AUCTION-BASED AGENT-ORIENTED PROCESS CONTROL
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Abstract: The introduction of advanced communication and instrumentation facilities to the area of process control systems add flexibility and adaptability at the cost of complexity and heterogeneity. The agent paradigm is well suited for design, development and maintenance of the emerging systems. In this paper the application of auction-based agent interactions in distributed systems that are constrained to deal with local information for satisfaction of global requirements is discussed. The focus of the presented work is on the reduction of communicative acts through prediction in such auction-based interactions while still satisfying global system constraints. The results show that with predictive elements a better performance could be reached with even less communication than in a non-predictive setting. Copyright © 2006 IFAC

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1. INTRODUCTION

Process control is one of the most natural application domains for the agent oriented software engineering, as the process controllers generally require to be autonomous reactive systems (Jennings and Wooldridge, 1998). With the advent of fast and reliable computing resources and improved communication facilities most of the process control systems grew to be more complex, distributed and demanding. Emphasis is on flexibility, changeability and system availability in addition to the traditional requirements of safety, reliability, efficiency and integrity (Seilonen, et al., 2002a). Certain aspects of these distributed process control systems advocate in favor of adopting the agent oriented approach (Jennings and Bussmann, 2003; Parunak, 1998). Moreover, it has been observed that in the development of process control systems there is a growing interest in including additional functionalities (i.e., monitoring, maintenance, process improvement, abnormal situation handling etc.) apart from the core functionality (i.e., controlling physical processes). In realizing these functionalities the agent oriented approach again seems to be the most appropriate and conducive one (Seilonen, et al., 2002a).

The advantageous features of the agent-oriented paradigm have attracted a number of researchers to investigate as well as to practically show its applicability in process control (Parunak, 1998; Seilonen, et al., 2002b). Most of the applications of agent technology are built up on an agent society rather than individual functional agent. While designing a multi-agent system for process control one of the principal problems is to design the interaction so as to achieve single or multiple system wide objectives. The system-wide goal attainment should be achieved in terms of a trade-off between individual goal attainments of the constituent agents. Concepts originating from the field of microeconomics are often used in this purpose. Agents, in such models are portrayed as self-interested entities having their own preferences manifested through utility functions and they are interested in maximizing their utilities in every occasion they are allowed to. The purpose of developing an interaction mechanism is therefore to form an institution where the agents can interact for their own interest yet the system-wide or global goals are fulfilled to some considerable extent.

Agent-oriented auction based systems are becoming more and more common. These applications are coming into play in scenarios where a number of distributed components compete for resources or tasks. For example, a number of industrial work-cells may compete for a small number of transport facilities (i.e., conveyor, guided vehicles etc.), an electric
power plant can decisively load its available productive resources, or a number of applications may look for database access or memory allotment. Quite often the decision problems appear to be combinatorial where the decision space is large.

In industrial applications agent based solutions could be of various strength and features. In this paper the focus is on a lightweight agent-based solution where following considerations deserved importance:

- Formulation of the interaction such that the individual agents are motivated to improve system-wide performance criteria besides satisfaction of their own goals.
- Minimizing the amount of communication in terms of frequency of communication as well as in terms of the length of the information passed.
- Employing the benefit of emergent behaviors through the interactions of the simple and lightweight elements.

The realm of applications that closely resembles the application discussed in the context of the paper is that where combinatorial choices have to be done in order to find the best suitable option of resource or task allocation. The focus of the work is to investigate how predictive elements can be embedded in such a system and their effects on the performance with respect to the above mentioned criteria.

The paper is organized as follows. The following section describes the problem scenario for which the agent-based solution is developed. Section 3 introduces several possible solutions for designing the interactions of the agents in the context of the application. Section 4 presents the simulation platform built. The corresponding simulation results are presented and compared in Section 5. The concluding section includes a summary and an outlook on further work.

2. PROBLEM DESCRIPTION

The system considered within the context of this article is that of (Antoniadis, 2005) but additional constraints are added. Salient features of the system are presented in the following and a schematic of it is shown in Fig. 1. The system consists of a number of lignite bunkers (usually 8) which are to be filled using a movable and reversible belt conveyor and carriage system.

The bunkers are used to store lignite which is subsequently fed to burner units. For extracting the lignite from the bunkers a mill is installed at the bottom of each of them. In the context of the current work it is assumed that bunkers might provide lignite to a single main burner unit or to different burner units and therefore the demanded amount of lignite to each of the bunkers as well as the rate of lignite outflow through different mills may vary.

