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THE AUTOMATED AIRCRAFT REWORK SYSTEM (AARS) A SYSTEM INTEGRATION APPROACH

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Abstract

The Mercer Engineering Research Center (MERC), under contract to the United States Air Force (USAF) since 1989, has been actively involved in providing the Warner Robins Air Logistics Center (WR-ALC) with a robotic workcell designed to perform rework automated defastening and hole location/transfer operations on F-15 wings. This paper describes the activities required to develop and implement this workcell, known as the Automated Aircraft Rework System (AARS). AARS is scheduled to be completely installed and in operation at WR-ALC by September 1994.

Statement of Problem

The Mercer Engineering Research Center (MERC) was awarded a contract from the United States Air Force (USAF) in January 1989 entitled "Tooling for Fastener Hole Reproduction". The purpose of this task order was the investigation and development of automated tooling concepts to perform fastener hole location on F-15 aircraft wing upper torque box panels, and the subsequent transfer of those locations to replacement skin panels.

The F-15 Eagle Fighter was one of the first modern aircraft to be designed with the aid of computer technology. The majority of the production effort on the F-15 was accomplished through manual methods, following standard aerospace manufacturing practices. Skin panel fastener hole drilling by manual means resulted in unique fastener patterns for each panel, and therefore panels are non-interchangeable among respective aircraft. Unique fastener patterns were not considered a problem until Periodic Depot Maintenance (PDM) rework requirements for the F-15 called for the replacement of wing skin panels.

Due to the non-interchangeability of wing skin panels, replacement skin panels must be supplied blank, without fastener holes, and with excess trim material on the fit edges. The primary reason for this is to allow the rework or repair facility personnel to custom fit the replacement panel to the aircraft. The resulting process is both very labor and skill intensive.

Scope and Methods of Approach

The MERC plan-of-attack for the AARS effort called first for a problem definition effort consisting of the study and evaluation of the F-15 wing PDM rework processes performed at the Warner Robins Air Logistics Center (WR-ALC). The primary goal was to fully understand the manual methodology involved in the hole location/transfer process and to then be able to define the requirements for an automated system.

Basic System Requirements

Based upon the observations of the wing rework processes, the basic system requirements for the AARS were defined, as follows:

-Accuracy/Repeatability: System must be capable of maintaining tight process tolerances over a large work envelope, specifically, to locate hole centers and transfer those locations at less than a 0.005" deviation from the original position.

-Flexibility: System must possess a significant level of artificial intelligence, capable of location and transfer processes on any unique fastener pattern.

-Low Technical Risk: Any system selected must be comprised of proven, reliable technology; simple and easy to maintain.

-Off-Line Programming and Inspection Capabilities: System must possess both of these capabilities in order to verify and validate the processes performed, as well as to integrate the highest quality possible into these processes.

-Ease-of-Operability: Any system chosen must be simple for maintenance personnel to operate, with a minimal amount of training required.

-Safety: Any system chosen must be safe to operate and designed with operator protection in mind.

With this definition of basic system requirements completed, MERC was ready to begin investigations of state-of-the-art robotic technology and vendors qualified to meet the requirements.

Level of Automation

While defining the basic system requirements, the required level of automation had to be resolved. MERC engineers considered varying degrees to which the hole location/transfer process should be automated. Enhanced types of manual tooling aids such as drill blankets were evaluated and eventually rejected because, while the quality of the hole transfer process could be improved, additional tooling setup and takedown time would be required. As well, varying skill levels of the maintenance personnel involved would also effect the level of quality improvement afforded through the use of enhanced types of manual tooling.

Also considered was the adaptation of existing machine tooling. This concept was similarly rejected for a number of reasons, among them that due to the curvature of the wing skin panels, any applicable tooling would have to possess a minimum of five (5) degrees of freedom in order to assure the maintainment of surface normality for enhanced process accuracy. It was therefore determined that while most machining centers and pattern contouring machines possessed the required accuracy, they lacked the necessary flexibility in control and processing required for the task.

It soon became apparent that the only applicable system was one fully automated, or robotic in nature. It was also apparent that fastener hole location and transfer is a process for which any chosen robotic system must possess high repeatability characteristics in order to perform. High repeatability is required in order to properly transfer the fastener hole center locations to the replacement skin panels - necessitating that the chosen robotic system be capable of reliably returning back to the correct hole center location. Due to these considerations, MERC determined that a gantry configuration robot would be ideal for the application, especially since a gantry robot is able to achieve the same level of performance across the entire work envelope.

A System Configuration Merit Analysis was performed by MERC based upon the above discussion, and the results are presented in Table 1 on the following page.

