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RACE PULLS FOR SHARED CONTROL

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Abstract

Maintaining and supporting an aircraft fleet, in a climate of reduced manpower and financial resources, dictates effective utilization of robotics and automation technologies. To help develop a winning robotics and automation program the Air Force Logistics Command created the Robotics and Automation Center of Excellence (RACE). RACE is a command wide focal point. An organic source of expertise to assist the Air Logistic Center (ALC) product directorates in improving process productivity through the judicious insertion of robotics and automation technologies. RACE is a champion for pulling emerging technologies into the aircraft logistic centers. One of those technology pulls is shared control. The small batch sizes, feature uncertainity, and varying work load conspire to make classic industrial robotic solutions impractical. One can view ALC process problems in the context of space robotics without the time delay. The ALCs will benefit greatly from the implementation of a common architecture that supports a range of control actions from fully autonomous to teleoperated. Working with national laboratories and private industry we hope to transistion shared control technology to the depot floor. This paper provides an overview of the RACE internal initiatives and customer support, with particular emphasis on production processes that will benefit from shared control technology.

1 Introduction

In the late 1980s the Air Force commissioned several studies to examine the current and future role of robotics and automation technologies in the Air Logistic Centers (ALC) [8, 1]. Past efforts at technology insertion had been plagued with lack of a cohesive implementation strategy. In addition, total process improvement was often not taken into account. Finally, a lack of in-house expertise forced a complete reliance on contracted efforts. This combination of factors sometimes resulted in technology insertion programs that were overly complex and/or could not perform their intended functions. The Air Force Studies Board report entitled *Advanced Robotics for Air Force Operations* recommended that the Air Force establish a Robotics and Automation Center in a division that would have responsiblity for all robotics related R&D and automation applications [1]. An Acquisition Logistics Division (ALD) report entitled *Robotics Assessment for Logistics Command* recommended that one of the ALCs be assigned as the lead center for robotics technology [8]. The Air Force response to those recommendations was to merge them. In June 1990 the San Antonio ALC (SA-ALC) was given the lead assignment with responsibility for research and implementation of AFLC robotics and technology. The SA-ALC response was to form the Robotics and Automation Center of Excellence (RACE) in February 1991.

The RACE is unique. There is no other organization within the command, or the entire Air Force, which is chartered to perform a similar function. The RACE vision is: *A command-wide focal point. A source of organic expertise ready to assist the product directorates, in improving process productivity by judicious insertion of robotics and automation technology. A champion for the emerging technologies necessary to propel aircraft remanufacturing into the future.* That vision is being brought to fruition under the Technology and Industrial Support Directorate. The core RACE team is in place. A strategic implementation plan (SIP) has been approved and we are hard at work achieving the SIP objectives. A draft Program Action Directorative (PAD) is in the final stages of coordination at Air Force Material Command(AFMC) HQ.

We are supporting customers at each of the five ALCs. RACE team members have also been agressively *selling* the RACE concept inside and outside the Air Force. That sales pitch forms the first part of this paper. In order to perform our mission we must make people aware of our capabilities and objectives. Section two provides a detailed overview of the RACE concept. Section three dicusses our customer support. Current services and future directions are presented. The five major technical areas we are concentrating on are overviewed, with a particular emphasis on the shared control applications. For the purposes of this document we broadly define shared control as the architecture that permits the blending of human and robot actions to accomplish a process. Conclusions are the subject of section four.

2 The RACE Concept

The RACE is the command-wide focal point for robotics and automation technologies. We track all the ALC robotics and automation insertion projects and crossfeed that information to all centers. The six member interdisciplinary RACE team constantly strives to maintain and increase our expertise. Along with understanding the fundamental principals, we are fluent in the current industrial state of the art. We also follow the progress of the academic research community through technical publications and conference attendance. Our objective is to be versed in both the technology and the customer's process. We function as a *robotics solution impedance matcher*, aligning the user requirements with industry capabilities to maximize return on investment. Detailed knowledge of current projects and emerging technologies permits us to specify the most advanced technology suitable to the problem at hand. One of our goals is to pull technology into the depot. Our partners in that technology pull effort are both the national laboratories and industry.

