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TELEROBOTICS FOR DEPOT MODERNIZATION

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Abstract

The time is right to transition telerobotics beyond the traditional hazardous environment domain into industrial repair and remanufacturing applications. Air Force depots are prime examples of an industrial environment where small batch sizes, feature uncertainty, and varying workload, conspired to make classical industrial robotic solutions impractical and telerobotics a key enabling technology. The AFMC Robotics and Automation Center of Excellence (RACE) has launched the Unified Telerobotics Architecture Project (UTAP) to champion the development of the support infrastructure necessary to foster creative development and innovative utilization of emerging telerobotic technologies for depot applications. The objective of this paper is to demonstrate that telerobotics is a viable solution to a wide range of dual use applications, highlight the benefits from a unified approach, and provide an overview of the UTAP.

1 Introduction

The United States Air Force has five major Air Logistic Centers (ALC), or depots, that perform periodic weapon system maintenance. A significant portion of the periodic maintenance workload involves repair and remanufacturing. The small batch sizes, feature uncertainty, and varying workload that characterize the depot remanufacturing environment conspire to make classical industrial robotic solutions impractical for a wide range of depot processes. The robotics and artificial intelligence necessary to solve those problems with a completely automated system is beyond our grasp technically and economically. An equally demanding constraint is applied by a depot level workforce resistant to complete automation, and a management structure soured by the unfulfilled hyperbole of past robotics projects. But the requirement for robotic/automation based solutions is growing. New processes that are environmentally safe, but too demanding for human operators, the need for increased process consistency with lower manufacturing tolerances, and competition with industry all point to a larger role for judicious application of advanced robotics technology. The critical missing element is a method to bridge the gap, both culturally and technically, between manual operation and full automation. Telerobotics provides the means for building that bridge.

We broadly define telerobotics as the *technologies and systems that permit a human operator to direct and/or supervise the operation of a remote robotic effector mechanism* [1, 6]. Telerobotics does not imply a particular solution, but rather encompasses the whole range of application driven solutions ranging from telepresence to supervisory control. The key premise is to augment, not replace, the human operator by blending the individual abilities of each *system.* Humans have superior cognitive and pattern recognition skills, while the robot is a tireless precise positioning system. The telerobotic system is not a threat to job security, but rather a new innovative tool that adapts to the operator to maximize productivity.

Unfortunately, telerobotics is more of a concept than an off-the-shelf technology. The basic components are available, and prototypes exist in various forms in numerous laboratories. However, developmental efforts have been targeted toward undersea, space and nuclear material handling applications. Solutions tend toward point designs customized to the particular application. Development of low cost systems was not a priority. Viewing the existing telerobotics market as a small niche, the major robot vendors have been reluctant to expend the resources necessary to modify their control systems to support a broad range of telerobotic solutions. Consequently, the manufacturing sector has been slow to embrace telerobotics and efforts to transition the technology from the laboratory to the shop floor are in their infancy. Therefore, we are presented with the unique and compelling opportunity to significantly influence the development of an emerging technology with the potential to radically enhance the productivity of the depot, and industrial, remanufacturing processes. The challenge is to implement the lessons learned from the mistakes of the past, to change our robotics technology insertion philosophy. Instead of developing *one-of* systems, we must embrace the creation of a unified systems concept that supports a large range of applications, provides an evolutionary path for incorporating new technologies, and reduces life cycle costs.

The Air Force Materiel Command Robotics and Automation Center of Excellence is championing the development of a unified framework or infrastructure that supports judicious insertion of telerobotics technology. The intent of this paper is threefold. First we present the case for telerobotics as a key enabling technology for depot process ranging from large aircraft paint stripping to surface finishing of component parts. Section three highlights the benefits of utilizing an unified architecture (infrastructure) to implement process solutions. In section four, our efforts to make that unified infrastructure a reality via the Unified Telerobotic Architecture Project (UTAP) are discussed. Conclusions are in section five.

2 Why telerobotics?

The best way to present the case for telerobotics for depot modernization is to overview the requirements for several target applications. Previous papers have presented detailed discussions of the telerobotic solutions to aircraft skin repair and fuel tank sealing/desealing [4, 5]. The remainder of this section is devoted to overviews of two processes targeted for prototype development under the UTAP. Specific process requirements (angle of incidence, standoff, accuracy) are in [6].