System Technical Requirements

MERC investigated several major manufacturers of gantry robots, as well as machine vision system and end effector tooling vendors. To aid in the final selection of system components, somewhat more comprehensive, system technical requirements were developed:

-Work Envelope Size: A minimum of 18' x 30'.

-Dynamic Referencing/Positioning Capability: Global and Point-to-Point Referencing required.

-System Degrees-of-Freedom (DOF): A minimum of five (5) axes of motion required.

-Controller/Database Capability: Ample data storage, realtime process speed/feedback response, fully downloadable.

-End Effector Tooling: Capability for realtime monitoring of torque, thrust, and dynamic feedback.

Table 1
SYSTEM CONFIGURATION MERIT ANALYSIS

SYSTEM DESCRIPTION	MERIT	COST		SUMMARY
		Material	Labor	
1. Drill guides, plastic templates (transfer media) (Manual)	2	Low ($15,000)	Intensive High skill level required	The Air Force currently uses aluminum transfer templates. They have had poor success at their facility and at McDonnell Douglas' St. Louis facility in using drill guides and plastic templates.
2. Laser scan plotted drill/fastener layout (robotic)	4	Moderate ($250,000)	Intensive High skill level	A laser scan can achieve the required dimensional data necessary to produce a quality plot. Problems include alignment, plot accuracy, plotting size and large human error potential.
3. Touch Probe dimensioning automated drilling (robotic)	7	High ($1,000,000)	Low Reduced skill level	Has advantages in that the required skill level is reduced. Technical problems include probe force, robotic accuracy, interfacing and fixture tooling.
4. Vision/probe hole location automated drilling robotic	8	High ($1,000,000)	Low Reduces Skill level	Has advantages over system 3 in that it can be programmed to adjust to wide ranges of assembly tolerances used in the actual production of the F-15. Same technical problems as system 3.
5. Vision hole location with laster interferometry for volumetric accuracy (robotic)	8.5	High (1,500,000)	Low Reduced skill level	Has advantages over system 4 in that robot repeatability is not as much a requirement because it can be accurately fixed by laser triangulation. Will allow for greater variance in machine.
6. Probe Location Laser Global referencing (robotic)	8.5	High (1,500,000)	Low Reduced skill level	Not as attractive as system 5 because the vision system would most likely be faster than the probe system.
7. Probe/Vision Location with Laser for Volumetric Accuracy (robotic)	9	High (1,700,000)	Low Reduced skill level	The best total system because: 1) flexibility due to vision adjustment 2) probing for exact center location 3) laser can be used for normality 4) volumatic accuracy

System Component Selection

Based upon the technical requirements, the major components of the system were selected as follows:

-PaR Systems XR 225 Gantry Robot: The XR 225 offers excellent accuracy and repeatability performance, with a 225 pound wrist capacity, and the work envelope can be sized to order.

-PaR Systems CIMROC 4000x Robot Controller: The 4000x supervisory controller is based upon an IBM-AT compatible computer using the PC-DOS operating system, and has the advantage of being fully integrated and compatible with the XR 225 robot.

-Adept AGS Machine Vision System: This system affords excellent vision processing capability through efficient handling of variations in lighting, surface finish, and contrast while still providing the image resolution necessary for accurate hole center location. Additionally, the vision system requires minimal effort for integration to the robot.

-EOA Systems CNC Aerodrill: A programmable drilling end effector, offering a full range of performance parameter control, and fully compatible with the robot utilizing the AeroQuick Change adaptor for automated tool pickup and dropoff.

-CENTRO 200 Tactile Offset Sensor: Provides data for referencing by the robot to the part/fixture assembly within the workcell, as well end effector tooling offset data.

-Tooling Fixture(s): Part determinate, and critical to successful automated hole location/transfer operations. The fixture(s) must rigidly support the part to ensure high process accuracy and repeatability.

Table 2 on the following page, illustrates the selected components and vendors as well as their respective system responsibilities.

The individual components selected were all of proven technology, but their integration into a functional automated system for the performance of fastener location and transfer had not previously been accomplished. For this reason, a proof-of-concept effort was performed.

Proof-of-Concept Effort

The primary goal of the proof-of-concept effort was to both demonstrate and validate the capabilities of the AARS to successfully perform automated fastener hole location and transfer operations. Additionally, the feasibility of performing automated defastening with the system was to be demonstrated also.

Specific capabilities to be demonstrated included:

-Proper location referencing and surface contour determination (ie., relative normality of fastener hole locations) of an F-15 outboard wing skin.

