An Intelligent Control Architecture for the Microwave Fabrication of Composite Materials Based on the Generic Task Approach to Knowledge-Based Systems

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Abstract

An architecture for intelligent real-time control is presented. The architecture is rooted in the Generic Task (GT) approach to knowledge-based systems and incorporates plan generation and real-time plan execution-monitoring components. The plan generation component produces a plan representation which typically contains a large collection of possible paths from initial to desired process states. Selection of the precise path taken through the plan is determined by the execution-monitoring component. The execution-monitoring component incrementally determines appropriate partial paths through the plan based on sensory input gathered from real-time process monitoring. This real-time selection of appropriate partial paths is facilitated through the use of a sponsor-selector mechanism. The usefulness of the approach is demonstrated by applying the control architecture to the control of a microwave-based composite material fabricator.

1.0 Introduction

Various approaches to real-time knowledge-based process control have been proposed in the AI literature. Many approaches are based on extensions of classical planning systems such as STRIPS [Fikes 71] but are inappropriate for dynamic environments in which the external world may change independently of applying actions from the plan. Purely static planning is inappropriate in many highly unpredictable domains because the consequences of plan actions cannot be accurately determined prior to plan execution. Additionally, traditional rule-based planning systems may be difficult to develop, extend and maintain in the absence of a guiding framework because they represent knowledge at a level of abstraction which is too low to effectively support specific types of problem solving such as routine design.

Reactive or behavior-oriented approaches attempt to address the problem of planning in dynamic environments by allowing plans to "react" to unpredictable conditions as they are executed. Much of this research has been applied to autonomous vehicle control and robotics. Examples of reactive approaches include layered, decentralized behavior-oriented systems [Brooks 86], universal planning [Schoppers 87], PRS [Georgeff 87] and RAPS [Firby 88]. However, these approaches are also not without their limitations. Purely reactive approaches have been criticized as computationally intractable for large problems, therefore limiting their utility in certain complex real-time environments [Ginsberg 89]. Additionally, behavior-oriented systems exhibit interesting behavior due to simple interaction with complex environments, but are not optimal for supporting high-level goal-directed reasoning. Many systems feature purely reactive plans which would not be useful in environments where the availability of sensor information was not reliable or predictable at the time of plan generation.

Our approach attempts to avoid these problems by combining plan generation and real-time plan execution into a single system. The planner does not generate a single "universal" plan, rather it synthesizes a plan blueprint from which a fabrication plan is subsequently assembled using a library of pre-complied control methods. The fabrication plan is typically a combination of multiple plan fragments, each with its own control methods and the conditions under which they should be used. Fabrication plans can, at their extremes, be purely reactive or purely static but they are typically hybrids. The control actions which are con-

tained in the plan are embedded within the control methods. The real-time execution module executes fabrication plans by monitoring process information and selecting the plan fragment sequence in real-time. Thus, the generated fabrication plan is really a set of potential plan fragments together with control methods and it is the task of the execution module to select appropriate plan fragments and their associated control methods in real-time based on sensor data. The actual control methods selected will therefore vary based on sensor data, without any requirement for generating a new fabrication plan.

The architecture used to implement this system is based on the Generic Task (GT) approach to knowledge-based systems [Chandrasekaran 86]. The GT approach maintains that certain tasks have common features which can be identified and used as a basis for the creation of specific tools designed to facilitate problem-solving. Tools developed to support GT problem-solving provide both knowledge representations and control strategies appropriate to the problem-solving type. Among the classes of problems which have been addressed through the GT approach are routine design and planning [Chandrasekaran 89]. The synthesis of fabrication plan blueprints is an example of a routine planning activity.

The control architecture presented here exploits the benefits of the GT methodology by integrating established approaches to knowledge-based plan generation and real-time plan execution-monitoring. The plan generation component is based on the DSPL language for routine design and planning [Brown 89]. The plan execution-monitoring component is based on another GT problem-solving mechanism termed a sponsor-selector system [Brown 84, Punch90a, Punch90b]. We have applied this approach to the domain of polymeric composite material curing.

The remaining sections of the paper will review the composite material cure problem, give a detailed overview of the overall architecture and review some preliminary results.

