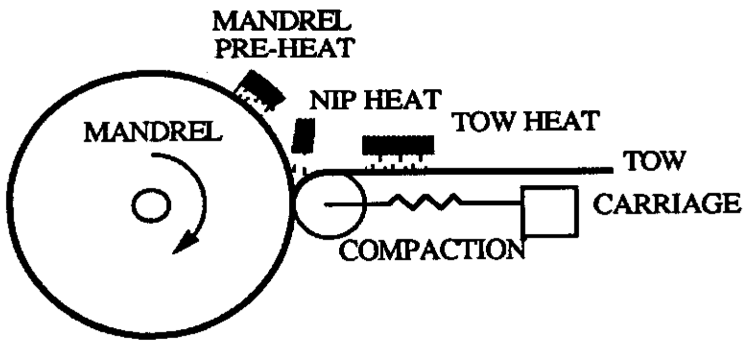

Figure 2. In-Situ Consolidation.

however, the process variable specifics (temperatures, flow rates, etc.) are not available.

To support the initial consolidation process, a part form mandrel made from a dissolvable material will be used. The material selected is designed to have a coefficient of thermal expansion and thermal conductivity similar to the thermoplastic prepreg. Therefore, the process parameters should not have to change significantly as part thickness increases during lamination .

Investigation of various sensors will continue throughout the project. The initial sensors will measure the temperature of the tow and laminate, and the applied consolidation pressure. These parameters will be compared with off-line testing of the final products to develop a meaningful correlation. The sensors will then be used to adjust the process speed, heat input, and compaction pressure on-line.

The project schedule calls for development of the initial testbed by fall 1990. Consolidation experiments will begin during the summer of 1990 and continue into 1991. Installation of the robotic fiber placement system in the AMRF is scheduled for late 1991.

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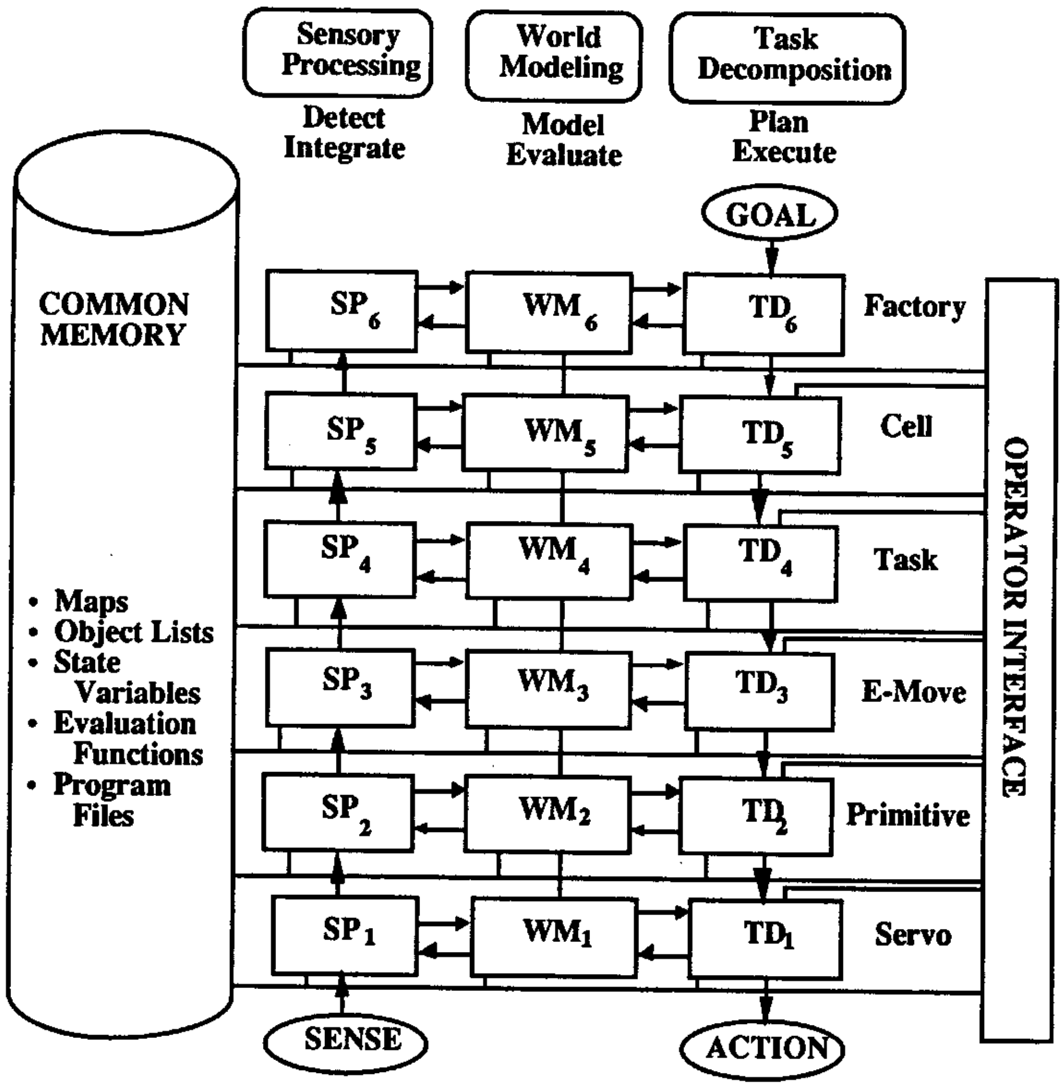