-Vision system location (mapping) and storage to the robot controller database of at least two hundred (200) fastener hole locations. Goals for the location/transfer accuracy were less than 0.005" deviation in mapped position, and +/- 1° for surface normality correction.

-Location referencing and surface contour determination of the replacement skin panel, followed by transfer of the mapped fastener hole location via 1/8" pilot holes.

Significant integration effort was required prior to performing the proof-of-concept effort. Probably most critical was that of integrating the vision system to the robot, and development of the vision mapping methodology.

The methodology initially developed for vision mapping operations consisted of generating an AutoCAD drawing of an F-15 upper outboard skin panel utilizing data from McDonnell Douglas assembly drawings. This drawing served to provide initial positioning data to the robot by depicting the nominal locations of the fasteners within 0.125" of the actual physical location. The drawing data was converted via an RS-274D interface to machine control code for interpretation by the CIMROC controller. From this initial positioning data provided to the robot, the actual fastener hole position would fall within the field-of-view (fov) of the vision system camera for mapping. The nominal

Table 2

SYSTEM COMPONENTS	SUGGESTED VENDORS	SYSTEM RESPONSIBILITY
System Integrator	MERC	Responsible for: System Development/Implementation Engineering Tasks, Training of WR-ALC Personnel in System Operation, System Support (Liaison Engineering)
Robot Model XR 225 18' X 30' Gantry	Par Systems	Machine tool platform for hole location/transfer. Main component for tooling integration
System Controller CIMROC 4000	Par Systems	Will control robot during all aspects of both fastener location and transfer operations
End-Effector Tooling CNC Aerodrill	EOA Systems, Inc.	Responsible for robot end of arm tooling
Tactile Offset Sensor CENTRO 200	CENTRO Automation	Will be used to determine surface contour, edge reference, and fixture location data
Machine Vision System	Adept	Responsible for fastener, hole location
Tooling Fixtures	MERC	Will be used to support wing and/or panels during hole location/transfer operations

hole locations provided on the drawings were numbered according to Air Force convention, and this numbering convention was also utilized by the robot controller for databank storage.

The AARS proof-of-concept effort was conducted at the PaR Systems facility in Shoreview, MN utilizing PaR's laboratory setup of an XR 225 robot, CIMROC 4000x controller, EOA Systems CNC Aerodrill, and CENTRO 200 Tactile Offset Sensor (probe). Also utilized was an Adept vision system which was leased for the effort. The proof-of-concept demonstration to the Air Force proved to be very successful, with all goals set for the effort being met or exceeded (see Table 3).

AARS Prototype Development

MERC was awarded the contract for the AARS Prototype Development effort in September of 1991. This contract defined the engineering services required to design, document, and prototype the AARS, and was divided into two phases: a Basic Period (Phase One) and an Option Period (Phase Two).

Phase One Efforts

During Phase One, MERC was tasked to lease or procure the necessary tooling and subsystems to further demonstrate automated fastener hole location and transfer, as well as the additional requirement to demonstrate automated defastening capability. MERC was also tasked to complete a conceptual design of a large wing jig, capable of rigidly fixturing an entire F-15 wing within the robot's work envelope.

The main goal of the Phase One effort was once again to demonstrate the system's capability to perform hole location and transfer, but more importantly, to also perform automated defastening operations. Critical to the successful demonstration of this capability was the performance of vision system.

Vision System Programming

The F-15 upper wing skin panels are tied to the wing substructure with just over 2200 fasteners. The fasteners utilized are primarily comprised of four major types: coin slots, hi-loks, jo-bolts, and taper-

Table 3

GOAL	VALUE	ATTAINED
CAD/Vision Positioning Capability	± .125	± .125
Hole Location Accuracy	.005 (Global)	± .0015
Hole Transfer Accuracy	.005 (Global)	±.005
Hole Normality	± 1 Degree	±.3 Degree
Bad Hole Determination	Operator Notification	Attained
Vision/Robotic Communication Protocol	Demonstrate Interface	Attained

loks. Coin slot fasteners are threaded, and the preferred removal method is to manually back them out. The other fastener types all require drilling for removal. This difference served as the basis for the required development efforts for a defastening end effector for use with the robot as well as the necessary programming of the vision system.

MERC procured an Adept AGS Machine Vision system during Phase One and performed additional programming of the system to enable it to perform mapping for automated defastening operations. The goal of this additional programming was to provide the vision system with the capability to map the wing skin surface and identify fastener type, size, and location. The programming was accomplished using Adept's Visionware programming environment, through the creation of specific inspection sequences. The basic logic for these sequences was as follows:

1. Locate the object within the field-of-view (fov) and fit an arc to it.
2. Determine the diameter of the fit arc.
3. Determine the center x,y coordinates.
4. Perform a rudimentary inspection to determine if a slot is present.