A key tenant of our technology pull effort is to know when to say when. The depots are littered with monuments to technology. The RACE mission is to: *Champion the development and judicious insertion of the robotics and automation technologies necessary to enhance the competitive posture of the ALC product directorates.* We define robotics as the intelligent methodology associated with design, development and judicious insertion of electromechanical manipulators into the industrial base processes. A robot is a reprogrammable electromechanical device with a variety of sensors used to move or manipulate parts and tools in space to achieve a particular task. If a technology component does not improve the quality of the insertion effort, does not contribute directly to the success or evolution of the system, it is inappropriate and must not be acquired. Once a system has been successfully inserted at one depot we work to push that technology into similar processes at other locations. Finally we conduct all of our activities with a look toward the future of the technology and target processes.

The RACE is a customer driven organization. Our primary customers are the product directorate engineers. Those individuals are responsible for enhancing the productivity of a wide variety of industrial processes involved in remanufacturing aircraft. Raw technology doesn't solve their problems. They need sophisticated systems that can be operated by the current workforce. The system must increase productivity and improve the operators working conditions. The shop floor worker must buy into the technology. A successful project is not just meeting some performance specifications, rather the measure of success is whether the project is supported by the workforce and functions as advertised in a production environment. The need to understand our customer and his processes is why the RACE is located at an ALC. Colocation allows us to directly interface with our customers to determine their requirements and act as consultants throughout the life cycle of the insertion project. Our tasking is to provide technical guidance to the product directorates, to ensure their needs are met and competent solutions are produced. We do not perform program management tasks. The product directorates own the processes as well as the associated problems. Ownership of a solution is a critical component of a successful robotics insertion project. We do not make or dictate policy. The customer, who is involved in every phase of the development process, manages the program. When the solution is implemented, it truly belongs to them. Accomplishing that mission will help provide the Air Force with the finest aircraft maintenance and repair facilities in the world.

The validity of the RACE concept is dependent on our ability to improve the acquisition and operation of ALC robotic and automation systems. Our basic premise is to begin solving problems that have a high payback to the government but are also relatively simple to answer. A logical approach of building upon successes is being utilized while the RACE develops the expertise to tackle larger and more difficult problems. With the successful insertion of robotics and automation in those *easy* applications, the culture will shift to one that is more supportive of advanced system development. As the culture shifts we will shift our focus more toward the applied research portion of our mission.

3 Customer Support

The RACE team provides technical support throughout the life cycle of a robotics project. The level of support depends on the technical background of the product directorate engineer. We can completely off-load the technical aspects of the project or simply review a proposal. The usual starting point for our interaction with the process owner is a technical feasibility study. After becoming familiar with their processes, we evaluate alternative solution concepts and assess technical risk and cost. The objective at this stage is not a detailed evaluation, but rather a fundamental analysis upon which to decide if the concept warrents further development of a funding proposal. If the technical and economic aspects of the project are favorable, RACE team members will assist the customer in preparing a proposal to an appropriate funding agency. We will also support that proposal through the review process. Once funding is available our staff can prepare the detailed performance specifications for purchase of off-the-shelf equipment, or the Statement of Work(SOW) and Request for Proposal(RFP), for more complex system procurements. We review contractor bids and provide technical guidance at the required design reviews. For small projects that are pulling an established technology into the ALC, the RACE can eliminate the need for an engineering support contract by using organic engineering resources to perform the implementation.

To assist in the insertion process, Robotics Implementation Working Groups (RIWG), consisting of local project managers and engineers, are being established at each ALC. These groups provide the interface between the RACE and the product directorates. The RIWG members are the eyes and the ears of the RACE to help identify potential robotics or automation applications. The RACE team is marketing a 20 hour seminar series on robotic fundamentals to enhance the background of the RIWG members and other engineers at each ALC. The seminar has been enthusiastically received at SA-ALC and will be given at OC-ALC in September. As current projects progress into the implementation stage we will also assist in the training of the shop floor operators.

3.1 Project Areas

The RACE is currently involved in a variety of projects at each of the ALCs. While the specifics are different, the individual insertion projects can be separated into five major technical thrust areas. A brief overview of large scale systems, industrial automation, and retrofits is presented followed by a more detailed discussion of the two areas that require shared control.

3.1.1 Large Aircraft Systems

The ALCs have a requirement for robotic systems capable of moving painting and stripping tools around the fuselage of all size aircraft. We believe this problem can be subdivided into two catagories based on aircraft size, and a single system developed for each. Those two prototypes should serve as standards around which additional systems are installed as appropriate. There is no technical reason to pay development costs for more than two systems. The Air Force has a working prototype for fighter size aircraft about to enter production at WR-ALC. Other current projects will produce designs that are capable of painting/stripping cargo aircraft. We are working on the SOW for a system capable of painting the C-5. The technology to solve the problem exists. That system will be capable of painting any of the other cargo aircraft in the fleet. The major open technical issue is centered around determining the optimum method for moving a commercial spray painting robot around the surface of the aircraft and the hanger floor.