Figure 1. RCS Control Hierarchy.

consolidation experiments. A simple "contact placement winder" is now being developed as the testbed hardware so that the various process parameters involved in in-situ consolidation can be studied. This process is illustrated in Figure 2. The intention is to determine various combinations of temperature, pressure, and tow feed rate which result in successful consolidation of the tow prepreg. In order to determine an initial set of parameters, a thermal model of the process is being developed using a finite element analysis package.

Various organizations have experimented with a number of heating methods. Among the more popular are: lasers, hot gas, resistive, and infrared heaters. One method which appears both flexible and cost effective is a hot gas heater. The selected heater discharges up to 1400°F air through many small orifices which produce small but high velocity air streams (260 mph by 40 mil diameter). The high speed air cuts through the laminar air layer adjacent to the tow and quickly and efficiently transfers heat into the composite. The hot gas heater concept has been successfully used with thermoplastics by others, Fiber placement and in-situ thermoplastic consolidation are both emerging manufacturing technologies [1-4]. While several organizations are exploring in-situ consolidation techniques, only a few have reported success, and they are reluctant to disclose the details of their discoveries. Before a fully robotic system for fabricating complex geometries can be implemented, a successful in-situ consolidation process must be developed.

Because of these uncertainties, a testbed system is being implemented which will be used to investigate and develop suitable consolidation and fiber placement techniques. Based upon the testbed results, a prototype robotic fiber placement system will be designed and installed in the AMRF. This fiber placement system will consist of two cooperating manipulators, each likely to have four to six degrees of freedom. While one manipulator maneuvers the part form, the other manipulator will apply the prepreg. This arrangement is expected to permit far greater access to difficult part geometries and greater flexibility than is possible with current equipment.

The manipulators' link dimensions and joint ranges have yet to be determined. Graphics simulation will be used to evaluate various alternatives for effective work volume and dynamic limitations. Since the system will be evolutionary in the sense that untested mechanical and thermal systems are being developed, graphics simulation and modeling will be used extensively throughout the project. This will assist the understanding of the effect of the process variables and to predict the performance of the system.

The control system will be based on the NIST-developed Real-time Control System (RCS) [5-7]. The result of over a decade of research on advanced manipulator and systems control, RCS is a hierarchially structured control system which utilizes sensory feedback to make real-time modifications of the robot motion. RCS provides logical separation and organized integration of the various functions of the controller. Adhering to the hierarchy also allows for alterations and enhancements to be easily made.