A serial communication protocol was established between the Adept vision processor and the CIMROC 4000x robot controller for transfer and processing of the vision data. Each fastener hole location on the wing is uniquely numbered, and this numbering convention was maintained for the robot controller database. Since the coin slot fasteners were the only type which required backout, the determination by the vision system as to whether or not a slot was present on the fastener head was the primary criteria for tool selection by the robot controller.

Defastening End Effector Development

MERC was also tasked with the development of a prototype defastening end effector, specifically to perform backout of coin slot fasteners. MERC created a technical specification for the tool, and the decision was made to issue a subcontract to EOA Systems for production of the prototype. EOA Systems was chosen for a number of reasons, among them that the tool would have physical characteristics very similar to that of the Aerodrill, and would therefore be totally compatible with the XR 225 robot wrist. Additionally, the prototype would utilize the same controller as the Aerodrill. The design of the prototype consisted of a stepper motor for slowly rotating the tool tip until the slot was engaged, and a large air pulse motor for backing out the fasteners.

Upon completion of the vision programming and development of the prototype defastening end effector, MERC performed another demonstration of system capability to the Government. This demonstration was again performed at the PaR Systems facility, utilizing their laboratory robot setup.

Capability Validation Demonstration

This demonstration differed from the first not only by the addition of the automated defastening capability, but also in that the system's capability to perform automated vision mapping, defastening, and hole location/transfer operations was conducted on an actual F-15 wing, fixtured within the workcell using a modified Air Force wing transportation dolly. An additional difference was that a Chesapeake Systems Laser Profiler was used in place of the CENTRO 200 Tactile Offset Sensor for normality determination.

The AARS Capability Validation demonstration was conducted over a two day period, concentrating on the outboard skin panel of the F-15 wing. The first day was devoted to demonstrating the system's ability to perform automated defastening operations. This included vision mapping and fastener removal by both backout and drilling.

At the completion of the first day's activities, the outboard skin panel was removed. The second day of the demonstration was devoted to vision mapping of the exposed wing substructure, followed by transfer of the mapped hole locations to a blank skin panel which had been placed back over the substructure. All system capabilities were successfully demonstrated to the Government's satisfaction.

Phase One of the AARS Prototype Development effort was completed with the successful System Capability Validation demonstration, leading to the Air Force's exercising of Option I of the contract for the Phase Two effort in June of 1993.

Phase Two Efforts

With receipt of the AARS Phase Two award, MERC is currently performing a number of required engineering efforts in support of installing the AARS at WR-ALC. These efforts are discussed below.

System Procurement

MERC is procuring an XR 225 robot, CIMROC 4000x controller, and support items (end effector and drill bit racks) from PaR Systems, and a CNC Aerodrill and controller from EOA Systems. Chesapeake Systems discontinued production of their Laser Profiler series, and after an extensive search, a Perceptron Surface Sensor was selected and is also being procured for the system.

Other items required for the system have been identified and are being procured. Among these is a Camera Cable Extender unit from FSR, Inc. It was determined this unit was necessary due to the long length of camera cable which must be installed within the robot (approximately 144 ft.) and the concern that signal loss due to this length would adversely affect the vision system performance. Also being procured is a custom operator workstation which will house the Adept and Perceptron controllers, as well as the robot, vision, and Aerodrill controller monitors and keyboards.

The system in it's final configuration is depicted in Figures 1 and 2.

