Automated Scarfing and Surface Finishing Apparatus for Complex Contour Composite Structures

Edwin A. Erlbacher, Ph.D.
Lester E. Godwin

PushCorp, Inc.
2345 Merritt Drive
Garland, Texas 75041
www.pushcorp.com
(972) 840-0208

ABSTRACT

This paper describes the justification, design and operation of a Scarfing Tool for Automated Repair of Composites (STARC) system. The repair of aircraft composites is currently a manual process that subjects workers to adverse working conditions and often leads to costly mistakes and poor repair quality. To minimize these potential problems, a lightweight, portable manipulator has been developed to automate the scarfing process.

The STARC is a lightweight parallel link Stewart Platform capable of machining scarf profiles as well as performing a variety of other robotic operations. The primary benefits of the STARC manipulator are its accuracy, repeatability, high stiffness to weight ratio and its simple modular design.

To automatically machine scarf profiles, an integrated laser machine vision system first measures the contoured surface profile. From this data, machine path trajectories are calculated to create the appropriate scarf geometry on the surface. The STARC manipulator then utilizes a high-speed spindle motor, mounted on the movable platform, to perform the machining operation. A modular, open-architecture robot control orchestrates these various operations, and provides a simple, intuitive operator interface.

In this configuration, the STARC meets all the major design goals of providing flexibility, a substantial work envelope, the required six degrees-of-freedom, light weight portability and ease-of-use to create high-quality scarf profiles on contoured surfaces.

BACKGROUND

Given that composite materials are becoming more prevalent in present and future aircraft structures, the need for quick and effective composite skin repair is growing accordingly. Currently the repair of composite aircraft skins is accomplished via time consuming and labor intensive manual methods. A large class of these repairs involves correcting impact damage of complex contoured aircraft skin components incurred in service or during manufacture.

Performing proper repairs are even more important on modern composite aircraft because, unlike past metal skinned aircraft with rigid frames, composite aircraft rely on the skin itself for strength. The composite skins on today's aircraft, in many cases, are the structural support that holds the aircraft together.

The scarfing repair operation involves machining or grinding away successive ply layers from the skin to create a tapered or stepped dish scarf profile around the damaged area. The size and shape of the scarf profile depends on the loading and the type and extent of damage. Once the scarf profile is produced, the structure is restored by applying multiple ply layers with the correct thickness and orientation. This tedious operation restores the structural integrity of the part by replacing the damaged carbon fabric and tape with new material according to the original part design. Once all the ply layers are replaced, the surface is heated under a vacuum to bond the new material. Finally surface imperfections are filled and the skin is ground smooth so that it corresponds to the original design contour.

Currently, the scarfing operations are performed manually resulting in severe problems that affect both repair technician health and part quality:

- Fatigue and lack of concentration lead to errors that cause excessive scrap and rework of high value parts.
- Long term medical problems that result from the repetitive manual tasks associated with scarfing operations.
- Potential health hazards resulting from inhaling airborne composite particles.
- Excessive repair time and skill levels.
- Difficulties in achieving dimensional joint and part requirements due to the inherent variability of the manual operation.

Automating the composite repair scarfing process presents a unique opportunity to replace manual operations and allow the use of automation tools to quickly achieve superior part tolerances, quality, and consistency

Composite Repair Processes and Materials

This project was funded by U.S. Navy SBIR Contract No. N00421-97-C-1207 because current composite repair operations are labor intensive and produce inconsistent scarf profiles. Being a manual process, it is difficult to consistently achieve the critical geometric profiles required on today's contoured composite aerodynamic surfaces. Typically composite repair operations involve a combination of low technology hand-held rotary grinding tools and highly skilled hourly personnel.

Precisely controlling the hand-held grinding tool is exceedingly difficult and requires intense concentration to prevent over-grinding or gouging the part. This is especially true on contoured parts that make up a large percentage of the surfaces on modern aircraft. In general, the skill of the repair technician is used to compensate for the relative simplicity of tools used to grind the scarfed profile. According to industry and military experts, only a small percentage of people have the ability to perform these operations. At one particular defense contractor, there was only a *single* man considered to be capable of producing adequate scarf profiles on highly contoured parts.

Hand-tools used to produce scarf profiles typically include straight and right angle hand-held air grinders used in conjunction with a variety of abrasive disks. Air motor speeds typically range up to 12,000 RPM. Disk media used include diamond coated, coated abrasive and Scotch Brite products ranging from 2 inches (51mm) to 5 inches (127mm) in diameter. The disk grit size varies from coarse to fine depending on the amount of control that is needed in removing material. Coarse grit is used in the initial stages to remove more material quickly. Finer grit is then used to touch up the profile and provide the final desired surface finish.