The fundamental paradigm of RCS is a three-legged hierarchy of computing modules (Figure 1), serviced by a communications system and a global memory. The three legs consist of Task Decomposition (TD) modules, World Modeling (WM) modules, and Sensory Processing (SP) modules. The task decomposition modules perform real-time planning and task monitoring functions; they decompose task goals both spatially and temporally. The sensory processing modules filter, correlate, detect, and integrate sensory information over both space and time in order to recognize and measure patterns, features, objects, events, and relationships in the external world. The world modeling modules answer queries, make predictions, and compute evaluation functions on the state space defined by the information stored in global memory. Global memory is a database which contains the system's best estimate of the state of the external world.

In this application the control system must simultaneously coordinate the two manipulators and the consolidation equipment. It is anticipated that material temperatures at various locations, will be used to make adjustments to the fiber placement process.

PROJECT STATUS

Using a review of current research programs and literature as a guideline, current efforts have been focused on the design and development of the research testbed. An informal survey of composite part manufacturers indicated that there is significant interest in the automated processing of carbon/PEEK (Poly-ether-ether-ketone) prepreg. Therefore, carbon/PEEK was selected as the thermoplastic prepreg to be used for initial vacuum is applied to compact the laminate. The bag is then removed and the hand layup continues. After all plies have been laminated, the part is again bagged and readied for the autoclave process. Hand layup, while very flexible, is very time and labor intensive, exposes workers to potential health hazards, and is less repeatable then an automated process.

Filament winding and tape laying are two popular mechanized processes used to fabricate high-performance parts. In filament winding, a fiber bundle or tow is guided under tension onto a rotating mandrel. The tension and the part's convex surface combine to produce a compaction force. Thus, filament winding is usually limited to axisymmetric shapes having convex surfaces. Tape laying generates the compaction force directly through a lay-down head. In tape laying, consecutive bands of 3 to 6-inch wide prepreg tape are rolled onto a part form. Tape laying is limited to surfaces having flat or mild contours.

To address these deficiencies, some organizations in the composites industry have directed research efforts toward developing a fiber placement process. Fiber placement combines aspects of both tape laying and filament winding. Like filament winding, fiber placement uses the narrow bands of prepreg tow. Like tape laying, the tow is applied onto the part form under direct pressure. With contact placement, the tow's path is not limited to convex geodesic paths. Thus, very complex shapes and fiber orientations can be produced.

In-situ Consolidation

In-situ consolidation refers to the welding or consolidating of the thermoplastic prepreg during lamination. As the band of prepreg approaches the bond zone or "nip", the band and the substrate, or previously applied laminae, are heated above the melt temperature. At the nip, pressure is applied to insure intimate contact between the two surfaces. As the material cools, the two surfaces consolidate into a single structure. Several problems arise in this scenario. For example, the desire for an economic, and therefore, rapid lay-down rate conflicts with the requirement to maintain an effective processing temperature and pressure long enough to achieve successful consolidation.

Since virtually all high-performance composite parts have been made of thermoset prepregs, the processing of thermoplastic prepregs is not well understood. Satisfactory consolidation has yet to be universally defined. Furthermore standard methods for the direct measurement of consolidation in thermoplastic prepregs do not exist. Despite problems, the pursuit of in-situ consolidation promises significant rewards. When in-situ thermoplastic consolidation is achieved, expensive autoclaves and associated cure cycles, as well as the refrigeration and special handling which are required for thermoset prepregs may no longer be necessary.

COMPOSITES WORKSTATION PROJECT GOALS

The purpose of this project is to enhance the automated production of high-performance parts made of composites. The project's goal is to use the control techniques of the AMRF to demonstrate the feasibility of a robotic thermoplastic fiber placement process. In this process, the prepreg tow or tows are consolidated in place as they are applied to complex shaped part forms. Much of this work will concentrate on developing the techniques required to fabricate parts whose geometry currently makes automated production difficult. These parts are defined here as being non-axisymmetric with concave surfaces and/or multiple axes of rotation.

BACKGROUND

The following three sections present a brief overview of composite materials and the associated manufacturing processes. This material is discussed in order to provide the necessary background information which led to the development of the research goals for the AMRF Composites Workstation.

