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AGENT-BASED CONTROL FOR THERMOFORMING PROCESSES

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Abstract: Modern manufacturing systems deal with highly dynamic and complex processes and need to adapt to the rapid changes in manufacturing environments. Model-based control greatly improves process adaptiveness by integrating deep knowledge of process phenomena with advanced simulation tools. Agent-based technologies provide a favourable framework for implementing model-based control. An agent-based architecture developed for model-based control and an implementation for the thermoforming process are presented. How the architecture facilitates interoperability is described. *Copyright © 2006 IFAC*

Keywords: control systems, adaptive control, model-based control, agent

1. INTRODUCTION

In today's manufacturing industry, production processes can only be profitable if they are highly optimized for quality and short cycle times. They must master changes in materials and process technologies, and adapt to major changes in production requirements. The next generation manufacturing systems require system architectures that are adaptive in environments that are dynamic and to processes that are non-linear and often characterized by uncertain information. This uncertainty is a result of incomplete process specifications for new products or new manufacturing conditions.

Control architectures for real-time control of manufacturing processes commonly need to satisfy requirements such as reliability, robustness, interoperability, and reconfigurability. Traditional, centralized architectures based on PID or H-infinity control mechanisms are being found to be insufficiently flexible to respond well to these types of highly dynamic processes. Model-based control built on the integration of process know-how and simulation tools can address these ever increasing control requirements (Thomson *et al.*, 2004). A model-based control system uses an overall process model which integrates sub-models of various process phenomena. These models represent different physical phenomena involved in the process. The process models can have different time scales, and as a result, the control strategy can be highly complex.

Agent technology provides a way to design and implement distributed intelligent manufacturing systems, which are highly adaptive, and has features that are favourable for building model-based control systems. Multi-agent systems allow decentralization of control, which reduces complexity and increases flexibility. In addition, agent-based systems can cope with multiple models that are very different in size and that operate on dissimilar time scales.

In this paper, an agent-based architecture that can support model-based control systems is introduced. The architecture can accommodate a group of agents which can be configured for any manufacturing process. In addition, the architecture facilitates interoperability especially within an enterprise. It does this by standardizing control system interaction and by simplifying operator intervention.

The remainder of this paper is structured as follows. Section 2 briefly defines the requirements for an adaptive control system and how an agent-based application can satisfy these requirements. In section 3 the description of an agent-based architecture which supports model-based control is given. Section 4 describes the thermoforming process, and then, model-based control for thermoforming is detailed in section 5. Section 6 gives a discussion and section 7 presents some conclusions.

2. MODEL-BASED CONTROL USING AGENT-BASED TECHNOLOGY

Model-based control provides a framework in which required control parameters are calculated using state variables in mathematical and/or heuristic models of the process. Model-based control can cope with complex processes, where each sub-process is modelled by one model or several sub-models. Given enough knowledge of the process physics, processes can be simulated to accurately reflect the physical phenomena to be controlled. The complexity involved can be quite high, since there is a need to contend with non-linear phenomena and the coupling of process parameters.

Model-based control permits greater process adaptability by having a deep knowledge of the phenomena involved in the process and in the surrounding environment. Process models can achieve great precision, especially by being able to estimate certain required state variables that are not measurable during the process. Due to the deep knowledge nature of the process models, model-based systems can control processes that are highly dynamic, and composed of multiple, coupled sub-processes. An example for the thermoforming process is given in Section 4.

2.1 Agent-based technology

Recently, agent technology has been considered as an important approach for developing industrial distributed systems (Jennings et al., 1995; Jennings and Wooldridge, 1998). An agent is a software program (or hardware) that performs a user-delegated task; it works in a preset environment and interacts with other agents through their logically intelligent programs. The definition of agents used in this paper is that proposed by Weiss (1999): "Agents are autonomous, computational entities that can be viewed as perceiving their environment through sensors and acting upon their environment through effectors." Sensors and effectors can be either physical devices or software.

Agent-based systems can easily effect an architecture which delivers the adaptability required for controlling the production of each part in a dynamic process. Each functional agent in this system has a modularized internal structure and is independent from other agents. Such a structure enables the system to be flexible, and thus ensures good adaptiveness and upgradeability. Part of the adaptiveness is each agent's ability to self-duplicate in order to perform simultaneous multiple tasks.