The time required to produce an acceptable scarf can vary from several hours to days depending on a number of factors including the area and depth (number of plys) of the scarf, the severity of surface contours, and the type of composite material. Obviously a larger and deeper scarf requires more processing time to produce. Likewise it is much more difficult and time consuming to achieve acceptable results on highly contoured parts. In all cases individual ply layers must be carefully ground away one at a time to give a consistent exposure of underlying layers in the conical or stepped profile.

In removing individual plys, once an abrasive media is selected, the primary factor controlling the material removal rate is the amount of force applied to the tool by the operator. Based on observation of operators at work, the applied force appears to vary from nearly zero for very fine touch-ups to roughly 5 lb. (22 N) for heavy material removal. The operator-applied force is extremely variable at higher force levels and is difficult to maintain for extended periods of time. In addition, when applying high forces with hand-held grinding tools, the tools become more difficult to control thereby increasing the risk of errors.

Compounding the difficulty of performing composite repairs is the fact that many times the scarfing and repair operations must be performed on the actual aircraft. When damage occurs on large structural parts of the aircraft, it is prohibitively difficult to remove the parts for repair. Manual scarfing operations must therefore proceed despite the fact that the repair may be in an awkward or difficult to access area. This increases the difficulty of all aspects of the repair process and makes the need for an automated solution readily apparent.

Scarf Geometry

Any area on an aircraft has the potential to incur damage and require repairs. Therefore the geometry of repair areas vary considerably. Based on observations at various defense contractors and military depot repair facilities, scarf repairs can vary in size from 3 in. (76 mm) to 48 in. (1220 mm) in diameter. The actual size and shape of a given scarf depends on a number of factors including the size of the damage, the thickness of the panel, and the degree of contour. Fig. 1 shows a properly shaped scarf on a complex contoured part. This scarf was produced by the STARC system.

On flat composite parts the scarf profile is typically circular or elliptical. The final diameter of the scarf is a function of the scarf angle (typically ranging from a 10:1 to a 30:1 slope), and the material thickness. As an example, the resulting scarf diameter of a 0.5 in. (13 mm) thick panel scarfed with a 20:1 scarf angle would be on the order of 20 in. (508 mm).

On contoured parts the scarf can take on any shape as dictated by the surface contour and the scarf angle. Typical aircraft parts have surface contours that range from nearly flat to a radius of curvature of less than 1 in. (25 mm). To maintain the proper scarf angle on these contoured parts, the repair technician visually notes the amount of each composite ply showing as the grinding operation progresses.

In current manual scarfing operations, the individual ply thickness is known. Therefore the repair technician grinds the part to reveal a constant amount of each ply to crudely control the scarf angle. For example, if each ply thickness is 0.014 in. (0.35 mm) and a 20:1 scarf angle is desired then the part should be ground such that each ply has a 0.280 in. (7.1 mm) reveal. The repair technician grinds the part to achieve this reveal for each ply, letting the contour of the part determine the overall shape of the scarfed area. The problem with this technique is that, in many instances, plys with similar ply orientations are placed directly on top of one another. This makes what is actually multiple overlaid plys appear as a single ply thickness. Obviously this unnoticed added thickness leads to gross inaccuracies in the scarf angle when the above scarfing technique is used.

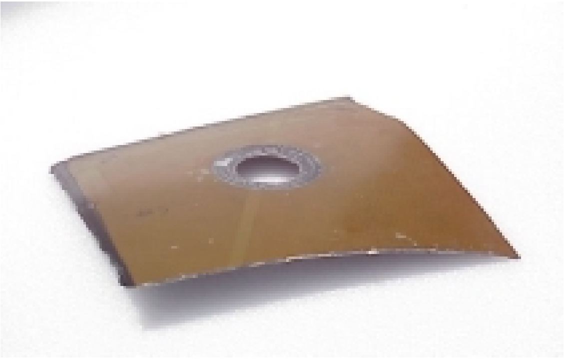

Fig. 1 Scarfed composite part produced by the STARC

A final geometric feature to consider in composite repair is the thickness of the panel at the repair location. Observed panel thickness varied considerably from a minimum of 0.050 in. (1.3 mm) for skin panels to more than 3.0 in. (76.2 mm) for structural members and dynamic mechanical linkages. According to defense contractor personnel, skin thickness tolerances are typically +10%, -0% of nominal. Extremely thick and thin panels each have their own respective challenges in producing high quality repairs. Thick panels require much larger scarfs and therefore much more material must be removed. On the other hand, when repairing thin panels, care must be taken to avoid panel deflection, breakout and de-lamination of the part on the backside resulting from applying too much force.

