CONCEPTUAL DESIGN OF AN AIRCRAFT AUTOMATED COATING REMOVAL SYSTEM*

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ABSTRACT

Paint stripping of the U.S. Air Force's large transport aircrafts is currently a labor-intensive, manual process. Significant reductions in costs, personnel and turnaround time can be accomplished by the judicious use of automation in some process tasks. This paper presents the conceptual design of a coating removal system for the tail surfaces of the C-5 plane. Emphasis is placed on the technology selection to optimize human-automation synergy with respect to overall costs, throughput, quality, safety, and reliability. Trade-offs between field-proven vs. research-requiring technologies, and between expected gain vs. cost and complexity, have led to a conceptual design which is semi-autonomous (relying on the human for task specification and disturbance handling) yet incorporates sensor-based automation (for sweep path generation and tracking, surface following, stripping quality control and tape/breach handling).

INTRODUCTION

The U.S. Air Force's C-5 is one of the largest aircraft in the world. It has an overall length of 75.3 m (247.8 ft), a wingspan of 67.9 m (222.75 ft), and a height of 19.8 m (65.1 ft). Each craft in the C-5 fleet currently undergoes external refurbishment once about every five years. This task includes a detailed visual inspection, paint removal, damage repair, and repainting. The removal process incorporates a series of tasks including positioning and anchoring the aircraft, removing the engine, inspecting the external surfaces for anomalies, taping surface breaches (e.g., articulation seams and venting ports) to prevent contamination and/or damage to internal components, and selective paint removal (i.e., the controlled removal of specific top coating layers). Most of the paint removal is currently accomplished by plastic media blasting (PMB)—the erosion of the paint by fine grains of plastic propelled by compressed air. The blast stream is controlled by a human operator directly manipulating a "blasting gun," dynamically choosing the erosion path, and visually monitoring process quality. This open-air process leads to significant air quality degradation, requires specialized clean-up facilities for the recovery of discharged media and waste, necessitates the use of full body suits with fresh-air respirators, and prevents the simultaneous performance of any of the other tasks. Hence, the PMB paint removal task is a significant process and facility bottleneck. Portions of the paint removal task are sufficiently well defined to be prime candidates for automation. Thus, the Air Force is investigating the use of automated systems to reduce paint stripping turnaround time, personnel, and costs. Due to requirements in infrastructure costs and rapid fielding of test-bed systems, the automation design must be constrained to the most effective exploitation of existing technologies.

The following section discusses the development guidelines for this conceptual design and presents an analysis of the low-level task assignments. The subsequent two sections present operational and hardware designs, respectively. A summary section follows.

DEVELOPMENT GUIDELINES AND DESIGN OVERVIEW

The PMB paint removal task has been identified by the U.S. Air Force as a likely candidate for cost-saving automation. The savings are expected to come from an overall reduction in necessary manpower and turnaround time, and from a reduction/delay in the need for additional PMB hangar facilities. With cost and rapid fieldability as the primary drivers, the exploitation of existing facilities, equipment, and available automation technologies is critical for the design. This includes the use of the existing PMB as the primary mode of coating removal [as opposed to other technologies that could also be considered for automation (e.g., wheat starch blasting, chemical stripping, air/metal/water blasting, laser stripping, flashlamp stripping, pinchlamp stripping)] and the exploitation of field-proven telerobotics concepts (as opposed to other, more research-demanding approaches).

The U.S. Air Force decided to restrict the task to the tail section of the C-5 for the proof-of-principle experiments of the design concepts, as well as for the testing and feasibility evaluation of the automated paint stripping test bed. This selection is supported by several factors: (1) The tail section is sufficiently large to be representative of the overall aircraft. (2) Due to the height involved, it currently represents one of the greatest safety hazards for the human operator. (3) Automation equipment deployed to address the tail will not interfere with the paint removal operations being simultaneously conducted on the rest of the aircraft. (4) Successful completion of an automated tail paint stripping system would be of real and direct benefit, regardless of any future extension of automation.