Composite Materials

High-performance composite parts are generally laminated structures. Each ply is normally reinforced with continuous, unidirectional fibers. The designer specifies the fiber orientation in each ply in order to optimize the structural properties of the part. This results in a part that is lightweight and strong, but expensive to produce. Conversely, consumer goods do not have the stringent performance requirements, and they must be produced at lower cost. Typically, consumer products use discontinuous, randomly oriented fiber reinforcement and are not laminated. The Composites Workstation project will focus on automation techniques for producing high-performance composite components.

Fiber reinforced polymer composite materials, or simply composites, consist of a polymer matrix material and a fiber reinforcing material. The most commonly used fiber materials are glass, carbon, and aramid. In general, carbon fibers have greater specific strength and stiffness than other fiber materials and hence, high performance components most often use carbon fibers. There are many polymer matrix materials. These materials are often classified as either thermoplastic or thermoset. As the terms imply, thermoplastic polymers can be formed and reformed with the application of heat, while thermoset polymers undergo a cure reaction which forms a rigid and permanent polymer network.

In order to facilitate the laminated construction of high performance components, material manufacturers have combined the fiber and matrix materials to form what are referred to as prepregs. Prepregs are available in various fiber/matrix material combinations and in various flat roll forms for use by part manufacturers. Prepregs are typically about 0.005 inch thick and range in width from one-eighth inch tow forms, through three and six-inch tapes, up to 60-inch wide broadgoods.

Until recently, the demands of high-performance applications could not be met by using thermoplastic-based composites. As a result, virtually all high-performance composite components are currently made from thermoset polymers. Recently, thermoplastic prepregs have been developed which meet the demands of many aircraft and defense components. Thermoplastic-based prepregs have several potential advantages over the corresponding thermoset prepregs. The thermoset prepregs must be cured in an autoclave (pressurized oven), which typically requires several hours. Prior to cure, the thermoset prepregs are unstable and have a limited shelf life even when refrigerated. On the other hand, thermoplastics are stable at room temperature and have an unlimited shelf life. Thus, if high performance composite parts can be produced using on-line consolidation of thermoplastic prepregs, considerable savings can be realized in terms of both equipment costs and overall processing times.

Fiber Placement

Success with composites has led to demands for increasingly complex parts. These demands often exceed the capabilities of existing manufacturing technology. Until new methods are developed, these complex parts must be produced by hand layup. In hand layup, consecutive plies are manually applied onto a part form in specified locations and orientations. Periodically, a plastic sheet (called a "bag") is placed over the laminate and a

AMRF COMPOSITE FABRICATION WORKSTATION [1]

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ABSTRACT

The Robot Systems Division of the National Institute of Standards and Technology (NIST) has initiated development of an advanced manufacturing workstation for the fabrication of composite parts. The focus of this project will be the application of sensor-based hierarchically controlled robot systems to automated fiber placement of thermoplastic composite materials. In such a system, continuous fiber reinforced thermoplastic polymer is fed from a spool and applied onto a mandrel or part form. The orientation of the fiber is based on the part's geometry and structural design. As the composite material is applied, it is heated to melt the polymer matrix, and then consolidates in place as it cools. The intention of this project is to demonstrate that the use of fiber placement via two cooperating robot manipulators and in-situ consolidation, can provide the capability to efficiently produce complex shaped composite parts.

INTRODUCTION

The aircraft and defense industry's demand for light-weight, high performance components has lead to rapid increases in both the development and use of fiber reinforced polymer composite materials. Unfortunately, the manufacture of high performance composite parts remains very time and labor intensive. New manufacturing methods are needed for the efficient production of parts using these materials.

The Automated Manufacturing Research Facility (AMRF) is a testbed at the National Institute of Standards and Technology (NIST) in which many factory automation issues are being addressed. The AMRF consists of several workstations which are used to study machining, deburing, inspection and handling of metal parts, as well as the associated control, data processing, machine programming, and scheduling issues. A new composites workstation is being developed and incorporated into the AMRF in order to apply AMRF principles to the fabrication of high-performance, complex-shaped thermoplastic composite parts. This paper gives a background on the manufacturing of high-performance composite parts, and outlines the research goals and status of this workstation.

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