2.0 Domain Overview

Traditionally, polymeric composite materials have been cured in autoclaves through the application of heat and pressure [Strong 89]. Initially, these fabrication processes were manually monitored and controlled by human operators. Conventional control systems were eventually employed to assist in adjusting autoclave temperature and pressure to follow a static material-specific curing profile. Unfortunately, variances in processing equipment and material characteristics make the use of static processing profiles problematic. Subsequently, expert systems were developed to intelligently control autoclave fabrication by dynamically adjusting the control strategy in real-time based on monitored process variables and other information [Abrams 87]. Although the use of these techniques offers improved material quality and represents an important real-world application of knowledge-based systems technology, these systems are ultimately limited by the inherent drawbacks of the underlying autoclave-based processing technology. Autoclave processing is neither a particularly fast nor highly controllable approach to composite material fabrication.

Microwave fabrication technology offers advantages in terms of reduced processing times, lower energy consumption and high controllability [Asmussen 87]. Under this technology, composite materials are cured through interaction with a microwave-frequency electromagnetic (EM) field. Advantages of the microwave approach include the ability to instantaneously and selectively deliver microwave energy to the composite. However, microwave processes are less "stable" than typical autoclave processes in the sense that they demand real-time adjustment of the EM field characteristics to avoid potentially damaging thermal gradients and charring in the material under cure.

Many microwave-based composite material fabrication processes may be roughly divided into three processing phases: initial material heating; cure temperature maintenance; and cooling. The fabrication objectives are typically different for each processing phase. For example, during initial heating it is important

to raise the temperature of the composite as rapidly as possible, even if material heating is non-uniform. Conversely, during the maintenance phase it is more important to minimize temperature gradients in the material.

Microwave fabrication technology introduces a formidable real-world control problem. Part geometry, mass distribution, composite material dielectric properties and other factors combine to significantly perturb the applied EM field. As a result, interaction between the part and the EM field is difficult to predict and heating is generally uneven. It is therefore necessary to adjust the EM field characteristics to attempt to maintain a favorable temperature distribution in the part. Since determining EM field interactions with even simple-shaped parts would involve solving computationally prohibitive sets of complex differential equations, standard algorithmic approaches to control appear to be unsuitable for this domain.

The experimental microwave cavity developed in our laboratory is designed to support a wide range of EM fields through the use of a pair of motor controlled tuning mechanisms. A closed-loop feedback controller has been incorporated to address various low-level control tasks including mode-tracking, data gathering, power management, drift compensation and motor control. This arrangement relieves the plan execution monitoring component of the responsibility for the lowest-level control issues. The motor-controlled probe depth and cavity length tuning mechanisms allow EM field characteristics to be controlled within the cavity. Specifically, a series of discrete transverse electric, transverse magnetic and hybrid field types can be selected and maintained during fabrication by making suitable probe depth (L_p) and cavity length (L_c) adjustments [Decker 93]. A diagram of the prototype single-mode resonant cavity is shown in Figure 1.

2.1 The Fabrication Model

The control architecture utilizes specific models to support reasoning during plan generation and execution. Each composite part has a unique fabrication (case) model associated with it. Fabrication models contain knowledge about material type, fabrication hardware configuration and a hierarchical structural representation used to describe part geometry. Parts are conceptually partitioned into a number of disjoint non-overlapping regions, each of which may be composed of one or more other regions. The lowest-level regions in this representation are called elements. Elements may be loaded with various types of sensors such as fiber-optic temperature probes.

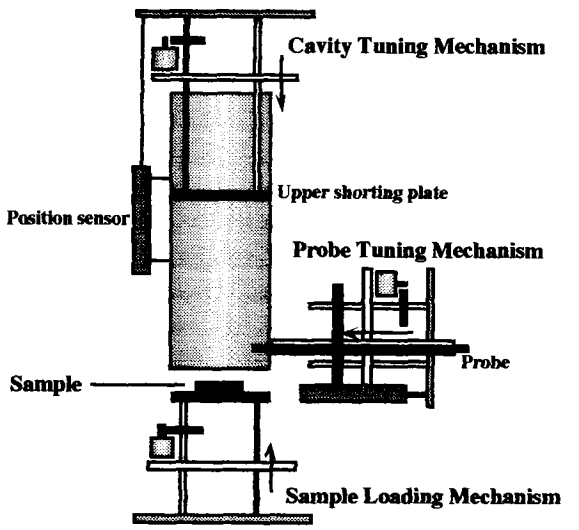

Figure 1 - Microwave Cavity

The representation may be visualized as a spatial mesh of equal-sized elements through which adjacency, thermodynamic and heat transfer characteristics, mass distribution, sensor placement and other knowledge is used to support reasoning during plan generation. Symbolic regions are successively composed from elements and other regions. The concept of regions is used to support the formation of higher level observations about the part and to assist plan generation by defining a common language to describe part features. Constraints such as "the temperature gradient in the part should be less than 10 °C," are easily expressed through reference to the symbolic regions provided by the model. Part models also include knowledge regarding matrix and fiber types, fiber and resin volume fractions, empirically determined spatial EM field interactions and other factors. A sample part and the corresponding structural representation are shown in Figure 2.