STARC SYSTEM DESIGN GOALS

The ideal automated scarfing system, based on industry and military provided information, should be capable of producing exact scarf profiles of any size on any composite part on or off of any aircraft. Unfortunately limitations of time and funds require that a compromise be made. The logical approach taken in arriving at this compromise has been to determine a set of design parameters that will allow the STARC system to perform adequately for a large subset of widely varying composite repair situations. The resulting original basic design requirements are presented below:

1. The STARC system should be composed of a portable parallel link Stewart Platform manipulator and a separate controller connected via interface cables.
2. The manipulator should be able to be attached to an aircraft via a variety of methods including vacuum cups, straps, and hard attachment points. In addition the manipulator will be able to work in a freestanding mode separate from the aircraft.
3. The STARC should include a dust collection system where a lightweight, tent-like enclosure will be placed over the manipulator. A vacuum system will produce a negative pressure inside the enclosure so that the dust is removed and captured in filters. The composite dust may then be disposed of properly.

4. The manipulator should have a 36 in. (914mm) diameter workspace on a planar surface. The extent of usable workspace will decrease with higher contoured surfaces.
5. The effective workspace height above a planar surface should be at least 20 in. (508mm)
6. The manipulator should operate with a minimum height clearance of 24 in. (609mm)
7. The manipulator must be able to operate on surfaces with a minimum 3 in. (76mm) radius of concave or convex curvature.
8. The manipulator should have lightweight linear actuators.
9. The manipulator should weigh 100 lbs. (45kg) or less.
10. The manipulator should have a payload capacity of 30 lbs. (13.6kg) in any orientation.
11. The manipulator will have a maximum tool point speed of at least 10 in. (250mm) per second.
12. The manipulator should be able to easily accommodate a variety of different tools to perform various other non-scarfing operations.
13. The grinding motor should be an AC brushless servomotor housed in a sealed frame.
14. The manipulator must have a positional repeatability of +/- 0.010 in. (0.25mm)
15. The manipulator should have the capability to measure surface contour geometry for path planning and verification purposes.
16. The manipulator and controller should be designed such that the two may be separated by at least 50 ft. (15m)
17. The controller should be housed in a portable (wheeled), enclosure not larger than 24 x 24 x 72 in. (609 x 609 x1828 mm)
18. The controller should have a graphical user interface to make the system easy to operate so that shop personnel can effectively use the system with minimal training.
19. The controller should be able to generate tool paths to enable the manipulator to scan and measure a contoured surface, produce scarf profiles, jog the tool interactively, and move to specific points and orientations in a relative and absolute mode.
20. The controller should be able to create and display 3D representations of contoured surfaces as designed and as measured by the STARC system.
21. The controller should be sufficiently interactive to allow the operator to modify programmed tool paths based on special circumstances that may arise in different repair situations.
22. The controller should be capable of importing existing 3-D CAD data files in a variety of formats. (IGES, CATIA, ACIS, DXF, etc.)
23. The controller should be programmable (similar to a commercial robot or CNC machine tool) so that the manipulator may be used for other future unforeseen applications.

The STARC manipulator, in its current form, achieves almost all of these original design criteria. The only items not achieved were Item 3 (Dust collection) and Item 22 (CAD data files). Item 3 was found to be impractical and for the most part unnecessary. Instead a vacuum shroud and inlet located close to the router bit itself will perform adequately. Item 22 was also found to be unnecessary. Using imported 3-D CAD models to generate cutter trajectories relies on the accurate correspondence of the manufactured surface to the original design data. Due to design tolerances and manufacturing variations in fabricating contoured composite panels, the degree of correspondence between as-designed and as-built surface can vary significantly. Also storing 3-D surface data for all possible aircraft would be logistically impractical. The 3-D surface measurement system is capable of measuring the actual, as-built, surface contour to a high accuracy, eliminating the need for original design data.

The following sections will describe, in detail, the current embodiment of the STARC manipulator and how the manipulator achieves the above goals.

STARC SYSTEM DESIGN

Mechanical Design

A parallel link Stewart Platform style manipulator provides the means to generate the motion trajectories required to machine a scarf profile. The Stewart Platform was chosen despite the fact that other industrial serial-link robot arms have been used extensively in the past for a variety of grinding tasks. These commercial robots have the necessary dexterity to effectively perform scarfing operations. However, these robot arms have several major drawbacks for portable aircraft scarfing operations. A serial-link robot with the required stiffness and reach would be too heavy and far from portable. A gantry robot is another type of manipulator that could also be used to perform scarfing operations, but similar to a serial-link robot, the size and weight of the manipulator make it impractical.