For the most part, present day control of manufacturing processes is not adaptive and is based on maintaining control variables at or near fixed points. Run-up or the start of production after changeover is a very significant problem (Eldridge *et al.*, 2002). Starting a process is predominantly trial and error, where much time is spent finding the correct settings for process variables, and as a consequence, many parts or much material is wasted. In addition, maintaining control is highly compromised because of variation in process materials and operating conditions as material lots change, machines heat up, environmental conditions vary, and machine components wear. For example, for the thermoforming of complex plastic parts, there are typically 3-5 poorly formed parts during process run-up and a rejection rate of about 5% during production. For the first time processing of new parts, the tuning of the process takes much longer and the rejection rate is much higher.

An adaptive control system then needs to be able to adjust process parameters in order to be in control within a minimum period of time at run-up and to maintain control as each part is being made. For example, error rate targets for model-based control for thermoforming are 1 part during run-up and 0 parts during processing. In order to accomplish these rates, process models must allow precise calculations of control parameters, deal with different levels of granularity in terms of control parameter response time, and perform a large number of calculations with many process variables. In addition, it is desirable to have real-time diagnostics while a process is running in order to maintain quality levels.

3. AGENT-BASED ARCHTECTURE

The central issues in an agent-based architecture are the responsibilities and the behaviours of individual agents, the coordination of activities among agents, and the communication protocols to be employed. Agents used in this project are reactive agents, which sense their environment either by physical or software sensors, and then, issue actions by actuators and/or by communication with other agents.

3.1 General architecture

The main features of the architecture are shown in Figure 1. The architecture is composed of the process or physical layer, the control model, the data model, the diagnosis model, the error recovery model, and the process model.

The control model must simultaneously handle a number of different tasks: acquisition of sensor data, calculation of control parameters from state variables determined by the process model, execution of an optimized plan based on the state variables, and delivery of control parameters to the devices in the physical layer.

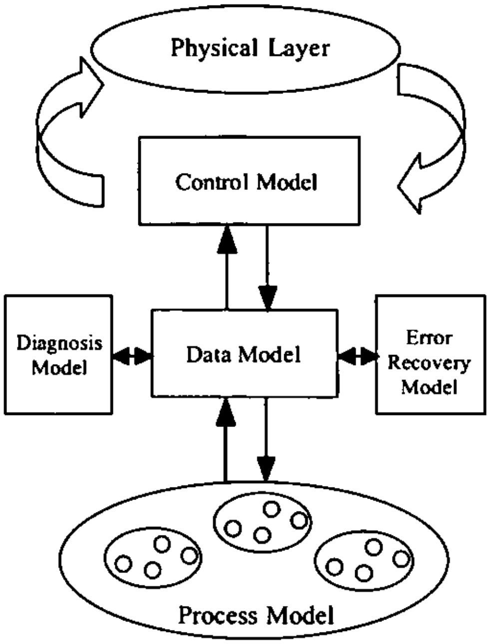

Fig.1. A conceptual view of the agent-based architecture

The process model can be a single model or a set of many sub-models. Sub-models are used when the process cannot be completely represented as one detailed model or when a single model is too slow or too inaccurate for real-time control. Each process sub-model performs at its own rate and continuously calculates state variables using sensor data from the data model. It then places the state variables into the data model to be used by other agents, especially the control model.

The data model stores data from the physical layer, all process information, as well as state parameters calculated by the process model. The data model allows the integration of data used by and created by all agents. The data model is implemented as a virtual database resident in computer memory.

The diagnosis model monitors the behavior of the process. To do this, diagnostics check data from physical layer devices, state variables developed by the process model and all sub-models, as well as control parameters calculated by the control model in realtime. Checks are made for availability and applicability of physical devices at the beginning of the process. The values of sensor data are continuously evaluated in terms of range and degree of change. Special logistical algorithms evaluate the interrelationships among state variables in order to check the consistency of process models. When errors occur, flags are set in the data model.

The error recovery model checks for error flags and then executes preset procedures for error recovery. The error recovery model has access to all the information pertaining to the error, including sensor readings, location, priority of action, etc., available in the data model. When an error occurs, the affected sub-models are halted. Determination is made if the production process can continue with reduced data or not. If yes, the exception is handled by agents separate from the process execution agents which correct the problem if possible, and then, indicate when the affected sub-models can continue. For extreme difficulties, an operator is informed about an exception event and intervention is requested.