Only one bunker can be filled at a time through the belt conveyors while the mills operate simultaneously irrespective of whether they fill the same or different burner units. The width of the conveyor filling unit covers the width of 4 bunkers and therefore the first 4 bunkers from left can only be filled using anti-clockwise rotation of the conveyor belt while the other 4 bunkers can only be filled using clockwise rotation of the conveyor belt. However, the number of switching events of the filling between bunkers must be kept low, in order to minimize stress on the conveyor belt and its motors.

![Fig. 1. Schematic of studied bunker system](image)

The maximum capacity for each bunker is 500 tons and as soon as the lignite level in a bunker reaches the minimum level of 75 tons the corresponding mill stops delivering. The application which should control this plant should satisfy one strict constraint, namely:

*The lignite level in any bunker should neither drop below a given minimum level nor must it exceed the maximum capacity of the bunker.*

As soon as all of the available bunkers are filled up to a certain level the operation of the conveyor is stopped. For the current experiment this acceptable level is set to 470 tons. Furthermore, faults may occur during the filling mechanism, and the number of operating mills can arbitrarily change during the filling due to mill faults.

The control task is to decide on the sideways motion of the conveyor over the bunkers and the motion of the conveyor belt in clockwise or anti-clockwise direction and thus provide lignite to the bunkers so that they can keep supplying the underlying burners. Certain system-wide non-functional requirements are also expected, these could be stated as follows:

1. To keep the deviation of the lignite levels among the bunkers to a minimum.
2. To keep the average of the lignite levels as high as possible.
3. To minimize the message-length as well as the frequency of message passing operations among the components of the application so that the traffic generated by the application does not consume large network overhead.
4. To keep the movement of the conveyor and especially the switching of the conveyor motors rotation direction to a minimum.

A possible control application could have used optimization algorithms taking into account the changes of the lignite levels. But as the outflows through the mills are not fixed and do not change according to some predetermined rules the optimization algorithm would need to recalculate its optimal strategy every time changes occur and hence could be overloaded with calculative efforts. Moreover, when the occurrences of such changes are too frequent the optimization result may not be valid for the proposed time horizon and therefore after a run of disturbances the system could slip into instability.

In the presented work, various schemes of interactions have been evaluated. Principally, auction-oriented agent-based solutions are proposed. Apart from simple auction-based interaction a scheme with some predictive capabilities of the constituent agents are also introduced which then reduces the rate of message passing but should still maintain a system-wide optimal result. Moreover, it is attempted to keep the system flexible in case of change of preferences or demands and scalable in terms of the number of controlled elements. The proposed strategies are discussed in detail in Section 3.

The auction-based control approach is certainly a heuristic one and its feasibility can better be studied through simulations and tests. Therefore, a simulation and test platform is designed which is described in Section 4.

3. PROPOSED SOLUTIONS

The simplest of the strategies that can be implemented in the auction based multi agent system is to carry out auctions at regular intervals and thus decide on the winner and opportune him with resource allocation. Certainly the most critical question in this strategy is how frequent should the auctions be performed. There is usually a trade off between the frequency of auctions and the performance of the system. Moreover, if the time span between successive auctions is widened the messages passed to the central auctioneer become larger as the auctioneers decide on a single outcome if no lignite is supplied. For the problem at hand since the lignite requirements for each of the bunkers may change arbitrarily, a bunker agent can only make predictions about its future states. When the time span of prediction is not too large the predictions cannot get wrong by a large margin. The bunker agents do not contain any intelligence; rather they simply calculate the slope of the bid function (function of bids with respect to bunker’s lignite level) and pass that to the auctioneer agent along with the bid at the instant of bid submission. The slope of the bid function is calculated assuming the worst case since the upper limit of the lignite demand is known to the bunker agent. If the time span between the auctions is not too large the marginal bid can be a single value which is the slope of the line joining the initial and final state in the bid function. When the time span becomes large (i.e., ten minutes or more) the linear assumption deviates greatly from the actual change of the bid function and thus may cause erratic results when used. Therefore, it is needed to pass rather a time dependant function to the auctioneer agent and the auctioneer agent can then calculate the future bids more appropriately.

Now, as the auctioneer agent receives the bid value and the slope of the bid functions it calculates an estimate of bids that could be offered by the bunker agents at future instants if no lignite is supplied. While calculating the future bids it assumes an average estimate for the extracted lignite volume. Since the bid function is of negative slope (which is due to the fact that bids drop with increasing bunker level) each of the estimated future bids are higher than the current bid unless the bunker receives lignite on successive time slots. The conveyor chooses the future state which will bring highest gain which is calculated in terms of the offered bids and the cost of conveyor action.