The Stewart Platform manipulator is a known technology that has been used successfully in flight simulators, and more recently, CNC machine tools. The primary benefits of Stewart Platform manipulators are their high stiffness to weight ratio and their simple modular design. The main disadvantage is the limited work volume, although this is not so critical for scarfing. Modular design means that the manipulator is inherently scaleable by simply changing the size of the base and length of the actuators. If a larger work volume is needed for a particular application, the manipulator will only need a larger base, and longer actuators. Everything else, the controller, joints, tooling, etc. can remain the same.

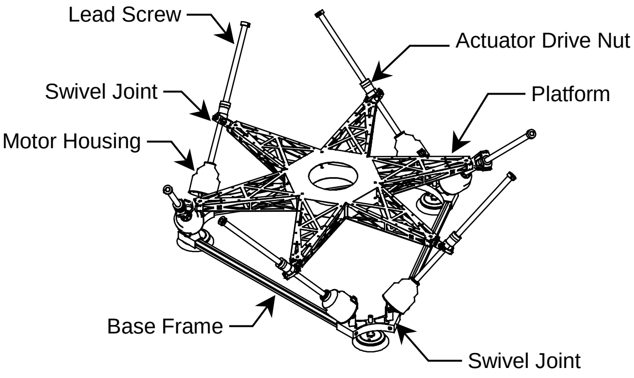

Fig. 2 STARC Stewart Platform Manipulator

For the Stewart Platform, the geometry of the attachment points of the actuators to the base and platform determine the overall configuration. The octahedral Stewart Platform configuration was chosen for this project because it is considered to be the most rigid structure and the manipulator kinematics are more easily solved. The octahedral has a 6-6 configuration, which means that the actuators are connected at six separate points on the platform and at six separate points on the base.

The type of joints used on the Stewart Platform has a direct effect on the size and shape of the work volume of the manipulator. The joints must allow the lead-screw actuators to swivel and rotate as the platform is moved about. The larger the allowable joint motion, the greater the work volume. Since the STARC will have 12 fastening points for the 6 actuators, the joints only require a two degree-of-freedom swivel joint.

For a given manipulator pose, the position and orientation of the platform tool point is determined solely from the location of each actuator drive nut along the lead screw. The control algorithms require accurate positional feedback from each actuator to close the control loop. To determine the actuator drive nut location, resolvers are mounted on the motor shaft within the motor housing to provide feedback. The lead screw pitch is known, so the actuator nut linear displacement can be easily calculated based on the resolver angular position feedback. With these features the Stewart Platform manipulator provides the same basic functions as any six-degree-of-freedom robot.

To enable the basic Stewart Platform to become an effective scarfing tool, a special process module must be attached to the manipulator's platform. This process module, shown in Fig. 3, consists of a removable lightweight frame that houses the servo spindle motor and components for the non-contact surface measurement system.

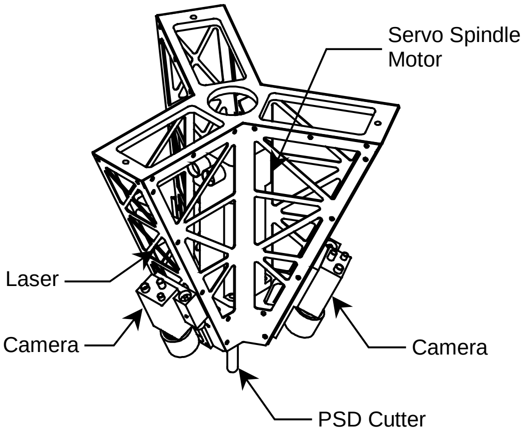

Fig 3. STARC Process Module

The servo spindle motor spins a special polycrystalline diamond (PCD) coated cutting tool. This type of cutter is designed to withstand the abrasive properties of composite material. The servo spindle motor has feedback control to maintain nearly constant speed under a wide range of load conditions. The servomotor is a sealed, AC brushless type motor to ensure long life and minimal maintenance in the harsh environment. The servomotor provides infinite and reversible speed settings from 0 to 6,000 RPM.

The non-contact surface measurement system is composed of two CCD cameras arranged as a stereo pair and a single solid-state laser. The cameras are connected via coaxial cable to a framegrabber card located inside the STARC controller. The laser is also connected to the STARC controller via a dedicated digital control line so that the laser can be activated via the control software.

During the surface measurement operation the laser is activated to illuminate a point on the surface. The calibrated CCD cameras each take a picture of the surface and determine the pixel coordinates of the center of the laser spot. With the pixel coordinates for each camera now known, the 3-D location of the laser spot can be calculated through triangulation. To measure a contoured surface, the manipulator scans an area of the surface in a rectangular grid pattern. This grid of raw 3-D coordinates is then used to calculate a B-spline mathematical representation of the surface patch.

Electrical Design

In an effort to save time and money, the STARC electrical design emphasized using readily available off-the-shelf components that minimized wiring and eased any required reconfiguration. Because of these priorities size and weight considerations were basically ignored. Therefore the STARC controller, while quite functional, has considerable potential for optimization with regard to reducing size and weight.