A single automated system capable of paint stripping the entire tail section of the C-5 requires significant reach capability. Since the horizontal stabilizer is 20.8 m (68.75 ft) long and nearly 19 m (62 ft) above the floor, mounting the system on the existing gantry platform was considered most economical. This platform is suspended from the ceiling by two telescopic supports and moves vertically and laterally (in line with the span of the horizontal stabilizer). The platform is of sufficient length to straddle each horizontal stabilizer and thereby permit the operator to reach all points on, and to get within a few feet of, the entire tail's surface. To strip the entire tail section, the system must be able to direct the blast above and below the platform (to reach the two opposing surfaces of the horizontal stabilizer) and toward each side of the platform (to reach the two opposing sides of the vertical stabilizer) while still permitting safe human use of the platform when necessary (e.g., inspection, maintenance, touchup).

Automated PMB paint removal is analyzed as six primary subtasks: (1) task specification and initialization; (2) sweep path generation and safe tracking—determination and motion control of an end-effector path to cover a predefined surface region without contacting modeled obstacles; (3) surface following—maintaining a predefined offset distance and orientation between the surface and the end-effector-mounted nozzle during arbitrary translational motions; (4) real-time, quality feedback control—dynamically adjusting the end-effector's translation rate to obtain a predefined residual coating quality, (e.g., fully exposing the primer coat); (5) unexpected obstacle avoidance—preventing contact with any dynamic or unmodeled obstacle; and (6) disturbance handling—acceptably resolving any unexpected condition (e.g., sensor failure, abnormal blast pressure, etc.). These subtasks have been evaluated with respect to expected gain vs. automation complexity and overall costs, resulting in a distribution of tasks between the human (manual operation) and machine (automation) based on available resources. For example, either a fully manual or a fully automated system clearly represents under utilization of capabilities. Since the application environment is extremely well defined and dynamic obstacles can be excluded, automating dynamic object avoidance is unnecessary and wasteful. Automating only surface following yields an improvement over the current system. However, it is not considered an optimal exploitation of available automated control technologies. The most synergistic coupling of capabilities was found to be the human providing task specification and initialization, unexpected obstacle avoidance, and disturbance handling, and automation being used for surface following, path generation and safe tracking, and real-time quality feedback control. The detailed cost vs. benefit analysis of automating quality control through a (visual) sensor feedback scheme requires experimental data on the stripping quality sensitivity to translation rate, the related sensor data processing requirements, and the ability of a human operator to accurately control this process, none of which are available at this time. These experiments are planned to be performed during the detailed design analysis phase using feasibility proof-of-principle hardware.

OPERATIONAL DESIGN

In the proposed design, the human operator is responsible for disturbance handling and task specification, as well as initial placement of the system, monitoring stripping quality, and supervising the safety of the operations. The automated controller is responsible for maintaining the proper surface following distance, pre-calculating paths which satisfy the operator's specifications and assure collision-free operation among the known obstacles, executing the pre-calculated paths at run-time, and maintaining the operator's specified stripping quality. Additionally, the mechanical system includes some passive compliance near the end-effector to maintain proper surface orientation and improve surface depth following, as well as to provide an additional safety measure during transition-to-contact motions.

The overall system could be utilized in three distinct modes: off-line, on-line manual, and on-line automated. The off-line mode would permit the automated system to develop optimal paths based on the operator's task definitions. In this mode the operator would specify parameters defining a particular stripping task to the automated control system. Then the system would calculate the required motions to safely and efficiently perform the task based on its internal model of the environment. (The controlled nature of the stripping environment permits the safe use of model-based navigation with a static world model, given accurate self-location estimates.) This mode would be entirely performed on the operator's displays, both in task specification and verification.

The manual mode of operation involves automating only the surface following task. The user would explicitly direct the sweep motion of the system telerobotically and have the necessary input devices and video/graphic displays for safe operation. This mode would not be efficient for long-term use of the system but could be very useful for touch-up activities, stripping of unmodeled surfaces, and back-up operation (in the event of an automated system failure).