The digraph of Fig. 2 shows the above mentioned concept. The digraph is drawn for a system consisting of 4 bunkers and the calculations are carried out for 3 future time steps. The initial and final nodes marked by zeros denote respectively the initial position of the conveyor at the time the bids are submitted and the end of action. The nodes in between are marked with the number of the bunker which should be filled. The edges or path segments are attached with the calculated gains that can be achieved when that particular sequence of filling action is followed. The most profitable path is then found and the conveyor acts accordingly until the next auction.

Dijkstra’s algorithm (Dijkstra, 1959) for finding the shortest path is used to find the most profitable path for the conveyor till the next auction. Before applying this algorithm, the weights of the edges needed to be recalculated, firstly, for avoiding negative weights when the gain is less than the cost for conveyor actions and secondly, for formulating the problem as a shortest path problem. Therefore, the weights of the
edges at each level are again adjusted as its difference from the maximum gain of that step.

Fig. 2. Auctioneer’s digraph for the decision of future winners.

The above mentioned predictive decision making for auctions can have twofold utilization. Firstly, it can reduce the number of messages passed among the auctioneer and the bidder elements and secondly, it might be useful in cases where the response of one or more bidders fail to arrive at the auctioneer within an allotted time and still the auctioneer can not totally ignore the absentees bids and hence need to do an estimate.

When a particular bunker’s mill stops the auctioneer can be informed and then either it can announce a request for bids so that the bidders again send their bids or it can recalculate future paths assuming that the weight of the paths leading to or originating from the vertices embalming the inactive bunker is infinity. This leads ultimately to an ignorance of the paths during shortest path calculation.

The result of the combinatorial auctions which comes out of the shortest path calculation is a sequence of numbers denoting the winners of each stage and the conveyor then supplies lignite according to the plan to the appropriate bunker. A sequence of binary results should then be passed to the bunker agents denoting its allocation of the resource in the upcoming minutes. If the bunker agent foresees extreme mismatch in its demand and supply and recognizes a foreseen closure of mill it triggers an exigency and consequent auction.

4. SIMULATION PLATFORM

The simulation environment was built using the Java based agent development toolkit JADE (Java Agent Development Environment, Bellifemine, et al, 1999). JADE is freely available and has a rich Application Programming Interface (API). The simulation environment embodies the control application as well as the controlled element as an agent. Therefore, each of the bunkers and its corresponding controller are described using an agent. Similarly, the conveyor and its corresponding controller which plays the role of auctioneer are also modeled as separate agents. In the simulation environment it is possible to simulate occurrences like stalling of a bunker due to maintenance or fault and also to vary individual parameters of the bunker during simulation runtime or time the occurrence of such a change.

A visualization agent was created for visualization of the system states during simulations runs. The visualization agent gets updates from the agents representing the bunkers and the conveyor at a fixed regular interval (single simulation time step) while the communication between a conveyor and the bunker controller agent can be set up so as to perform it once in a simulation time step or less frequent (cf. Fig. 3). It can also actuate parameter changes, receive notices of emergencies and actuates the corresponding action. Moreover, JADE’s sniffer agent and its GUI facilitate tracing of individual messages and bids.

The communicative acts among the agents are portrayed in the sequence diagram of Fig. 3. As the comments attached with the messages show, the message of updating information about the state of the bunkers from bunker agent to the visualization agent occurs periodically with period $T_{\text{sim}}$ and the messages concerning auctions occur with a period which is integer multiple of $T_{\text{sim}}$. The messages concerning auctions are as follows:

1. Bid initiation: from the conveyor to the bunker agents requesting for submission of bids.
2. Bid submission: from the active bunkers to the auctioneer or conveyor agent informing their interest to get resource allocation as well as informing the bid value.
3. Winner declaration: from the conveyor agent to the bunker agents.

Fig. 3. Sequence diagram of the message passing among the agents in the simulation environment

5. SIMULATION RESULTS

The most important requirements on the auction-based control are to avoid the closure of any of the bunkers due to fall of the lignite level below the minimum level and to finish the filling process as soon as possible. The scenario discussed here considers varying outflow rates. This certainly affects the total filling duration and at instants generates very critical situations for keeping the lignite levels above the specified minimum. The filling strategy depicted in (Antoniadis, 2005), primarily designed for verification purposes, suffices as long as the bunkers’ lignite outflows through the mills are constant and fails
to handle such critical conditions. When the outflow is kept constant the auction based filling strategies give similar results for the filling duration.

First, the simple auction scheme is implemented where the bunker agents bid at every minute and the conveyor is actuated accordingly. The important observations should be to find out how well this strategy can handle urgent situations when one or more bunkers are on the verge of closure if not supplied with lignite promptly. To simulate such urgent situations it is assumed that the initial bunker levels are not fixed at 150 tons as in (Antoniadis, 2005) but they are chosen at random from a normal distribution of numbers ranging from 470 tons to 75 tons.