The STARC electrical control system is composed of the following major components:

- Seven servomotors with resolver position feedback (six for axis positioning and one spindle motor) located on the manipulator.
- Seven servo amplifiers located within the controller enclosure.
- An off-the-shelf Pentium 233 MHz PC compatible control and user interface console with an LCD touchscreen display.
- AC supply distribution circuitry
- 24 VDC logic and control circuitry

Servomotors are almost without exception, the standard choice for any robotic or CNC manipulator. The STARC utilizes brushless permanent magnet AC servomotors. This type of servomotor provides a high power-to-weight ratio with essentially zero maintenance. PushCorp, Inc. purchased the open-frame motor components and packaged them with the resolver feedback to create a small, highly integrated motor drive system.

In designing a servomotor system, there are a number of choices for motor position feedback sensors. Resolvers were chosen for the STARC manipulator for two reasons: they are very reliable and can withstand a great deal of wear and tear, they allow high-resolution feedback for position control and motor commutation with minimal interface wiring. The STARC resolvers provide 65536 counts per motor revolution. This combined with the lead-screw pitch provides a feedback resolution of slightly better than 0.0001 mm per resolver count.

The servo amplifiers are standard products purchased from Pacific Scientific. These amplifiers monitor the resolver feedback to close a velocity control loop and provide the drive current for the servomotors. Again to minimize wiring and speed system integration, the selected amplifiers utilize the industry standard SERCOS interface to communicate with the PC based high-level controller.

Fig 4. The STARC Controller

The SERCOS interface is a high-speed, digital protocol specialized for servomotor motion control and coordination that operates over a single fiber optic loop. With the fiber optic loop, reliable communications at up to 4 Mbps is possible even in an electrically noisy environment. Also of great benefit is that the typically extensive interface wiring is eliminated and replaced with a single, small fiber optic cable.

The control and user interface console is a standard product. This unit is a PC compatible with a Pentium 233 MHz CPU running the Microsoft NT 4.0 operating system. The console performs both as the high-level robot controller as well as the graphical user interface for the STARC.

An LCD panel provides the graphical display for the console. The LCD panel also includes a touchscreen interface eliminating the need for a separately attached mouse or trackball. Experience has shown that touchscreen interfaces are highly intuitive and are quickly accepted and mastered by machine operators.

Two additional interface cards were added to the basic console, a standard 10BaseT Ethernet LAN card, and an Motion Engineering, Inc. (MEI) DSP motion control card. The LAN card allows for network-based remote debugging, and remote operation of the STARC via standard TCP/IP protocols. The MEI motion control card provides the SERCOS interface to the control console as well as a DSP processor to execute the required high-speed, low-level closed loop motion control algorithms. High-level application software accesses the MEI card through a supplied software driver and application interface library.

Finally, the AC supply distribution circuitry and 24 VDC logic control circuitry provide the hard-wired relay interlock logic needed to safely implement power up, servo amplifier enable, emergency stop, and power down functions.

These major components provide the necessary subsystems to power and control the STARC servo motion system. The PC control console forms the control hardware hub of the system. It is the application software running on the control console that orchestrates all of the subsystems to enable the STARC to perform useful manufacturing and repair operations.

Control Software Architechture

The STARC system software is the result of integrating several diverse technologies into one cohesive, easy-to-use package. These technologies include: real-time axis motion control, six degree-of-freedom kinematics and coordinated motion trajectory generation, 3-D laser / machine-vision based metrology, 3-D surface geometry, and graphical user interface design.

With all of these diverse technologies, it was decided early on that a highly modular, object-oriented software architecture would be the best choice to implement, maintain and enhance the STARC. As a result the STARC controller software is composed of a hierarchy of interchangeable object modules each representing a specific functional technology.

This hierarchy enforces the concept of object-oriented inheritance to allow high-level modules to define a basic functional capability while lower level modules implement this capability for specific situations or hardware.

High-level applications, such as the software to machine a scarf, are then written to interface with the high-level modules in the hierarchy. The primary benefit of this hierarchy is that low-level modules can be easily changed to support different hardware, or even simulate hardware, with no changes to the high-level application. This is demonstrated in the STARC system, in that the exact same STARC control software can be run on any desktop computer in simulation mode by simply supplying a command-line parameter when starting the program.

The similar advantages are seen when trying different algorithms or data representations during development. Different modules can be plugged in without the need to make global changes to the high-level application software. Likewise it is possible that the basic STARC software could run on a wide variety of hardware platforms by merely changing out the lowest level "driver" modules to support different motion control or machine vision hardware, etc.