Facility Modifications

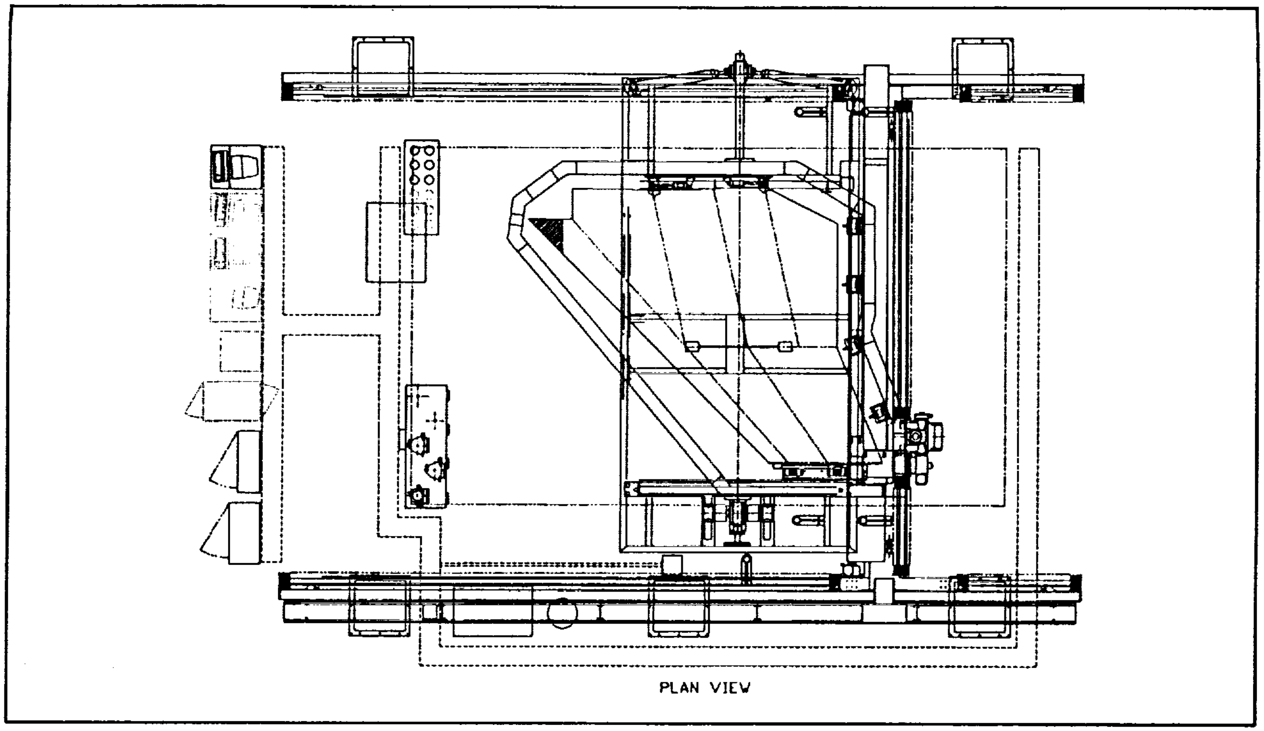
The Air Force has decided that AARS will be installed within Building 140 at WR-ALC, where the majority of rework operations on the F-15 wings are performed. Prior to the actual installation of the system, significant modifications to the facility must first be performed. In order to ensure that the highest level of accuracy and repeatability performance is maintained by the system, the robot must be mounted upon a vibration isolated, floating slab.

The internal work envelope of the robot is 18'x30'. Therefore, the required "footprint" of the system is approximately 30'x40'. At the designated workcell site within Building 140, the "footprint" area will excavated to a minimum depth of five feet. This depth will ensure that the 4 foot thick, 3000 psi concrete slab resting on Unisorb padding is correctly installed. Additionally, utility drops will be provided within 15 feet of the workcell site.

Wing Fixture

MERC completed the conceptual design for a wing fixture during Phase One. Enhancements to this design were identified, and the final design of the wing fixture has now been completed and fabrication efforts initiated.

The fixture design will provide a rigid platform for automated rework operations to be performed by the robot upon the wing. The design allows either a