The automated mode is designed as the typical mode of operation, in which calculated sweep paths are executed under semi-autonomous control. The operator first positions the device so that it does not interfere with the normal "hands-on" usage of the platform. He/she then mounts the platform and prepares the target region, including inspection, taping, etc., and installs self-location sensors at predetermined positions on the aircraft. The operator then dismounts the platform, goes to the control center, and specifies the task to be performed. The operator must then position the platform so that the initial task area can be reached. The automated control system will use self-location sensors to guide the operator in this initialization maneuver. Once an acceptable position is reached, the operator can start the automated task. During this operation, the operator will monitor appropriate displays and intervene when necessary. The system will automatically position the end-effector, engage an internal blast deflector shield to prevent surface damage, and start the blasting flow. When ready, the deflector shield will be lifted and the end-effector will traverse the preselected sweep path, maintaining proper surface following distance and orientation. The operator will retain responsibility over dynamic obstacle avoidance (the sweep path is free of static obstacle collisions) and disturbance handling. The blast deflector shield will be used whenever the end-effector is not in motion (e.g., startup, direction change, shutdown, or by explicit operator control) and whenever a tape or breach condition is detected. If the stripping quality is manually controlled, the operator monitors appropriate displays and adjusts the translation rate accordingly. If automatic, the operator specifies the desired stripping quality (e.g., by menu description or by manually adjusting the rate and engaging a "lock") and the system continually modifies the translation rate to maintain that quality level.

HARDWARE DESIGN

The hardware design consists of five primary components: the gross positioning device, the manipulator, the end-effector, the sensor systems, and the operator's control center.

Gross Positioning Device

The robotic system will exploit the facility's existing platform for primary deployment. However, due to platform motion and controls limitations, a gross positioning device is also required. This device will be anchored directly to the platform and will provide (1) the gross positioning of the manipulator for stripping surfaces above, below, and to either side of the platform without interfering with the safe human use of the platform, and (2) the fine lateral motion (in line with the fuselage) for sweep path following. Two designs have been proposed, as shown in Figure 1. Both are based on the deployment of a lateral beam along which the manipulator will translate. The first design employs fixed circular arcs on which the beam itself translates. The second design rigidly mounts the beam on two rotary-actuated spokes. In both cases, the manipulator's base position is defined by the angle α and the lateral position **L**. Due to the size and weight of the gross positioning device, its angular motion is not expected to be of sufficient resolution for the fine motion control necessary to follow the path trajectory specifications.

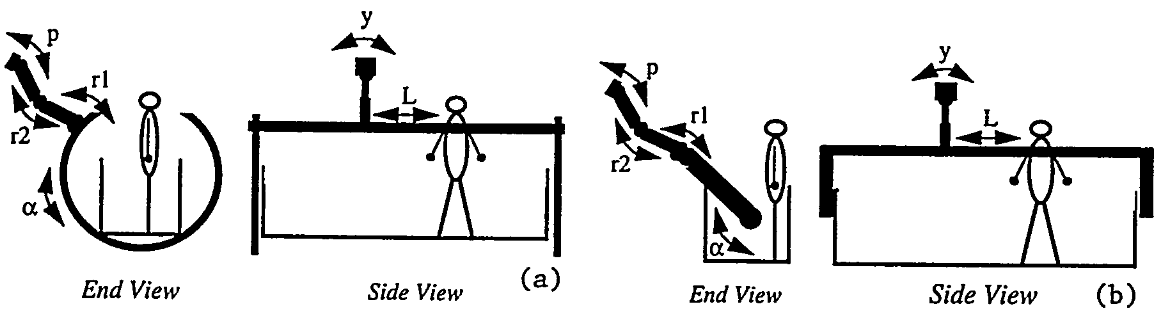

Figure 1. Conceptual designs of gross positioning device:
a) cylindrical beam support, and b) revolute spoke beam support.

Manipulator

The manipulator is responsible for positioning the end-effector according to the path trajectory specifications. This requires fine motion and control capabilities in all three position coordinates. The position can be easily defined in a cylindrical coordinate system with axis on the gross positioning beam. The cylindrical lengthwise motion would be provided through the lateral position, **L**, of the manipulator on the beam, (see Figure 1). The manipulator would be connected to the beam using a revolute joint to provide the fine angular motion and control, α'. The radial motion would be provided by the other joints of the manipulator which would consist of two links connected by either a prismatic joint or a revolute joint. In both cases, the work envelope of the manipulator and its base revolute joint is within a disc centered on and orthogonal to the lateral beam. The inner and outer radii of the disc will be defined during detailed design of the manipulator. Both the revolute and prismatic designs, as well as the two concepts described in Figure 1, will be examined in the final design analysis of the system.