Also, taking the opposite approach, new high-level applications can be rapidly developed since all of the low-level modules are available to be re-used. Development of the new high-level application is limited only to code involving the new task at hand. This greatly improves development efficiency, flexibility, and reliability.

Control Software Implementation

As stated above, high-level object modules define a "basic functional capability". In more concrete terms, the high-level object modules define a specific *interface*. This interface is essentially a list of various *methods* (functions or subroutines) and *properties* (configuration and operational parameters) that are available to utilize the object's features and functionality. Again, the high-level object modules only provide a definitive list of available methods and properties. It is the lower level objects that actually implement the methods and properties to perform useful work.

All of the functional object modules in the STARC system derive from the highest-level LObject module. This module provides support for saving and restoring properties to a file to support object configuration. More interestingly, the LObject module allows for a *distributed* software architecture in that it provides the capability to execute methods and change properties remotely via various communication streams including TCP/IP and other more basic serial interfaces such as RS232. Since all STARC object modules are derived from the LObject module, these objects inherit this LObject capability and can be configured and controlled via remote TCP/IP connects. This provides a great feature for debugging and remote monitoring and control, even from great distances.

The object hierarchy describing the manipulator functionality further illustrates the hierarchical design. The relevant object modules are shown in Fig. 5.

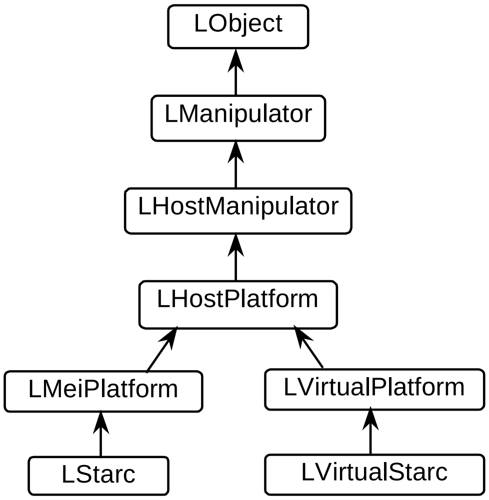

Fig 5. Object module hierarchy

At the top of the hierarchy is the aforementioned LObject. Below this is the LManipulator object. The object defines the basic interface (i.e., methods and properties) available to control a general manipulator. Methods in the interface include ones to move the manipulator to a position, jog the manipulator, stop motion, etc. Properties in the interface include manipulator configuration properties such as position limits, max velocity and acceleration, tool frame definition, etc. Other properties reflect the current manipulator status such as real-time position, velocity, and acceleration as well as manipulator state information such as the current enable state, errors etc.

Inheriting from the LManipulator object is the LHostManipulator object. This object implements the control logic for the interface defined by the LManipulator. In addition, the LHostManipulator object also implements the real-time trajectory generator that calculates the sequence of intermediate points to produce coordinated motion from one command position to the next. The LHostManipulator implements this logic on the main "host" PC in contrast to some other system which may have a separate coprocessor to perform the real-time trajectory generation functions.

Although the LHostManipulator object implements a trajectory generator, it has no code specific to the kinematics of a given manipulator. The next lower object in the hierarchy implements the functions that define the manipulator forward and inverse kinematics. For the Stewart Platform the LHostPlatform object supplies the kinematics functions for the parallel link manipulator. To implement other kinematics for serial link arms or any other configuration, simply replacing this module is all that is required.

At this point the hierarchy splits depending on the underlying hardware implementation. The LMeiPlatform object contains driver software to interface to a Motion Engineering DSP based motion control card. The LVirtualPlatform implements code to simulate an actual motion control system so that application software can be run and debugged in simulation mode with no motion hardware present.

Finally the LStarc and LVirtualStarc object modules provide actual and simulated functions that integrate the STARC specific process module. This includes functions to control the servo spindle access and a reference to the LSurfaceScanner object module containing functions to configure and control the 3-D surface measurement system.

The LManipulator object module represents only one branch of the entire software hierarchy. But it serves well to illustrate that this hierarchy provides for great flexibility and rapid application development. High-level applications are written to utilize the highest level interface possible in the hierarchy. In doing this, lower level modules can be changed or substituted with no changes to the application. For example, the same application can be changed from running on a Stewart Platform manipulator to a standard serial-link arm in a matter of minutes. This capability will allow the software to grow to encompass a myriad of applications and hardware platforms while still retaining a high degree of organization and maintainability.

STARC OPERATION

The overall operation of the STARC system is as follows. The Stewart Platform manipulator, as shown in Fig. 5, must be attached to the composite skin panel or worktable. The controller enclosure contains a vacuum generator that is activated via a switch on the control panel. A vacuum generator supplies the negative pressure that is required to secure the suction cups to the surface.