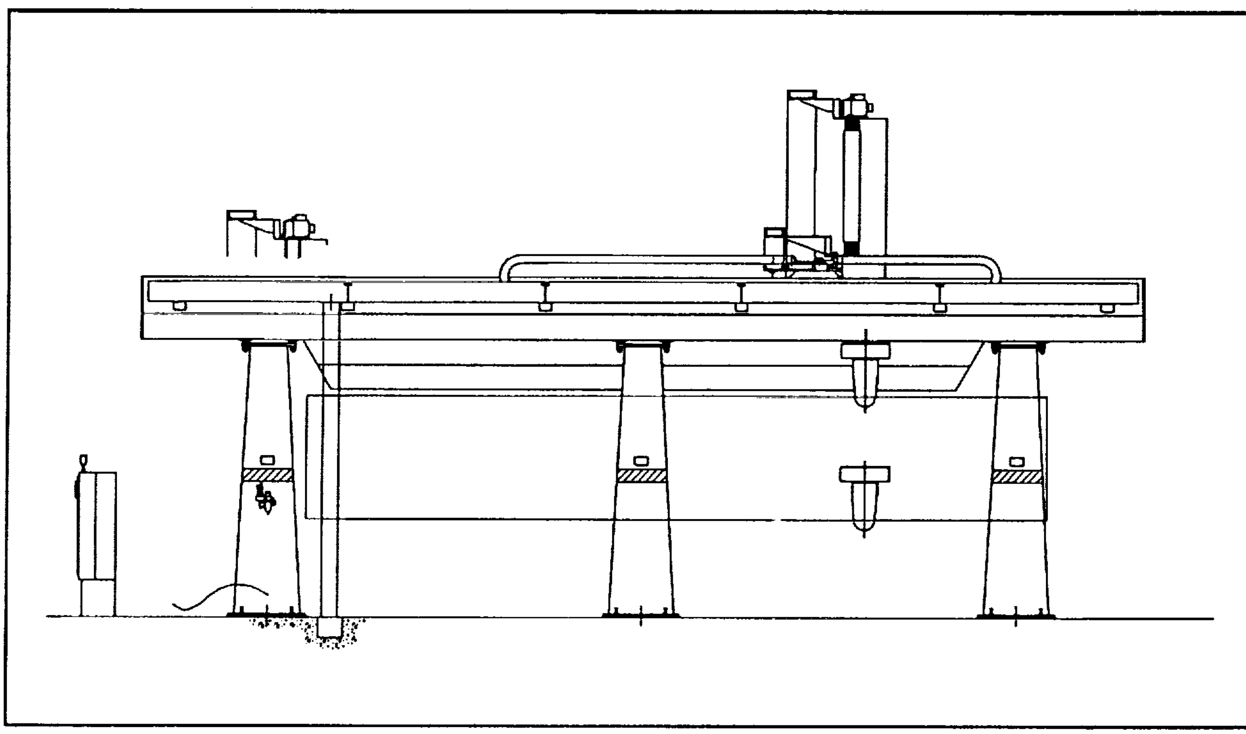


Figure 1 and 2 - AARS System Configuration

right- or a left-hand wing to be fixtured, with access to both upper and lower wing surfaces provided by the rotation capability of the design. The wing fixture design is depicted in Figures 3 and 4.

Subsystem Integration Enhancements

Enhancements to both the vision system and the defastening tool prototype were identified during the Phase One effort, as well as the desired control architecture for the serial communication protocol between robot and vision controllers. The vision system camera and light ring assembly will be mounted in tandem with the Perceptron Surface Sensor to an EOA Quickchange tool plate for compatibility with the robot wrist. This tool plate will be "pinned" by EOA so that all power and communication leads can routed directly through the wrist, enabling automated pickup and setdown by the robot.

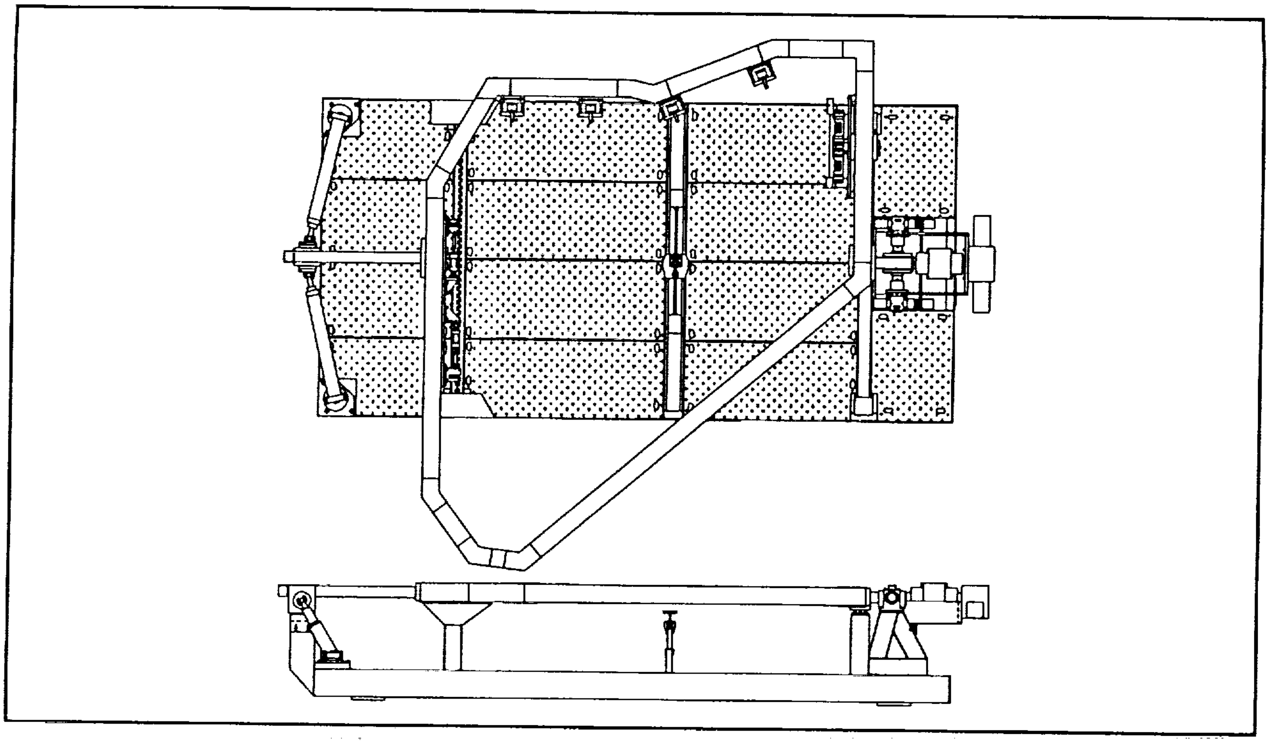
Vision system programming will also be enhanced, by customizing the inspection sequences created in Visionware with Adept's V+ line code. This additional programming will provide the vision system with a minimum level of artificial intelligence, enabling it to more optimally perform mapping operations through the automatic varying of parameters such as gray scale and binary thresholds. The system will also be able to vary it's primary search areas within the focused field-of-view automatically in order to compensate for different fastener head and hole sizes.