3.2 System Data Flow

The control model acquires values from the sensors in the physical layer and sends them to the data model. The process and sub-process models then use these measurements to calculate state variables. The values of the resulting state variables are passed to the data model. The control model obtains values for the state variables from the data model, calculates the control parameters, sends them to be actuated in the process, and then, writes them in the data model. During this procedure, the diagnosis model evaluates whether the input data, state variables and control parameters are acceptable.

All agents in the control architecture operate independently and asynchronously. The control model operates the cycle of acquiring sensor data and sending control parameters as fast as possible. Similarly, the process models retrieve sensor data and calculate state variables. The retrieval of sensor data and the calculation of state variables can occur at varying times; thus, calculations use the best information that is available, some new as well as some old. This design permits fast control cycles while allowing data to flow asynchronously. This feature of the architecture is required to allow varying complexity in the different data streams, while still setting control parameters with the best available information. The diagnosis and error recovery models operate asynchronously in a similar manner. It is possible to control processes where process sub-model execution varies from milliseconds to hours.

3.3 Implementation

For implementing the architecture, the Java Agent DEvelopment framework (JADE) software is used. JADE is a platform for developing agent applications completely written in Java. Since Java supports major network protocols, it is feasible to use JADE for the development of agent-based systems within a network environment.

Since JADE is used as a platform to implement realtime agent-based systems, there are specific requirements for the properties of this platform such

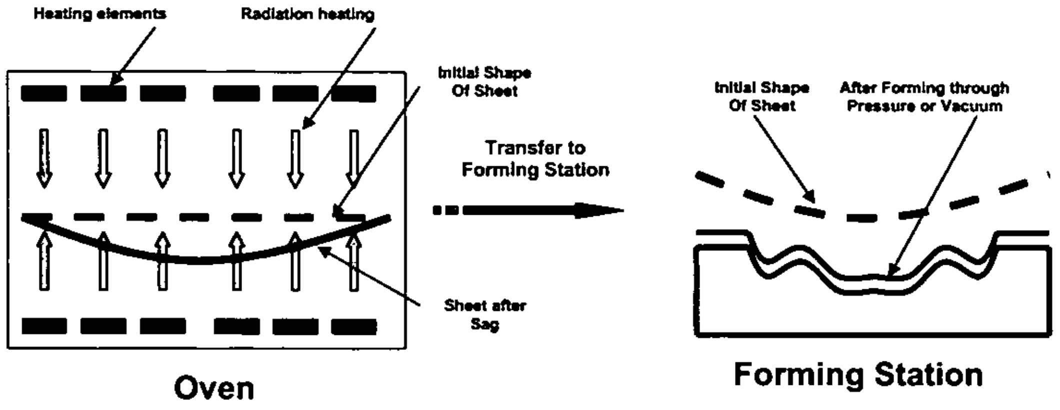

Fig. 2. The steps in a typical thermoforming process

as speed, memory, reliability, etc. Studies have been performed to evaluate JADE to find out to what extent it fulfils these criteria (Cortese *et al.*, 2003). Regarding memory requirements, it has been measured that the JADE agent platform requires a minimum of 100Kb memory during runtime, which is small enough to fit well within the memory capacities of the majority of automation controllers. The speed of message delivery is another important feature of JADE. In order for the agent platform to be fast enough for real-time control applications, it should be able to carry out interactions among agents and message delivery in the order of milliseconds or tens of milliseconds. Cortese *et al.* (2003) have performed a set of measurements to evaluate the performance of JADE messaging subsystem. Their results show that JADE is a good candidate for heavily loaded distributed applications since it scales linearly with load conditions.

3.4 Summary

The architecture for model-based control has the following characteristics:

- a process model that continuously calculates state variables, where the model can be one large model, and/or a set of related sub-models,
- a control model that acquires sensor data, calculates control parameters from process model state variables, and transmits the control parameters to the real process,
- an independent data model that stores all data and calculated process variables,
- a diagnostic system that checks sensor data and state variables computed by the process model,
- an error recovery model that tries to repair the system while production continues,
- asynchronous operation of all tasks: control, process model calculations, diagnostics and error recovery,
- task execution that is predefined by recipes for actions, since control systems have a limited set of states and possible actions.

Agent technology is an excellent fit for this architecture.

- Agents map well to the independent set of tasks.
- Agents can manage, calculate or control each data stream.
- Agents execute tasks and data handling asynchronously.
- An agent-based system allows autonomous diagnostics and error recovery.
- Agent technology allows for easy change of architectural components as process knowledge improves and processes are modified.