The auction-based problem is also faced with a multi-objective optimization. On one hand, there is the urgency of lignite supply as revealed through the bids and on the other hand the conveyor is burdened with a cost on the basis of which it decides whether the action of movement and/or reversal is justified or not. An equivalence of the two differing values is then established through parameterization. Here the parameter is the ratio of the bid and the conveyor cost. For this parameterization and also for the sake of equivalence the bids of the bunker agents are always normalized and the ratio of the normalized conveyor cost to the normalized bid is the parameter which needs to be fixed. Therefore, the first simulations have been carried out to fix this parameter. Simulations have been carried out on 1000 samples and for each of the samples the initial level of the bunkers have been taken from a normal distribution forcing occurrence of urgent scenarios. Assessments were done on the basis of occurrence of closure of bunker due to drop of lignite level below minimum, time required for finishing the filling operation and number of instances of conveyor movement and rotation.

The results of the simulations concerning the choice of the parameter which fixes the ratio of conveyor cost and normalized bids are as follows:

- Closure of the bunkers is of prime concern and as shown in Fig. 4 the occurrence of closure of one bunker mill rises sharply as the parameter is varied above 0.125 as one varies it further closures of 2 or more bunkers are encountered.
- Conveyor movement and/or reversal are observed through a cost calculation which assumes that the reversal of direction of the conveyor rotation will cost twice as much as the movement of the conveyor by one step. The results show that up to a parameter value of 0.4 the cost stays at the minimum level and then grows constantly.
- Regarding the average levels and standard deviations differences are not much remarkable as far as failure-free operation is concerned.

Evaluation of the results of the experiments suggests that a choice of the parameter as 0.125 or lower is justified.

Further observations have been carried out to investigate comparatively the performance of the two schemes. Results of 10000 samples of runs showed that with prediction one can gain just minimal benefit as far as completion time is concerned. The distribution of completion time is Gaussian in both the cases but the width of the distribution is narrower for the predictive case implying greater uniformity. Fig. 6 shows the observation on conveyor cost and it shows that the conveyor movement and reversal reduces with the inclusion of the discussed prediction mechanism. The marginal gain calculation could prove to
be inappropriate as the time span of prediction is increased and therefore it is seen that the rate of failure is rather increased when the time span is increased (cf. Table 1). But the failures are mainly due to the appearance of extremities of the initial states as the observations with all the bunkers at the same initial state of 150 tons results in zero failure for both the simple and predictive case. Moreover, closeness of the approximation to the actual values also accounts for less conveyor costs for the less time span between auction cases.

Fig. 6. Variation of conveyor costs for different auction schemes

Table 1. Probability of occurrence of bunker closure during operation derived from simulation data

<table>
<thead>
<tr>
<th>Auction scheme</th>
<th>Closure of 1 bunker</th>
<th>Closure of 2 bunkers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple auction</td>
<td>1.99%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Auction with 5 step</td>
<td>2.64%</td>
<td>0.02%</td>
</tr>
<tr>
<td>prediction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auction with 8 step</td>
<td>6.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>prediction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the amount of necessary communication it can roughly be stated that it linearly decreases with the number of prediction steps. This is due to the fact that in most network protocols the corresponding increase in user data to be sent will have no influence on the actual length of the sent messages. For example, even the shortest TCP/IP frame can carry the data necessary for dozens of prediction steps.

Based on the simulation results, an optimal choice of the system parameters is possible given a goal function that weights conveyor costs against the "cost" of communication and of bunker closures.

6. CONCLUSION AND OUTLOOK

The outcome of the work shows that it is possible to use the emergent behavior of individualistic elements to achieve fulfillment of global goals to a considerable extent. This could be quite useful in scenarios where the global requirement is to obtain optimization of multiple objectives. It is shown that it is possible to include prediction of the auctions within the auctioneer’s algorithm and reduce the communicative acts among the participants and still get better results concerning the fulfillment of the global requirements. Both the simple and predictive approaches work well even when the bidding elements have varying utilities or preferences.

The predictive action can even be further enriched by inclusion of a learning element. Further improvement of the system behavior is expected by employing a scheme similar to Model Predictive Control (MPC, Camacho and Bordons, 2004). In this scheme, which is the next step of the presented work, the prediction interval will be longer than the auction interval and thus in accordance with the theory of MPC, the auctioneer will have better overview of the system.

The presented work – as others in the area – shows that the design of multi agent systems involves a considerable amount of simulation and testing. It is the aim of this ongoing project to find some generic rules for the setting of the systems parameters based on the underlying systems dynamics.

REFERENCES