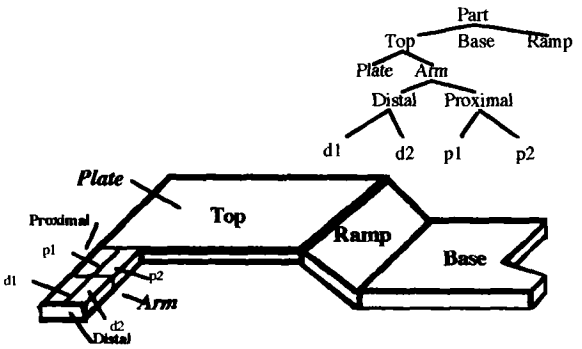

Figure 2 - Structural Representation

3.0 Architectural Overview

Plan generation and execution, though integrated in the overall system operation, are activities supported by separate problem-solving modules, each with its particular knowledge and control strategies. The plan generation component (planner) synthesizes a blueprint, a list of potentially applicable control methods to be used during fabrication. The assembler then integrates the specified control methods called out in the blueprint. The plan assembler synthesizes the final fabrication plan by retrieving from the method library those methods called out in the plan blueprint, creating sponsoring mechanisms for the specified methods and integrating the resulting fragments into a seamless fabrication plan.

The responsibilities of the execution monitor are to gather sensor data in real-time and to select the plan fragment sequence. The execution monitor therefore consists of two interacting components: the observation unit (for real-time data capture and analysis) and the execution unit (for plan fragment selection and execution.)

Figure 3 shows the overall architecture in the context of controlling a microwave composite curing process, the present laboratory system on which our approach is being tested. The planner generates a plan blueprint, which is assembled into a fabrication plan by the assembler and subsequently executed by the execution monitor. The observation unit in the execution monitor gathers sensor data using a standard control system interface. This control system is responsible for monitoring a collection of sensors which measure various aspects of the material state during fabrication. Currently, sensed parameters include temperature, incident and reflected power and physical positioning information for the motor-controlled cavity tuning mechanisms. Sensors and techniques for measuring other physical properties including the dielectric constant of the material are under investigation. This data is used by the execution unit to select the next plan fragment to execute.

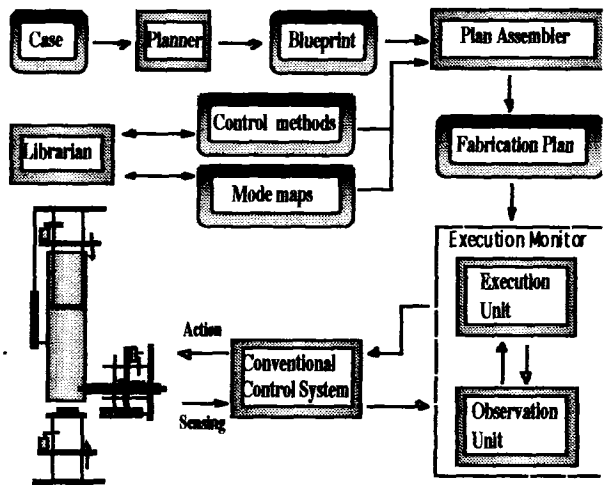

Figure 3 - Architecture

3.1 The Planner

The planning system uses compiled expert knowledge of the single-mode microwave composite fabrication process for control. The planner architecture is based on the DSPL framework for routine design and utilizes knowledge incorporated in the fabrication (case) model and compiled knowledge of composite material fabrication, thermodynamics and heat transfer to synthesize an appropriate fabrication plan blueprint. As output, the planner produces a blueprint consisting of a set of references to the potentially applicable control methods and the conditions under which they can be executed. The final fabrication plan may range in character from completely reactive in situations where a full complement of sensors is available but little or no experience

has been gained in processing parts of this type, to completely static in cases where there are few or no sensors but previous processing experience is available.