4. THERMOFORMING PROCESS

Thermoforming is a generic term for manufacturing of plastic components through a vacuum or a pressure forming process (Throne, 1996). The thermoforming process is composed of three basic phases: heating, forming and solidifying (Figure 2). First, a plastic sheet is heated in an oven between an upper and lower bank of elements to its softening temperature, and then moved to a forming station. There, the sheet is stretched by using vacuum or air pressure, often with the aid of a plug to push the plastic in order to achieve complex details. When the plug is removed, cool air is blown into the mould for faster solidification. The part is then removed and excess plastic is trimmed away.

Thermoforming is a high waste process, which means that the process has a lot of room for improvement in production efficiency, energy and material use as well as part quality. Research on the thermoforming process shows that the most critical phase of thermoforming is sheet heating, which directly affects subsequent phases of the process. Close temperature control during this phase results in reduced rejected parts, decreased energy consumption, and shortened cycle time.

As shown in Figure 3, all thermoforming polymers have forming windows defined by a lower (T_{lower}) and upper (T_{upper}) forming temperature. The polymer surface is prone to color change or blistering if the surface temperature goes above T_{upper}. On the other hand, the polymer is too stiff to be formed or will have micro-cracks while being formed if the plastic is below T_{lower} at forming. The lower and upper temperatures determine the boundary of formability.

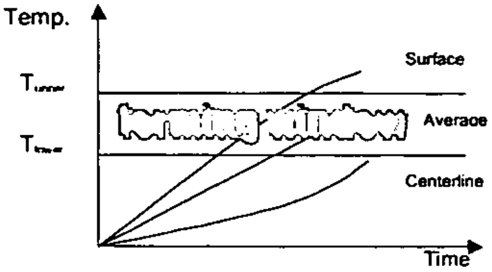

Fig. 3. Plastic sheet heating for thermoforming showing the temperature limits of the forming window of a heated plastic sheet, and the surface, center, and average temperatures

In thermoforming, the heating process is controlled by the rate at which radiation and convection energy are delivered to the plastic sheet surface. The energy arriving at the sheet surface controls the heating time. The primary purpose for the control of the thermoforming process is to transfer the correct amount of energy required to heat the plastic sheet and to maintain the temperature within the forming window (between T_{lower} and T_{upper}), while realizing the desired temperature distribution across the sheet. For a thin sheet, the internal temperature of the sheet is practically the same as the surface temperature. For a thick plastic sheet, the combination of conduction and radiation energy, which moves into the sheet interior, controls the heating time. In order to predict the formability of a thick sheet and improve production efficiency, the temperature profile inside the plastic sheet during heating needs to be predicted since it cannot be measured directly.

In a thick sheet, the temperature at the center of the sheet is significantly below the surface temperature due to the relatively slow thermal diffusive character of polymer sheet. Note that in Figure 3, the thermoforming process is not correctly controlled, i.e., the surface temperature is above the upper temperature, while the temperature at the center of the sheet is not yet at the lower temperature limit to allow forming. If we use this energy input, the sheet temperature profile results in rejected product. To ensure proper sheet heating, the controller must adjust the heating rate, i.e., the element temperature, and/or the length of stay in the oven. The approach improves how the material is distributed for a formed thermoplastic part via better sheet temperature control prior to forming. Improved control of material distribution increases part quality and results in fewer parts being rejected. Production efficiency is increased by using less energy and material for forming the same part. It is possible to set the control tactic to heat the sheet of plastic in a fixed time, in minimum time or with minimum energy.

5. MODEL-BASED CONTROL OF THE THERMOFORMING PROCESS

The main step for the creation of an agent-based control system is to build a process model and simulator. The process model determines critical state variables and the simulator simulates the process to predict process outcomes given the state variable history. For the modelling and simulation of the thermoforming process, the FormView software developed by the Industrial Materials Institute (IMI), National Research Council (Canada), was used. For each part, FormView uses an accurate finite element simulation model of the thermoforming process to compute time sequenced trajectories of sheet temperatures for different sheet zones. Since the thermoforming process is non-linear and has many process parameters, FormView can take a long time to calculate process parameters, and thus, it is not suitable to control the process for the required cycle time. Therefore, a set of sub-models was created to approximate process behavior for time critical process variables. Before process execution, FormView gives the parameters for the operating point of the process. Sub-models use linear approximations about the operating point. FormView continuously calculates the parameters for the operating point during the thermoforming process. Process parameters do not move much from the operating point between FormView calculations and a linear approximation is quite valid.