The level of serial communication protocol between the CIMROC and Adept controllers is being enhanced to further define and implement a more comprehensive level of post processing capability to include error handling and data validity checking. For example, the vision system and/or laser sensor will return to the robot controller process data and whether or not the data is valid. The robot controller will accept a list of parameters or data fields which will be stored within the record for archiving purposes. The validity of the data will be based on a single binary bit (0 or 1)
sent by the peripheral equipment to the CIMROC. The CIMROC will mark any data records in error and print the record number (per Air Force numbering convention) to hard copy if the validity of the data is NO. The system operator will then scan this hardcopy error list, decide the best course of action, interact directly with the peripheral equipment to alleviate the problem (ie. reprocess a vision image), rehabilitate recoverable data records, and mark those records which are irrecoverable.

Modifications are also being performed to the defastening tool prototype to incorporate enhancements identified during the Phase One effort. These enhancements primarily involve enabling the tool to utilize a two-step removal methodology for backing out the coin slot fasteners. During Phase One, some fasteners were stripped, or had the heads rounded off due to the inability to vary pressure to the large air pulse motor utilized. Tool modifications will include swapping out the stepper motor for a more powerful 2.5 hp spindle motor, and mounting a solenoid on, or very near the end effector to precisely monitor and vary pressure to the air pulse motor. Lessons learned during Phase One will also be employed so that the spindle motor will not only serve to locate the tool tip into the slot, but also as the primary backout tool. In the event that larger, or stubborn fasteners cannot be "broken free" with the spindle motor, the air pulse motor will used for very short intervals, or bursts, to breakout the fasteners.

Process Development Support

MERC is actively engaged in assisting WR-ALC personnel with preparations for the installation and optimal utilization of the AARS workcell. This support includes conducting working sessions with WR-ALC engineers and maintenance personnel which have served to help develop initial implementation procedures for the workcell. These procedures define use of the robot with both new and existing rework tooling and resources, as well as the recommended initial work volume to be scheduled using the workcell. The working sessions have also aided in the selection of qualified personnel to be trained as system operators. Additional support is being provided through recommended revisions to the F-15 wing rework Work Force Order (WFO) documentation, which will address issues including the effect that use of the workcell will have on rework flow time per wing and optimal process insertion recommendations.



