator accepts the proposal, the responder commits to perform the task; it sends a completion message to the initiator.

5.3 Communication Middleware.

We needed a communication middleware that allows the MAS to send/receive data to/from the Kraft Recovery Boiler model in Simulink. The MAS reads information of the status of the recovery boiler to determine the required control actions which are applied to the case. In our Simulation Model, the Client is the implementation in Simulink and the Server is the Multi-Agent System.

As a Server, we implement the Communication Agent referred to as a "TCP Agent". The TCP Agent is an agent that has the function to communicate with remote clients via a socket. Each message that arrives through the socket is analyzed and a message with this information is sent to the Control Agent. Each control action from the Control Agent is forwarded back to the simulation through the socket again.

As a Client we used Simulink. To open a Client Socket in Simulink, we needed Matlab code, so we used an "Embedded

Matlab function". We used "TCP/UDP/IP Toolbox" developed by Peter Rydester (2006) to set up TCP/IP connections in Matlab and to transmit data over a socket between Matlab processes and other applications. It is possible to act as server and/or client and transmit text strings, arrays of any data type, files or Matlab variables.

6. SIMULATION RESULTS

In order to test the operation of the MAS and to evaluate its performance, some scenarios were simulated and evaluated. Next, we still present, the result of one of the scenarios. We include the description of the message exchange of agents.

6.1 Simulation Parameters

Table 1. Simulation Parameters

Air		Units
Air Temperature	26.67	C
Humidity	60.00	%
Pressure	101325.00	Pa
Oxygen	23.00	%
Nitrogen	77.00	%
Reference Temperature	26.67	C
Temperature of combustion	134.44	C
Liquor		
Dry Solids	63.00	%
Na2SO4	0.00	%
Na2CO3	0.00	%
Water	37.00	%
Input Liquor temperature (Mixing Tank)	93.33	C
Input Liquor temperature (Entrainment)	104.44	C
Input Na2SO4 (Mixing Tank)	23.11	Ton/d
Dry Solids		
Na	19.50	%
C	37.00	%
H	3.50	%
S	5.90	%
O	33.30	%
Inert	0.00	%
Na2S	0.08	%
Input of Dry Solids (Mixing Tank)	1102.50	Ton/d
Steam Production		
Water Temperature (Economizer)	137.77	C
Drum Pressure	3.66	Mpa

6.1 Negotiation Process

- From t=0 to t=1000 there was no monitored action from the MAS. Fig 5 shows the sequence of messages exchanged between the agents.
- At t=1000 the status of the process was %Reduction = 88.0137 Steam=2536.03 Ton/d.
- Precisely at the moment that the agent "Reduction" gets into the system, it is detected a reduction below 90%, and it is sent a message of REQUEST to the agent "TCP4000"
- The agent "TCP4000" sends this message encapsulated in another message REQUEST to the control agent "Reduction"
- The agent "Reduction" builds a message CFP to initiate a negotiation with the agent "Vapor".
- After negotiating the agents get to the conclusion that the best strategy is to lower the liquor temperature to "101.21"
- This value is sent together with other two variables that did not suffer changes. The content of the message has the following variables: Air Temperature= 134.44 C, Liquor Input = 1750 Ton/d, Liquor Temperature = 101.21 C. The message sends these values to the simulation platform, where each one of them is written on the manipulated variables of the recovery boiler simulation.
- The immediate answer is the increase on the efficiency reduction to a percentage slightly over 90.
- At t=1100 the agent "Vapor" enters the system and receive a message indicating that the vapor production is below the fault limit (2700 ton/d).
- The agent "Vapor" starts a communication using the "FIPA-Contract-Net-Interaction-Protocol", sending a CFP message.
- The agent sends a proposal for the increase of the input liquor, which is accepted and forwarded to the simulation platform. Liquor Input = 1841.81 ton/d.
- With the increase of the liquor input, the efficiency reduction drops. The agent reduction receives a message which is processed to control the fault situation. Again the best control strategy was to decrease the liquor temperature to 100.07 C.
- The agent "Reduction" reacted quickly, taking the efficiency reduction to a value close to the safety limit.
- Because the vapor production has a slower dynamic than the reduction, the response to the control was slower than the efficiency response. At t=1400 the vapor production leave the fault zone and enters the safety zone. Fig 6 shows the action of the manipulated variables and the response of the controlled variables.

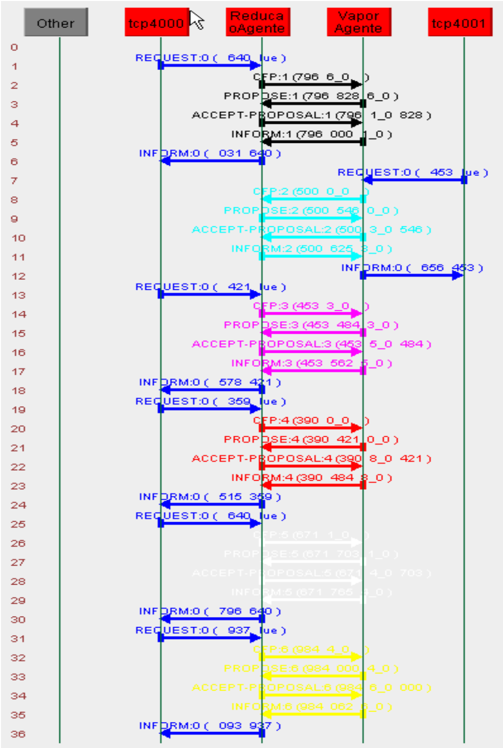

Figure 5. Negotiation process

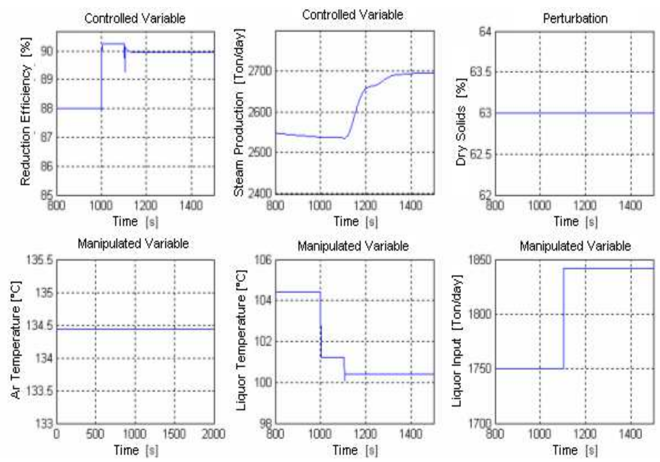

Figure 6. Response of the simulation system.

7. CONCLUSIONS

This paper presents the partial results of our work in applying multi-agents agents to develop an intelligent control system to a Kraft Recovery Boiler and the MAS implementation in the JADE platform, probably the fist application in a chemical process industry. The simulation system is implemented using Matlab and Simulink to simulate the Recovery Boiler and the JADE platform to develop and simulate the MAS. Through simulation, we evaluated the performance of the MAS controlling the recovery boiler. Our Simulation results show the feasibility of implementing a control system of a recovery boiler using a FIPA compliant MAS.

The MAS provide autonomous capabilities to the Recovery Boiler system and it allows agents to make negotiations without full knowledge of the system using the Contract Net Protocol.

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