Our domain analysis indicates that the plan blueprint generation task, at least for the composite cure problem, is a routine design task. A routine design task has a pre-tested sequence of actions that is appropriate for solving that particular problem. DSPL was designed as a tool for solving routine design problems and thus it is the basis for the planner. The structure of a DSPL problem-solver is fairly elaborate, containing a number of levels of abstraction and problem-solving methods associated with each level. However, at the top level, a DSPL problem-solver consists of a set of hierarchically organized design specialists. A specialist is a design agent that will attempt to design a portion of the overall component. It is a repository for knowledge required for designing that one portion, which it does by utilizing either local knowledge or the cooperative efforts of other sub-specialists.

This local knowledge is primarily encoded as a set of plans from which the design specialist must select, where a plan is encoded as a sequence of design steps or sub-specialists. Each specialist contains a pre-stored set of plans from which to select, as well as knowledge regarding the kind of problems for which each plan is most appropriate.

The specialist hierarchy within the planner coordinates the problem solving activities needed to fill out the detail in the plan blueprint, including utility of the various tuned modes, appropriate power levels for processing, schedules for movement between processing phases and so on. The overall processing strategy is fixed by a fabrication technology specialist and subsequently influenced by sensor availability, experience with processing the part, initial material cure extent, material type and part geometry. Additional specialists determine the EM field types which are best suited to the initial material setting requirements and the criteria for making transitions between the processing phases.

An actual fabrication plan fragment is shown in Figure 4 for a small portion of the overall microwave cure problem. Again, note that the planner and assembler do not generate a single plan, but a collection of plan fragments and the conditions under which they can be used. The fragment shown in Figure 4 is represented in the form of a knowledge-based selection mechanism called the sponsor-selector mechanism. The plan assembler generates many such plan fragments in a format utilizable by a knowledge-based selection system and these fragments, together with sponsored control methods, constitute the fabrication plan.

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"This model based on data taken by J. Wei (1992)"
"7.62 cm square 24-ply (crossply) sample - carbon fiber - 30g mass"
"DGEBA matrix with DDS cure system - 2 W/g Crossply power density"

RootSelector: RootSelector.
OrderedSponsorList: (initializationSponsor emergencySponsor
noOpSponsor modeSwitchSponsor powerControlSponsor
passiveCoolingSponsor).

Sponsor: initializationSponsor.
Headers: ('ProcessingPhase = #initialization' 'Rating').
Contents: ((true 'A')).
DefaultReturnValue: 'E'.
Item: (method initializationMethod).
Method: '
initializationMethod
  "Note the time we started to process the composite"
  StartTime := (Time now) asSeconds.

  "Set power to 2 W/g if crossply, 1.5W/g if unidirectional"
  (PlyType = #crossply) ifTrue: [RecommendedPower := CompositeMass *
2.0]
  ifFalse: [RecommendedPower := CompositeMass * 1.5].