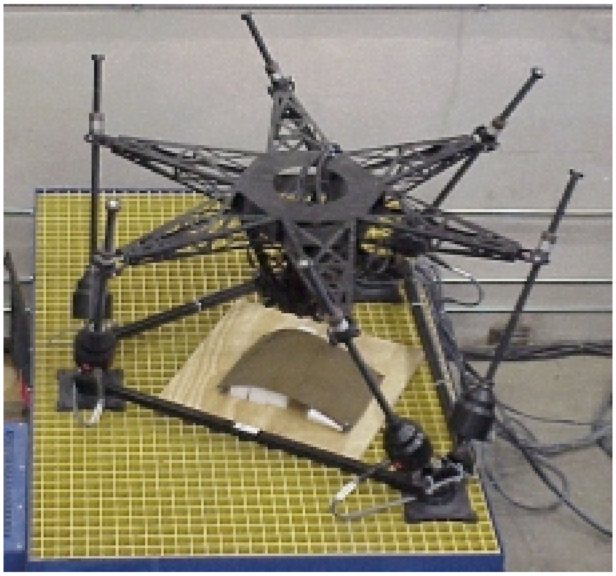

Fig 5. STARC System with contoured part

With the attachment complete, the system must then determine how to maneuver the tool over the surface to achieve the desired scarf profile. To calculate the proper tool path, four pieces of information must be known: the actual geometry of the part surface, the required scarf specifications, the desired final geometry of the repaired surface, and lastly, the appropriate machining parameters such as feed rates, and motor speeds.

Before any scarfing can begin, the geometry of the damaged surface must be determined. To accomplish this, the operator first jogs the manipulator with the laser turn on until the laser spot is centered on the damage area. The operator then initiates the surface measurement routine. The controller first takes a surface measurement at the current position to record the 3-D location of the center of the damage area. The controller then directs the manipulator to scan the surface using an attached laser and machine vision system in a raster grid pattern over the part surface.

Upon completing the scan, the raw surface position data is used to generate a mathematical 3-D surface representation of the actual surface profile. The surface representation is displayed on the STARC user interface so that the operator can visually compare the displayed and actual surfaces. This allows the operator to detect any gross errors.

Once the actual surface is measured and a 3-D surface representation is generated, the operator must input the proper scarf specifications for the repair. Scarf specifications are determined on a case by case basis. The operator can reference existing information regarding the selection of the proper scarf parameters for composite repairs. This information has been gathered through government and industry research over the last 20 years, and this has resulted in various composite repair procedures. These procedures clearly specify scarf parameters based on material type, material thickness, stress requirements, and extent of damage. In the final commercial STARC system, the operator would simply respond to a series of data entry questions presented by the system controller on the user interface.

Once all the scarf specifications are defined, the path planning module compares the measured 3-D surface representation and the user specified scarf geometric parameters to the desired final surface profile. An optimized path to achieve the desired scarf profile on the composite surface is then generated by the STARC controller. This path includes position and orientation information of the platform tool point as well as process related information such as feed rate, and the servo spindle motor speed along the path.

The operator then initiates the scarfing process. The servo spindle motor starts and the manipulator begins moving through the prescribed path. As the manipulator follows the path trajectory, feed speed and servo spindle motor speed is adjusted as dictated by the path-planning module. Control and monitoring of the scarfing process is handled through the graphical user interface. All information pertinent to the progress of the scarfing process is displayed in real time and stored in non-volatile memory for quality control purposes. Graphical controls allow the operator to interactively adjust process parameters if necessary as the operation continues.

The scarfing process is divided into two major operations. This two step process is required in order to maintain a relatively constant material removal load on the PCD cutter. Excessive cutter loads can stall the servo spindle motor and/or cause deflection of the STARC structural framework.

The first step of the scarfing process is a rough machining operation to remove the majority of the composite material. To perform this operation the manipulator moves the PCD cutter in a spiral path to produce a stepped dish profile with the basic overall dimensions of the final scarf. The scarfing steps become smaller in diameter and deeper as the process proceeds. The STARC continues this operation until the proper scarf depth is achieved. For some repair operations (i.e., a stepped scarf) is it desirable to stop a this point and move on to replace the composite material. In most cases, however, the second, final finish-machining step is performed.

For the finish-machining operation, a final cut is taken with the manipulator oriented normal to the desired scarf slope profile. The flat bottom on the PCD cutter removes the “steps” and produces a smooth, conical scarf profile in the composite skin. The PCD cutter mismatch on the scarf profile is typically within +/-0.004 in. (+/-0.1mm). This surface mismatch is the result of a flat-bottomed cutting tool following a curved surface. The small cutter mismatch irregularities are quickly and easily removed via a very light sanding. In fact light sanding will most likely required in any case to achieve the proper final surface finish for proper bonding.