3.1.2 Industrial Automation

This catagory encompasses a diverse variety of projects where our mission is strictly technology pull. The necessary equipment is commercially available and the basic process has been successfully applied in industry. Our role is to make the directorate engineers aware of the technology and assist in the implementation. Small projects in this class will be completed with organic engineering skills. One example is replacing a manual wench, used to manuver a large heavy x-ray tube, with a large industrial robot. The robot controller will also coordinate the movement of a 2 DOF positioning table. Along with improving the repeatibility and productivity of the x-ray processes, the system will also enhance operator quality of life.

Another example is installing a vision system to measure the clearance between gear teeth and housing on the fuel pump embedded in the fuel control system of a gas turbine engine. The fuel pump is disassembled when the fuel controls are rebuilt. Studies uncovered a clear relationship between the spacing between the gears and housing and the ability of the rebuilt engine to pass inspection. The proposed solution is to make several key measurements and then properly kit a housing with the apprioriate gear set. The required measurements are to precise to be performed reliably by a human operator.

3.1.3 Retrofits

Several production robotic systems have serious reliability and maintainability problems. We are assisting the product directorates in determining the most prudent course of action in eliminating those problems. Our services range from determining the technical nature of the problem, to proposing a solution, and then assisting in solution implementation. The biggest current effort involves replacement of the Modicon 5200 controllers installed in five paint stripping robots [4] and one automatic derivetor system [2]. The Modicon is no longer in production. Spare parts are very rare and the custom nature of the controller mandated development of all support software from the ground up. These designs were cursed with no evolutionary path for hardware or software upgrades. A complete controller retrofit is required if these systems are to remain in production.

3.1.4 Mobile Robots for NDI

As the age of our cargo aircraft increases so will the requirement for Non-Destructive Inspection(NDI) of large wing and fuselage areas. The inspection process can be repetitious and awkward for an unassisted human. The human is well suited for making judgements about the meaning of sensor readings. A robotic assistant is needed to put the sensor suite into the proper positions. A combination, or sharing, of the process responibilities is required to achieve a near term solution.

The RACE is starting a technical initiative in the area of mobile robots for aircraft skin NDI. Our involvement in this area began in response to a request from SM-ALC for evaluation of an unsolicated proposal for a mobile robot system for aircraft painting. During that evaluation, we discounted the idea for painting. However, the local NDI folks defined a future need for a small mobile system that could carry NDI sensors around the skin of an aircraft. The large robot systems mentioned above are well suited to painting/stripping applications where the process is traditionally accomplished in large dedicated hangers. However, large systems are not appropriate for flightline NDI applications.

The Air Force is not the only government agency interested in airframe NDI. The FAA Aging Aircraft Branch at the FAA Technical Center in Atlantic City, NJ is sponsoring a research project through the Carnegie Mellon Research Institute (CMRI) to develop a prototype mobile robot for eddy current inspection of airframe rivets. The CMRI is the applied research arm of the Carnegie Mellon University (CMU) Robotics Institute.

Following a walk before you attempt to run philosophy, the CMRI team is concentrating on a fairly simple crawler mechanism that will duplicate one of the inspection processes currently performed by USAir NDI technicans. The decision to stick with an existing process and sensing technology provides a robot performance baseline that is sadly missing in many past Air Force projects. Trying to change the process and simultaneously replacing the human operator is usually not a prudent decision. Baselining, with an eye toward future evolution, should enhance operator acceptance and their probability of project success.

The proposed mobile robot is basically a stick with two sets of servo motors and four sets of suction cups. A sketch of the crawler is attached. When performing a scan of a line of rivets, the end suction cups hold the crawler in place and its spine serves as a linear rail for the sensor head to move along. The crawler moves down the rivet line by attaching the sensor slide cups to the surface, releasing the end cups, and then using the linear actuator to move the rail forward. The end cups are attached and the scan process is repeated. The crawler can also move in a vertical direction, but the movement is not as graceful. This device is not designed to move to arbitrary locations on the aircraft surface.