  ProcessingPhase := #processing.
'.
....
```

Figure 4 - Sample Plan

The typical structure of a sponsor-selector is shown in Figure 5. It consists of a hierarchy of three parts: a selector, some number of sponsors, and a selection item associated with each sponsor. Sponsors provide a measure of how appropriate selection items are for selection under the current conditions. In this particular implementation, the selection items or "operators" consist of plan fragments and control methods. Associated with each group of sponsors is a single selector which can be used to resolve ambiguities when multiple items appear equally appropriate and to provide a global point-of-view on the selection process.

The assembler generates a sponsor for every control method called out in the plan blueprint, encoding in the sponsor the knowledge of when that control method is appropriate. Sponsors are grouped under a selector when that

sponsor set represents the plan options for a particular kind of plan decision. Selector generation is based on the processing phases of the controlled system.

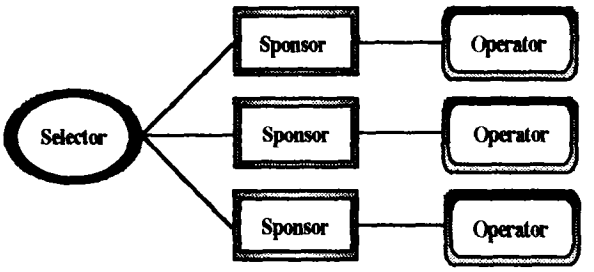

Figure 5 - Sponsor-Selector Structure

3.2 The Observation Unit

The observation unit continuously monitors process parameters and performs analysis on sensed data during plan execution. Observations are used in conjunction with the fabrication plan to effectively control the fabrication process through appropriate selection of sponsored control methods.

Assume that temperature probes have been placed at elements d1 and p2 using the example from Figure 2. The observation unit measures the temperature at elements d1 and p2 directly. Since they do not contain temperature probes, the temperatures of regions d2 and p1 are estimated through the use of the values of their neighboring elements (d1 and p2) using a simplified equation of heat transfer. The equation accounts for material mass, thermal conductivity, element adjacency and area of contact, various convective and conductive heat losses and so on. From this information (contained in the fabrication model) the observation unit estimates temperatures for elements d2 and p1. Subsequently, the observation unit estimates the temperature of the distal portion of the arm (the average of d1 and d2) and the average temperature for the arm (the averages of the distal and proximal region temperatures). Temperature gradients, heating rates and other information are similarly calculated for all elements and regions within the part. This information is then used by the execution unit (in conjunction with the fabrication plan) to select appropriate power levels and cavity modes for material processing.

3.3 The Execution Unit

The control of a microwave composite fabrication process is considered a soft real-time problem in the sense that missing a "deadline" is not normally catastrophic to overall system performance. Missing deadlines in this domain may imply a potential degradation of the ultimate finished material quality and resultant mechanical properties, but not total system failure. However, real-time response is still a concern since the resultant material quality degrades with failure to meet reasonable time constraints.

The execution unit applies the plan by selecting plan fragments based on data gathered by the observation unit, and must coordinate execution of the plan with sensing and control functions. The conventional controller relieves the execution unit of the need to supervise low-level feedback control loops involved with cavity tuning operations.

The execution unit accepts the fabrication plan generated by the assembler and instantiates the sponsor-selector mechanisms for use during plan fragment selection. For the plan shown in Figure 4, there are six plan fragments at the highest level and therefore six selectors to drive plan fragment selection. The fabrication plan provides conditions that indicate when movement occurs between major control sections (not shown in Figure 4). At each time step (the length of which was pre-determined for the duration of plan execution) the execution unit evaluates all the sponsors of the active selector and gathers their appropriateness measures for their associated control method. The selector then chooses the next item to execute based on the sponsor values and, if necessary, its priority list. The selected item may be another selector, so that the plan structure may be of arbitrary depth. Selection item characteristics are not restricted by the sponsor-selector architecture, and in fact many strategies have been encoded through the use of this mechanism (i.e., plans [Brown84], hypotheses [Punch90a], control methods

[Punch90b] etc.).

The sponsors thus act as "local" measures of how appropriate their associated items are for achieving the current goal, while the selector takes the more "global" view of selecting which of the applicable items is the most appropriate under the given problem-solving situation. This sponsor-selection process continues until movement to the next major phase of processing occurs. At that point the next selector is activated and the cycle repeats. Note that the movement to the next selector is actually achieved by providing a sponsor in the previous selector whose operator is to "switch to the next selector". Thus the resulting plan execution is variable, depending on the initial plan fragment set up (as a sponsor-selector system) and on the data gathered by the observation unit.

4.0 Preliminary Results

All components of the system have been implemented in VisualWorks™ SmallTalk. The system accepts a fabrication (case) model, synthesizes an applicable plan blueprint, assembles the appropriate control methods, builds sponsor-selector structures and executes the plan in real-time by running the sponsor-selectors. The execution monitor interfaces with a conventional control system which controls a laboratory-scale resonant microwave cavity [Sticklen 92]. This control system uses a Macintosh™ running LabView™ from which the observation unit gathers available data in real-time, based on pre-defined time steps. Thus we can execute plans for real-world control of composite material cure. Our current work focuses on the enhancing the coverage of control methods available for support of material processing and integrating support for these methods into the planner. We are therefore in the process of encoding additional knowledge about new control methods into the DSPL-based planner and adding control methods to the assembler library. We have developed a simple librarian tool for this purpose.

5.0 Conclusions

A control architecture for the microwave fabrication of polymeric composite materials has been presented. The control architecture includes planning and execution-monitoring components and is intended to control microwave fabrication processes in real-time. The control architecture is based on the Generic Task approach to knowledge-based system design and the DSPL language for routine design and planning. A sponsor-selector mechanism is utilized to facilitate the selection of control methods. The control architecture overcomes many of the disadvantages associated with traditional static planners and is designed for effective real-time knowledge-based control of complex dynamic processes.

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