The fine motions will be automatically controlled to follow the precalculated path selected by the operator. In addition, sensor feedback may affect the position, lateral traverse rate and deflector operation of the end-effector: Self-location inaccuracies may require loop-rate modification of the depth (position of the end-effector along a line orthogonal to the surface at the target point) according to depth control sensors; the lateral traverse rate determines cutting efficiency and is affected by stripping quality feedback; and detection of the tape will cause the blast deflectors to engage to prevent possible breaching.

End-Effector

A closed air (sealed) head design was chosen as the most appropriate end-effector for an automated PMB system. This design utilizes a sealed contact between the end-effector and the surface and requires vacuum recycling equipment. This results in a heavier, bulkier end-effector and some reduction in the surface area accessible to the automated stripping system. However, the advantages of this design far outweigh these considerations. A closed air head design effectively contains the blast environment and permits accurate deployment, leading to better targeting control, more accurate sensor positioning and control, more rapid sensor-based process feedback, decreased sensor requirements through a restricted field-of-view, and a safer work environment. Furthermore, the high cutting angle precision which can only be achieved with direct contact permits the use of optimized blast nozzles. Such nozzles have permitted the CAE company [1,2] to achieve significantly higher stripping uniformity and throughput levels, currently from 30 to 60 cm^2/s using a 10-cm-wide cut. Though CAE's proof-of-principle research is based on wheat starch media, similar results should be obtainable with a PMB optimized nozzle.

Overall system throughput is also enhanced by the blast atmosphere containment. Containment permits pipelining of basic removal activities. For example, rather than deferring the selective paint removal task until after all other tasks are completed, PMB can begin as soon as a given region is prepared, regardless of the concurrent activities being conducted in the hangar. Furthermore, if surface breaches (which currently require manual taping) could be automatically avoided through model-based navigation, accurate self-location, and sensor feedback, then this labor intensive operation could be reduced or eliminated. These throughput improvements would permit a more efficient use of the existing hangar facilities, and personnel, and thereby reduce overall costs.

The design of the end-effector is expected to be similar to CAE's current prototype [1]. However, we envision using contacting wheels for more accurate surface following and wide brushes for a better seal. The mounting design will permit a suitable range of motion through passive compliance in both pitch and yaw and limited depth compliance. This passive compliance eliminates the need for orientation control, sensing and actuation, and increases safety during both path following and initial contacting operations by buffering the sensor-based feedback motions.

Sensor Systems

Sensor feedback is required for accurate self-location, depth control, operator monitoring, traverse rate and stripping quality monitoring, and tape/breach detection. For self-location, multiple magnetic transducer-based local positioning systems are proposed. Such systems have demonstrated accuracies of ~2 mm with emitter-to-receiver ranges of up to ~3.5 m. However, ferrous objects in the vicinity of the emitter have been found to somewhat degrade the measurement accuracy/range. Testing is required to determine the best deployment of these sensors and to quantify their performance in the vicinity of the aircraft and automated PMB system. Since depth control requires a single one-dimensional force measurement, a one-dimensional load cell will be used to sense the average end-effector force and provide depth following feedback. This design simplifies data acquisition and processing, and reduces costs. A variety of sensors are suitable for operator evaluation and monitoring of the stripping process. However, cost, human experience, and multi-use functionality suggests that either color CCD or hyperspectral cameras should be used. These cameras would also be used in traverse rate monitoring (detection of the relative position of the leading edge of the stripping "front" by color edge detection), stripping quality monitoring (quantification of the relative amounts of exposed material in the stripped region by color histogramming), and tape/breach detection (indicating the presence of the protecting tape or surface breach by color recognition).

Operator's Control Center

The control center will provide human operators with the input devices and displays they need to effectively monitor and control the stripping process. Control/display requirements were determined by the same iterative task analysis process that was used to resolve the appropriate human/automation roles. A task network model describing work flow during system operation further guided the analysis and conceptual design of the control center.