The robotic system will alert inspectors to the presence of abnormal indications and the interpretation will be done by the inspectors. The robot is a tool to assist the operator, not replace him. The robot performs the tedious portions of the task and human provides the judgement skills. The task is divided into components that are ideally suited for the different skills of people and robots. We fully support this operator augmentation (shared) approach to robot system design. More and more people are seeing the virtues of semi-automated systems clearly designed with the human operator in mind. The augmentation approach is the best method to the mobile robot NDI insertion process.

Another major portion of this project is the automated logging of the inspection data. The data acquisition and archiving techniques developed for this project could be applied independent of the robotic system. Access to inspection data would permit application of statistical process control to the inspection process.

A prototype is currently being built. Tests conducted with the prototype will determine the feasibility of robotic inspection systems in real world environments. The FAA milestones call for a demonstration of the static scanning processes in November and locomotion tests early next year. If those tests are successful, we will bring the CMRI team down to Kelly to perform some additional tests on the C-5. The long range plan is to circulate videos of the C-5 crawler tests to NDI groups across the command and solicit comments and support for future development. The FAA initiative provides the Air Force with an excellent opportunity to gain a vital new technology with minimal technical risk. The RACE will champion the transfer of this technology from development to ALC specific application.

3.1.5 Telerobotics

Telerobotic technologies will play an increasing part in the solutions to ALC productivity enhancement problems. The small batch sizes, feature uncertainity, and varying workload conspire to make classical industrial robotic solutions impractical for a wide range of depot processes. We need systems that can bridge the gap between manual and complete automation. Shared control technologies provide the material to build that bridge. Telerobotics is a specific subset of shared control. We use the term telerobotics to define a broad class of robotic systems where the actions of the man and machine are tightly coupled. The robotic device responds to human inputs and transfers the human motion into end effector motion. However, unlike teleoperation, the robotic system incorporates some local decision making authority. The basic premise is to augment, not replace the human operator. Blend the individual abilities of each *system*. Humans have superior cognitive and pattern recognition skills, while the robot is a tireless precise positioning system. Thus, the human is still in control but gains the advantages of the machine precision and safety. The prototype center will be expanded to allow investigation of telerobotic concepts. We hope to leverage most of our technology requirements from the developments at the Jet Propulsion Laboratory (JPL). Efforts to form a cooperative working relationship with JPL are ongoing. The latest generation of commercial products also contain the elements upon which a shared control system could be built.

To provide more insight into why telerobotics is a crucial technology in the ALC environment the following several paragraphs highlight a telerobotic solution to an actual depot processes. The Telerobotic Laser Deriveting/Cutting System (TLDCS) is a shared control robotic system used to augment the operator in repairing side and wrap cowlings. Operators will use the TLDCS to derivet a damaged area on the cowling, cut out the damaged section, and then cut out an identically sized replacement patch. Technicians in the Aircraft Directorate repair over 450 side and wrap cowlings each year. Cowling repair times range from 60-450 hours depending on complexity. Roughly one third of the repair time is spent on deriveting and the cutting and triming of new aircraft skins. Removing one rivet is not a difficult job, however repeating that task a hundred times a day is physically demanding, tedious, and time consuming. Removing damaged skin sections is also a demanding labor intensive process and existing sheet metal cutting machines are not designed to quickly reproduce unique patterns. Adding to the task difficulty is the large size of some parts, which often forces the repair technician into awkward and potentially dangerous positions. Other hazards include the high noise environment and the razor sharp chips produced during drilling and cutting. The objective of this project is to increase the productivity and improve the worker quality of life for the aircraft skin repair process.

Projects to improve the deriveting process have been previously attempted. The Navy initiated a mobile derivetor project in 1983 [5]. The project objectives were too ambitious for the existing technology base and the end product was a large, complex system with limited flexibility that was not well received by shop personnel. The REPTECH office funded the development of a Robotic Deriveting and Drilling Cell installed at OO-ALC [2]. This system was designed to remove all of the rivets from a rigidily fixtured, stiff, flat workpiece. While the system is considered a success, the hard automation and mechanical drilling makes it unsuitable for quick removal of random rivet patterns from engine side cowls, a major workload at SA-ALC. A more serious limitation is the robot control system. The controller is no longer in production and duplicating this deriveting system would require an extensive software rewrite. Neither of those systems could be easily modified to include the ability to trim or cut sheet metal.