2.1 Aircraft Corrosion Control

At predefined intervals, aircraft are flown to the depots where existing paint is removed to allow surface inspection and repair of any corrosion damage. Before returning to active service, corrosion inhibitors are applied and the airframe is repainted. The productivity of all three processes; stripping, inspection, and painting can be improved by insertion of telerobotic systems. Paint removal is the initial target application in this area.

Process engineers responsible for corrosion control are being drawn to robotic systems due to efforts to eradicate the chemical stripping processes. Alternative paint removal techniques, while not environmentally hazardous, can be unsuitable for human application. High pressure (18K psi) water jet, CO2 ice pellets, flash lamps and lasers based application tools must be mounted as robot end-effectors. Even ignoring the obvious physical dangers, the application tools are too heavy (50 lbs or greater) for continuous human operation. Plastic Media Bead (PMB) and sodium bicarbonate blasting can be performed by operators in special air breathing suits, but the task is monotonous and messy. Another automation driver is the desire for stringent processes control. Many of the alternative stripping methods remove paint by blasting the aircraft or part with some media. Blasting introduces stress into the surface leading to reduced fatigue life. Tight control of the blasting process is necessary to minimize those side effects. Robotic systems provide a level of process control superior to that of a human operator. The unfriendly application environment, heavy payload, repetitive non-contact task nature of the task, and requirement for tight process control make the paint stripping operation ideally suited for robotic intervention.

The USAF has sponsored the development of large robotic paint stripping systems at three ALCs. Southwest Research Institute (SwRI) developed a custom system that is being used to strip F-16 aircraft with PMB and is being retrofitted for CO2 blasting of F-15s [7]. The Large Aircraft Robotic Paint Stripper (LARPS) REPTECH project is a large SCARA arm riding up and down on a column attached to an automated guide vehicle (AGV) [3]. The end-effector is a new commercial robot using a high pressure water process. Both SwRI and LARPS are big (50K lbs), expensive (>$2M), fully automated systems. But those processes are part of a large overall process that does not lend itself well to automation, ie the masking and general preparation of the aircraft for painting/stripping. At least half of the total process remains very manpower intensive. Add in the fact that several installations already have stacker (telecrane) platforms that allow human operators to access large portions of the aircraft surface and one can make a compelling argument for augmenting the existing workforce instead of replacing it.

A telerobotic aircraft paint removal scenario would look like the following. Attach a small robotic end-effector to the underside of the telecrane. The operator manually drives the stacker crane into the proper stripping position and then uses a joystick and the robots force sensing capability to register the actual worksite to a predetermined stripping trajectory. After setting stripping and other application parameters the operator becomes a supervisor as the system autonomously executes the stripping process. To perform the process the system must maintain a stripping process dependent separation/standoff distance and a tooling angle of incidence to the workpiece normal. While the primary mode of operation is supervisory, the system shall support a shared control feature that slaves end-effector position to the joystick with the system automatically regulating standoff and angle of incidence so that the operator can quickly remove any excess paint left by the autonomous process.

The robotic system is not responsible for all paint removal. The human operators, necessary for the preparation, would still be utilized to strip hard to reach locations. But the new tools free the operator from directly applying the stripping process to over 80% of the aircraft while dramatically improving process control. A properly designed telerobot system will support all stripping processes. Switching to painting and inspection tasks only requires some quick change tooling. Attached to mobile lift platforms the same system could perform flight line touch-up, or cross over to dual use applications like highway bridge repair.

2.2 Surface finishing

The standard procedure for repairing dents in engine nacelles is to fill the indentation with a fiberglass epoxy compound and then finish the surface to the required smoothness. Repair of aluminum-honeycomb aircraft skins frequently requires a similar blending process around the seams of the patched section. Grinding is also employed to remove the paint in the vicinity of the repair site. The common theme in these, and many other backshop operators, is the utilization of manual sanders and grinders. The health risks imposed by repetitive motions and dust inhalation combined with requirements for stricter process control and repair of more exotic composite parts are driving the search for incorporation of robotic technologies.