When the final pass is completed, the STARC moves away from the surface and stops the servo spindle motor. The vacuum system can then be deactivated and the STARC removed. From this point the composite repair process to replace the removed composite material may begin.

ACCOMPLISHMENTS AND FUTURE WORK

The STARC manipulator is an effective tool for producing high quality scarf profiles in composite materials. On going tests have shown that the STARC is capable of producing geometrically accurate, repeatable, high-quality scarf profiles. The STARC has successfully machined scarf profiles in highly contoured composite surfaces including concave and convex surfaces, and complex contoured surfaces with inflection points.

In addition to excellent dimensional results, a medium sized scarf 12 inches (300 mm) in diameter can be machined in less than 30 minutes. A similar scarf on a contoured surface could easily require 6 hours to produce manually and would be significantly less accurate.

During the development effort for the STARC several technical achievements were accomplished. The following is a short list highlighting these achievements:

- Developed a lightweight, portable, general-purpose manipulator with sufficient stiffness to perform machining operations.
- Developed distributed, real-time, open-architecture robot control software capable of controlling most any manipulator configuration for which the kinematics can be calculated in a reasonable length of time.
- Developed a Differential Evolution genetic algorithm for calculating the forward kinematics of a general Stewart Platform manipulator.
- Developed a automatic non-contact surface measurement system capable of mapping a complex contoured composite surface with minimal user intervention.
- Developed B-Spline surface techniques to produce cutting tool paths for producing scarf geometry in complex contoured parts.

- Developed an extremely user-friendly graphical user interface that allows most anyone to produce high-quality scarfs with minimal training.

Even with these many accomplishments, there are still areas that require some attention. First, and foremost, is that the STARC, while quite functional, is still a “laboratory” tool. Much work remains to be done to make the system ready for demanding field work. The STARC structural design could benefit significantly in increasing its overall stiffness and rigidity. Also, with a relatively small effort, the STARC mechanical design could be optimized so that it could be rapidly assembled and disassembled for maximum portability and minimal storage requirements.

Likewise the STARC controller could also benefit from a refinement of its electrical design. The primary goal of the current design was flexibility and ease of trying out various equipment, sensors, etc. With the overall STARC functionality now more understood, it should be possible to drastically reduce the size of the STARC controller. Given the advancements in servo motion electronics, even just since this project began, it is entirely possible that the STARC controller could be reduced to the size of a medium-sized suitcase.

Also, given the advancements in high-speed communication protocols, it should be possible to all but eliminate the currently extensive wiring between the manipulator and controller.

If these three features were implemented, the STARC could become a truly portable, highly flexible, general-purpose manipulator. Such a manipulator could find a host of uses for aircraft repair in the hanger as well as shipboard. Some of these uses include:

- Aircraft canopy polishing and repair
- Coating application
- Coating removal
- Routing access holes for maintenance operations
- Precision drilling operations, including fastener removal
- Sanding or finishing operations with the addition of a compliant force device

Even more interesting is that other more specialized manipulators can be developed that utilize the same manipulator controller. The STARC manipulator can be scaled upward or downward in size with no changes to the software or control algorithms. One can envision a hydraulically driven manipulator capable of highly dexterous six degree-of-freedom heavy lift operations such as bomb loading.

Other ideas include a specialized manipulator expressly designed for leading-edge wing repairs. The current STARC does not have the workspace dexterity to perform repairs on the small radii found on leading edges. This specialized leading edge repair manipulator would have five degrees-of-freedom manipulator could resemble a “C” frame. This frame would fit over the leading edge, and then, like the current STARC, use a high-speed servo spindle to machine a scarf profile directly on the leading edge.

The accomplishments achieved for this project combined to produce a highly flexible, general purpose manipulator. This manipulator has shown that it is quite capable of quickly producing accurate scarfs on highly contoured composite surfaces. However, given that scarfing is acknowledged to be one of the more difficult operations to execute, it is exciting to consider that possibility that scarfing represents only the first of a long list of operations this technology will ultimately make not only possible.

REFERENCES

1 Pocius, A.V, Wenz, R.P, 3M Research Laboratories, St. Paul MN, "Mechanical Surface Preparation of Graphite-Epoxy Composite for Adhesive Bonding," SAMPE Journal, September/October 1985.

2 Merlet, Jean-Pierre, "Designing a parallel Manipulator for a Specific Workspace," Research Report No. 2527, Institut National de Recherche en Infromatique et en Automatique, April 1995.

3 Merlet, Jean-Pierre, "An algorithm for the Forward Kinematics of General 6 D.O.F parallel manipulators," Research Report No. 1331, Institut National de Recherche en Infromatique et en Automatique, November 1990.