One of the important features of the process models is the use of a soft-sensor technique that allows calculations employing measurable parameters to accurately predict non-measurable parameters. A soft-sensor system can be defined as an algorithm that estimates inaccessible state variables of a specified process based on mathematic models of the process and the direct measurements of other available process variables (Hou, 2003). For example, the internal temperature distribution of the plastic sheet is determined by a sub-model which uses the surface temperature of the sheet measured at several points and the energy output of each heater. The internal temperature distribution is continuously calculated from the start of heating until the sheet is removed from the oven.

In addition to the internal temperature profile of the plastic sheet, it is necessary to characterize each plastic sheet in terms of specific heat capacity, thickness variations, molecular weight, and emissivity. Models must calculate realtime corrections for heater settings, and measurement of the final part thickness. The wide range of variables demonstrates the complexity of the process models, and the large variety of computation needed to calculate control parameters. As far as the necessary computation time, the calculation of internal sheet temperature profiles can be done in a few milliseconds using heater outputs and sheet surface temperatures, whereas corrections due to final part thickness measurements can take hours.

6. DISCUSSION

The goal of model-based control for any process is to have in-cycle control, i.e., to be able to adjust processing parameters during the production of a part. To do this, the cycle time from using sensor data through the calculation of state variables to obtaining control parameters must be very fast. However, certain data can only be measured after a part is made, for example, part thickness in thermoforming. In this case, the calculation of state variables can only be done cycle-to-cycle, and most likely, with a time gap of many parts. This information must be integrated with other data in order to have a coherent picture of the process. Depending on the criticality of the sensor data for the calculation of state variables, some processes may only be able to be controlled cycle-to-cycle.

Control of manufacturing processes is by nature realtime. There are the constraints imposed by the process since a quality part has to be made within a fixed period of time. For example, for in-cycle control of thermoforming, decisions typically have to be made in the first 5-10% of the fabrication cycle in order to be able to adjust process parameters to have an effect on part production. If decisions cannot be made this rapidly, then, control can only be done cycle-to-cycle. In-cycle control is always preferable since it allows adjustment of the process for each part, and this ensures better part quality.

The architecture described in this paper can handle hard real-time control. This can be done with a single processor, if the amount of computation is small. Nevertheless, for thermoforming, the amount of calculation for process models tends to be large and distributed over different time periods; therefore, multiple processors are required. Upon execution, the system dynamically allocates the execution of agents to available processors. This allows great flexibility to respond to variable amounts of computation and to achieve fast cycle times.

The control architecture described in this paper is deterministic, i.e., for a given set of inputs, the output is always the same. Thus, the system is designed such that there should be no contentions. This follows mostly from the fact that process control acts upon a repetitive sequence of tasks with little need for intervention. The use of this tactic avoids the need for negotiation between agents, and in turn, this simplifies the design of the agent-based architecture. It also permits a consistently fast response time.

Results using model-based control for thermoforming have been limited to production runs of a small number of parts. To date, there are less rejected parts at start up, better quality, reduction in energy use and more control over cycle time. When the new system has been used more by industry, overall performance statistics will be available.

The architecture for model-based control allows more control transparency and less operator intervention. This greatly improves interoperability. Currently, a factory with several thermoforming or other types of machines tends to have equipment of different ages from different vendors with different control systems. Model-based control makes interaction with control systems simpler and more uniform. Interfaces to machines using a model-based control system can be made to be almost identical for process operation. This is because information is in the control system not with the operator. The systems can also be centrally managed. Interoperability between companies is also improved since model based control reduces the variability of production and since production data is available for each part.

7. CONCLUSIONS

The use of an agent-based control system for thermoforming has proven to be very effective. Magi Control (Montreal) is now selling thermoforming controllers based on model-based control. Agent-based control is self-tuning; so, poor production at run-up and during production is held to a minimum. In addition, the system provides for easy modification of parameters as the environment changes or when changeover occurs. The target of 1 poor part during run-up and 0 parts during processing means moving from a quality regime of two sigma to six sigma. This is only attainable with the responsiveness of model-based control.

The architecture described in this paper is effective and has high adaptability for the control of complex processes. Control based upon process modelling also permits straightforward diagnostics and error correction, and parallel processing permits realtime response regardless of the process complexity and cycle time. Finally, the techniques described here are applicable to any process where state parameters can be induced from process know-how.

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