The customer does not consider the old approach of tight fixturing and preprogrammed motions an option. Management does not want to replace workers, but rather make them more productive and provide a safer environment. What is mandated is a better tool to replace the current hand sanders and polishers. Telerobotics provides that tool.

To augment the surface finishing task, a telerobotic system must support the following functionality. Instead of holding the hand tool, the operator grasps an input device (possibly a force reflecting joystick) that commands a robot permanently attached to the shop floor. Work pieces are still clamped onto dollies and rolled into the robot's work area, but no additional fixturing is required. Through a quick change mechanism the system is capable of matching the tooling to the task. The operator drives the robot into contact with the surface and performs a series of motions to complete the task under two shared control modes. In mode one the system maintains a contact force and a tooling angle of incidence to the workpiece normal. In mode two the system maintains a tooling angle of incidence to the workpiece normal while allowing the operator to modulate the applied contact force. Commands that would result in a contact force exceeding a predefined limit are automatically regulated at the limit. Both modes must be supported without any a priori knowledge of part geometry. However, the system must be flexible enough to efficiently incorporate automatic trajectory generation software when it becomes commercially available. Dual use applications of this technology range from polishing of bathroom fixtures to removing machining marks on airframe skins and ship impulsers.

3 Why a unified approach?

For a judicious insertion to take place one must specify the proper level of technology and deliver a system specification that is cost effective. The true potential of telerobotics can not be realized if every application requires a costly custom solution. A unified infrastructure for telerobotics is driven by the overriding objective of reducing system life cycle costs. Insertion cost decrease as supportability and reliability increase along with ease of upgrading.

3.1 Insertion Costs

Under the custom solution approach, software development and system integration are at least 60% of a new insertion project and almost always the bottleneck. A common framework allows basic commands for movement, gripping, trajectory generation, obstacle avoidance, and operator interface, etc to be developed at a higher level of abstraction. After paying for the initial software development, the scope of the software development task is reduced to developing the specific code that is required to implement a new process. Phase two of the UTAP will validate our estimate that initial development costs can be amortized within the first three applications. JPL estimated that a unified architecture could be reconfigured for a new application in one manweek.

3.2 Upgradability

The government procurement process requires that we rigorously specify the functional requirements of any system we contract for. The standards and specifications we mandate must be achievable by multiple vendors to allow full and open competition. Without standards we can not remain competitive as technology advances. Standardizing at the interface level, provides the hooks and scars for future upgrades without limiting the contractor's freedom to provide the most innovative and cost effective solution. For example, replacing a trajectory generator module must not require an extensive software rewrite because the existing generator is imbedded into some piece of spaghetti code. Switching joysticks should be no more complicated then switching printers on a computer system. By mandating standardization at the interface level we take the first step toward full interoperability. A unified architecture supports a system design methodology that evolves as the culture and technology evolve by providing a framework that builds in the future instead of locking it out.

3.3 Supportability

A common infrastructure breaks the one robot, one technician, one programmer, single operator loop we are currently trapped in. A unified architecture permits a common operator interface, reducing training requirements. The higher level of abstraction eliminates the need for programmers to be fluent in multiple robot languages, again reducing training time and expense. Adding a new system into an existing facility no longer mandates the creation of a whole separate support hierarchy. Upper level support is easily centralized. By avoiding custom mechanism designs, hardware maintenance support costs are also dramatically reduced and are now available from a variety of sources. A single internal organization will provide technical support for a whole depot. The need for an expensive support contract, usually with the original manufacturer of the custom system, is eliminated.

As the size of our workforce continues to decrease, increasing the productivity and range of skills of individual operators becomes more important. A single operator must become proficient in numerous processes and the robotic systems that are embedded in them. A common infrastructure will support a common operator interface allowing a seamless transition across all the telerobotic systems in the depot. Upon login the system will autoconfigure the look and feel to match known operator preferences.

3.4 Reliability

Software is the most unreliable portion of robotic systems. A common architecture allows a majority of the software to be ported from one application to the next. Minimizing the creation of new code maximizes system reliability. Selection of proven hardware components mitigates mechanical breakdown.