After studying the previously developed systems, it became evident that an alternative to conventional drilling was required. The solution to the problems of mechanical drilling of rivets (rapid tool wear, high part forces, spinning rivets) is laser drilling. Laser technology is routinely used to drill holes in sheet metal products. Once enough material is removed from the center of the rivet it is a simple operation for the human operator to punch out the rivet. For small workloads the expense and added complexity required to automatically punch out the rivet is not justified. Laser drilling is ideally suited for robotic application due to the non-contact nature of the task and the light payload applied to the end-effector from the flexible fiber optic cable used to channel the beam. Laser drilling also eliminates the noise and razor share chip hazards. The operator will be removed from the immediate worksite and the laser completely enclosed in a separate structure for safety.

An additional key benefit of the laser approach is the ability to use the laser to perform cutting operations. The laser system will be an industrial Nd:YAG (Neodymium:Yitrium, Aluminum, Garnet) solid state laser. Working with the laser vendors and in-house laboratory technicans we will conduct a series of experiments to characterize the heat effects of the laser and optimize our spot size and power accordingly. A flexible fiber optic cable will channel the laser beam to the end-effector of the robot. Cameras and proximity sensors will also be attached to the end-effector. Additional cameras will be mounted at appropriate locations inside the laser booth. The laser will be completely enclosed for operator safety. Safety interlocks will be in place to preclude laser firing while the operator is positioning the workpiece inside the booth.

The TLDCS will have the capability, similar to a conventional water jet cutter, to cut a unique pattern without operator programming or CAD data. The operator will only have to highlight the pattern on the surface and then the TLDCS will visually follow the pattern and cut out the part. The ability to augment the operator during the skin cutting and triming process is crucial to the economic success of this project.

A fully automated system is inappropriate for the varied size and placement of the workpieces. The TLDCS will be designed using the principles of shared control. System capabilities will range from a completely teleoperated mode, where the human operator precisely positions the laser over each rivet, to a semi-automated mode where he/she simply identifies the target rivets on a graphics screen and then the robot slaves to those positions and awaits the command to shoot. Individual operators will be able to select the mode that allows them to be most productive. Expensive fixturing is eliminated. Multipass teaching methods are not required. The operator simply puts the workpiece within the robot workspace and proceeds to derivet or cut. No more advance preparation is required than picking up a hand drill or mini grinder.

Deriveting and cutting are mandatory operations in the repair and replacement of all aircraft skins. While this project is specifically directed toward repair of side and wrap cowls, the TLDCS has the flexibility to remove rivets from any aircraft component and the cutting operation could be extended beyond sheet metal repair. The only limitation would be the physical size of the part. Large size parts would require a larger robotic system, but the basic architecture of the TLCDS would remain unchanged. This is **not** a one-of system, but rather a true prototype. The process of laser deriveting and cutting is just the first instantiation of generic telerobotic workstation. By placing the design emphasis on the controller architecture and operator interface we create a system that forms a baseline for all future depot telerobotic applications. The TLDCS architecture is suitable for additional applications ranging from spray painting and stripping to fuel tank sealant application. The successful completion of this project will pave the way for low cost judicious insertion of telerobotics technology throughout the depots. Telerobotics is a critical robotics and automation technology for improving the quality of depot processes.

3.2 Future Directions

The RACE is pursuing several additional initiatives to improve our customer support capability. A brief overview is provided below. For more details consult [7].

The development of a prototype center is a critical element. That center will contain several state-of-the-art commercial robots equipped with vision and force sensor systems. The robots will be used for: prototyping, education, and detailed system design. Funding for those systems has been secured and the procurement process is underway. Funding to procure a advanced robot system capable of evaluating technology emerging from the laboratory has been requested. Another key element of the prototype center is a graphical simulation system. That requirement has been identified, and is at the top of our unfunded requirements list.

We are also championing several technologies necessary to reduce robotic and automation system insertion expenses. Our objective is to foster the development of robotic systems that fit the PC analogy; an inexpensive, flexible platform which has a large support and software base and is easily customized for a particular application. To accomplish that vision, the ideas of reconfigurable software, modular robots, and standardized interfaces must be more fully developed.

4 Conclusions

The Air Force Material Command Robotics and Automation Center of Excellence (RACE) is open for business at SA-ALC. The RACE provides a command-wide focal point for process engineers who seek to improve efficiency through the judicious insertion of robotics and automation technology. Major initiatives are underway to transform the RACE concept into reality. RACE is a champion for pulling emerging technologies into the Aircraft Logistics Centers. Shared control is a key tenant in those technology pull activities. The RACE team is currently providing technical support to process engineers at all five ALCs. Projects range from painting the C-5 to automating a simple X-ray system. The RACE team is ready to work with you. Join us as we champion competitive processes through intelligent machines.

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