From these analyses, it was determined that the operator will require video displays of process quality from inside the stripping head, of the end-effector as seen from the platform, and of the platform and aircraft. He/she will require graphic displays of the aircraft model (including the end-effector, arm, and platform), a tracking graphic for traverse rate effectiveness (this may be overlaid on the process quality video), feedback indicating the end-effector's distance from the surface or contact force, and general system diagnostics (e.g., air pressure and PMB flow rate). The operator will also require a real-time hand controller for stripping quality (1 dof), platform control (2 dof), and positioning system control (3 dof), as well as a human-computer interface including a keyboard and a pointing device (e.g., mouse or lightpen), and a hard-wired emergency stop button.

Figure 2 illustrates the control center concept. The left-most console includes a large video display and a joystick, and is the manual control center. It will be used when the operator is manually operating the platform or manipulator, or is defining or controlling the stripping rate. The central console is for system and performance monitoring; it provides three video displays from the hangar, a single computer graphics display, and a joystick. This console will be used to monitor all stripping operations and, in automated mode, to control the stripping rate and intervene if disturbances are detected. The right-most console is the off-line control station. This station will be used to display the world model, to specify or program stripping paths, and to otherwise interact with the computer during non-stripping operations.

SUMMARY

This paper presented the conceptual design of a semi-autonomous coating removal system for the U.S. Air Force's C-5 transport aircraft. The overall design objectives were to reduce costs, personnel, and turnaround time while increasing quality and safety. The coating removal process was viewed as a series of six basic tasks: (1) mission specification and initialization; (2) sweep path generation and safe tracking; (3) surface following; (4) real-time, quality feedback control; (5) unexpected obstacle avoidance; and (6) disturbance handling. An iterative analysis was performed based on the comparative advantages and capabilities of a human operator vs. automated controls and on their impact on the overall design objectives. The resulting design is a synergistic coupling of human and machine, with the human operator responsible for the higher-level conceptual tasks of mission specification and initialization, unexpected/dynamic obstacle avoidance (environmentally rare), and disturbance handling, and the automated control system responsible for self-location, surface following, sweep path generation and safe tracking, and quality feedback control.

The system will operate in three distinct modes: off-line—for task specification, on-line manual—for backup and touch-up operations, and on-line automated—for general stripping. The robotic hardware will be anchored to an existing platform and will be composed of three primary devices: the gross positioner, the manipulator, and the end-effector (see Figure 3). The gross positioning device will enable the manipulator to be deployed in a full 360° circle along the entire length of the platform. The manipulator will provide fine positional control of the end-effector, while orientation will be through passive compliance. The end-effector will provide a seal blasting chamber with vacuum recycling of the blast media and nozzle(s) optimized for cutting quality and throughput. Navigation will be performed by a combination of manual specification, sensor feedback, and precalculated, model-based mission tours. It is anticipated that over 90% of the C-5's tail section can be handled by this proposed system and that remaining areas (e.g., corners, leading edges, taped surfaces) will be stripped by the currently employed, traditional methods (hand PMB or sanding). Experiments using proof-of-principle hardware are planned during the detailed design analysis phase of this effort to ascertain the feasibility and control parameters related to the handling of tape and the automation of stripping quality feedback.

Figure 2. Operator's control center (conceptual design).

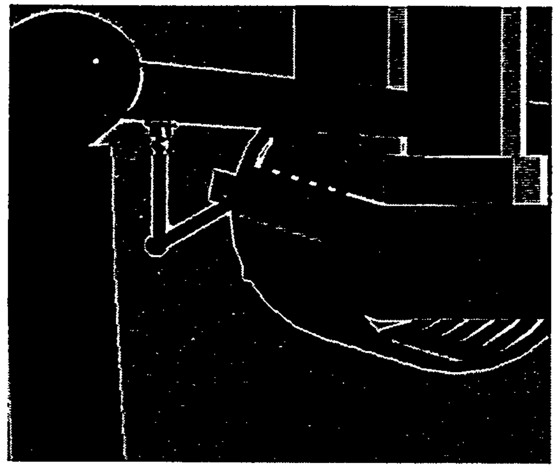

Figure 3. Robotic coating removal system (conceptual design).

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