4 UTAP Overview

The Robotics and Automation Center of Excellence (RACE) has embarked on a multi-year initiative to demonstrate the feasibility of telerobotic technologies to accomplish a wide range of manufacturing applications and to develop a unified architecture that radically reduces the life cycle costs of telerobotic systems. The Unified Telerobotic Architecture Project (UTAP) is tightly coupled to related efforts in the national labs and the domestic manufacturing industry to maximize leveraging and dual use technology transfer opportunities.

In Phase 0, completed in FY93, NASA's Jet Propulsion Laboratory (JPL) performed an engineering study to define a telerobotic architecture capable of performing a wide range of ALC remanufacturing applications. The study began by distilling a representative set of processes into a global set of functional requirements sufficient to span the needs of depot activities. The state of commercial and near-commercial technology was then surveyed to determine how these requirements may be met in an integrated system. A comparison of the functional requirements and the available technology products then produced an architecture of system components and their connectivity [1, 6]

RACE has tasked the National Institute of Science and Technology (NIST) to act as coordinator and prime contractor for the FY94 study of issues pertaining to the specification and validation of the architecture.

Phase 1, currently underway, is a joint effort by NIST and JPL to examine the feasibility of implementing the initial JPL architecture and to develop preliminary interface specifications between all functional blocks of the UTA. This effort will include consideration of telerobotic technologies being developed at national labs and emerging standards such as the Next Generation Controller Specification for an Open System Architectural Standard. A workshop will be held with industry and national lab representation to solicit input for the validation and consolidation of these preliminary interfaces into the UTA design. The output of this workshop will be a working document that describes the interfaces and functional blocks of the UTA for Phase 2.

In Phase 2, a systems integrator under contract to NIST shall be tasked to analyze the UTA interface specification and determine if an UTA compliant system can be implemented to solve the representative application set, or suggest modifications to the portions where compliance is not possible. The contractor will then validate their analysis by designing an UTA compliant system and performing the validation test set, which consists of:

- Autonomous regulation of separation/stand-off while the human operator controls the other two cartesian coordinates via joystick,
- Autonomous force regulation along a gently curved surface while the other two tangential cartesian coordinates are are controlled via joystick,
- Registration of a workpiece by use of a vision system and fiducials,
- Autonomous regulation of tooling angle of incidence to the workpiece normal, and,
- Vision based tracking of circular trajectory on a planar surface.

The contractor will demonstrate accomplishment of the tasks on physical hardware using an Adept motion servo system and then demonstrate the interoperability and modularity of the architecture by replacing the Adept system with a Trellis motion servo system. Specific designs for three prototype systems and an estimate of system integration costs and potential cost savings from a unified approach are also required.

Future phases of the UTAP are not as crisply defined, but the objective is to continue UTA refinement to the goal of a releasing the architecture specification in full system request for proposals in FY97. Phase 3, the prototype development phase, will see contracts awarded to systems integrators to implement the Architecture/Interface specifications as depot prototypes. Each selected process will demonstrate a different facet of telerobotic technologies and will provide a core capability of the system. The three projected applications are: Telerobotic Telecrane Paint Stripping (T2PS), Telerobotic Surface Finishing (TSF), and the Telerobotic Cutting System (TCS). A parallel effort to create more sophisticated *laboratory* prototypes which exercise even more of the potential of telerobotics is also anticipated. Currently our prototype center PUMA is being retrofitted with more commercial version of the Onika software environment developed at Carnegie Mellon University [2]. Fitted with a force and vision system, the enhanced PUMA will be used to investigate the advantages of full interoperability in a telerobotics environment. Phase 4 encompasses a 6 month operator prototype evaluation and analysis task. Throughout the prototyping and operator evaluation phases lessons learned will be feed back to produce a more robust architecture specification.

5 Conclusion

The problem is enhancing the quality of Air Logistic Center repair and remanufacturing processes. The constraints are technical, economical, and cultural. Creative development and innovative application of telerobotics technology is the solution. The challenge is to redirect our system design philosophy to a methodology that embraces integration of commercially available components under a unified telerobotic architecture or framework. In cooperation with other national laboratories and agencies the AFMC Robotics and Automation Center of Excellence is championing the development and prototyping of a unified architecture that will pave the way for judicious insertion of telerobotic systems into a wide range of dual-use applications.

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