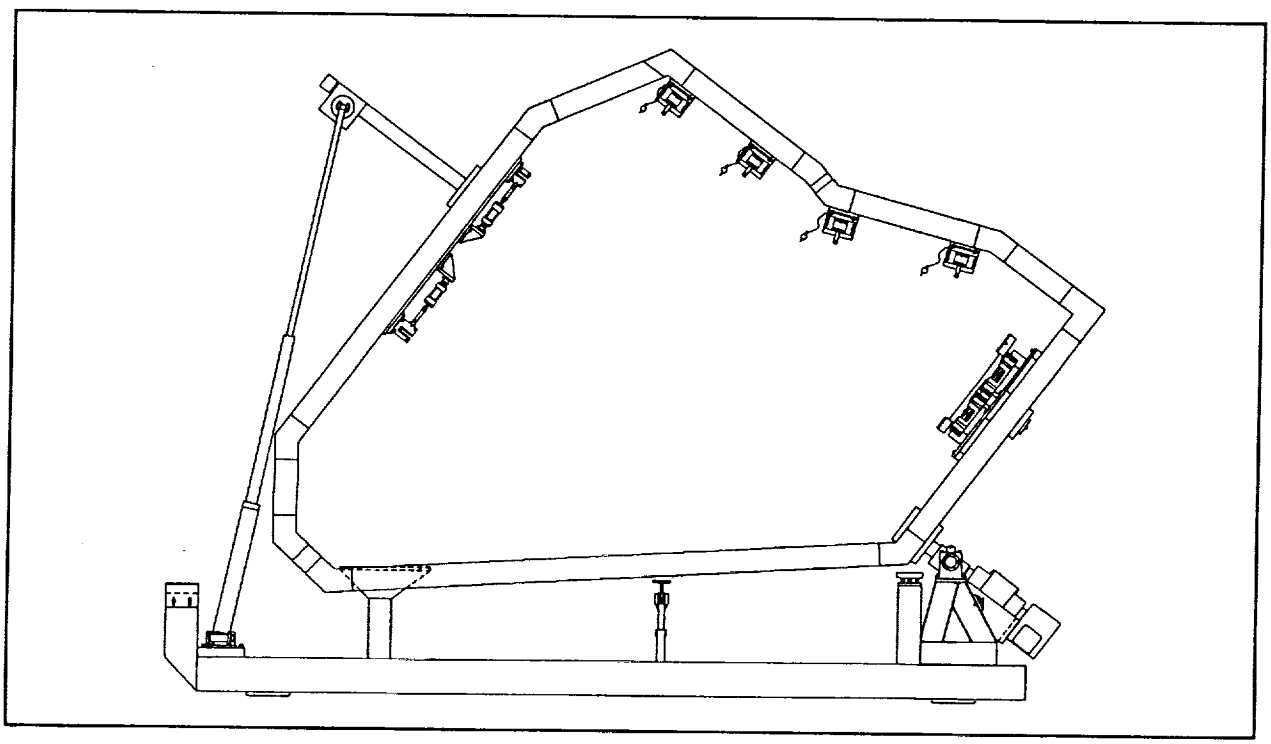


Figure 3 and 4 - AARS Wing Fixture Design

System Installation and Checkout

Workcell installation at WR-ALC will take place in June 1994. The system will be erected by MERC and PaR Systems personnel, and will undergo a procedure known as Mechanical Error Correction (MEC), during which a laser system will used to precisely align and level the robot for optimal accuracy and repeatability performance. The functionality of the robot and all peripheral equipment will then be completely verified following comprehensive qualification test procedures. Additionally, the wing fixture will be loaded with an actual F-15 wing and vision/laser mapping, defastening, and hole location/transfer trials will be conducted. At the completion of the performance trials, MERC will follow the Government approved Acceptance Test procedures and will conduct a formal Acceptance Runoff of the system for WR-ALC officials.

It is anticipated that MERC will spend the remainder of the program schedule (approximately two months) after system acceptance onsite, assisting WR-ALC maintenance personnel in familiarization with the system and its optimal use and benefit to the F-15 wing rework effort.

It is also anticipated that the AARS engineering prototype and supporting data developed during the Phase Two effort will provide sufficient information to the Air Force to support a decision to procure production configurations of this equipment.

Summary of Important Conclusions

The Air Force specified that the AARS have the capability to transfer hole locations to new structure within 0.005" of existing mate-with holes, and to maintain specified hole diameter tolerances (+0.0022"). Results achieved during the two laboratory demonstration efforts indicated a vision mapping location accuracy of +\-0.0015", and an average transfer accuracy of +\-0.0029". It was determined after remapping with the vision system that hole diameter tolerances were maintained to within +\-0.001". These results are even more encouraging when taking into account that the laboratory robot setup used is an older system lacking later generation refinements, has not undergone the MEC procedure in several years, and also is not mounted on a vibration-isolated slab.

The results of the automated defastening trials performed with the AARS indicated a 100% success rate, with all fasteners being removed through either backout or drilloff methodologies. Additionally, absolutely no damage to skin panels or substructure was incurred as a result of the defastening process. This is very important, in that a significant number of wing skin panels requiring replacement have resulted from organic rework damage, or specifically, damage incurred during manual defastening operations.

Implementation of the AARS workcell into the F-15 wing rework effort at WR-ALC will result in both significant enhancements to rework process quality and a marked reduction in required manhours. (see Figures 5 and 6) Additionally, the AARS has been designed with flexibility and future expandability in mind, and possible future applications already identified include the rework of additional F-15 and other aircraft components, automated NDI operations, and fuel foam removal operations.

Lastly, it is projected that full amortization of the total system investment costs will be realized within the first full year of operation.

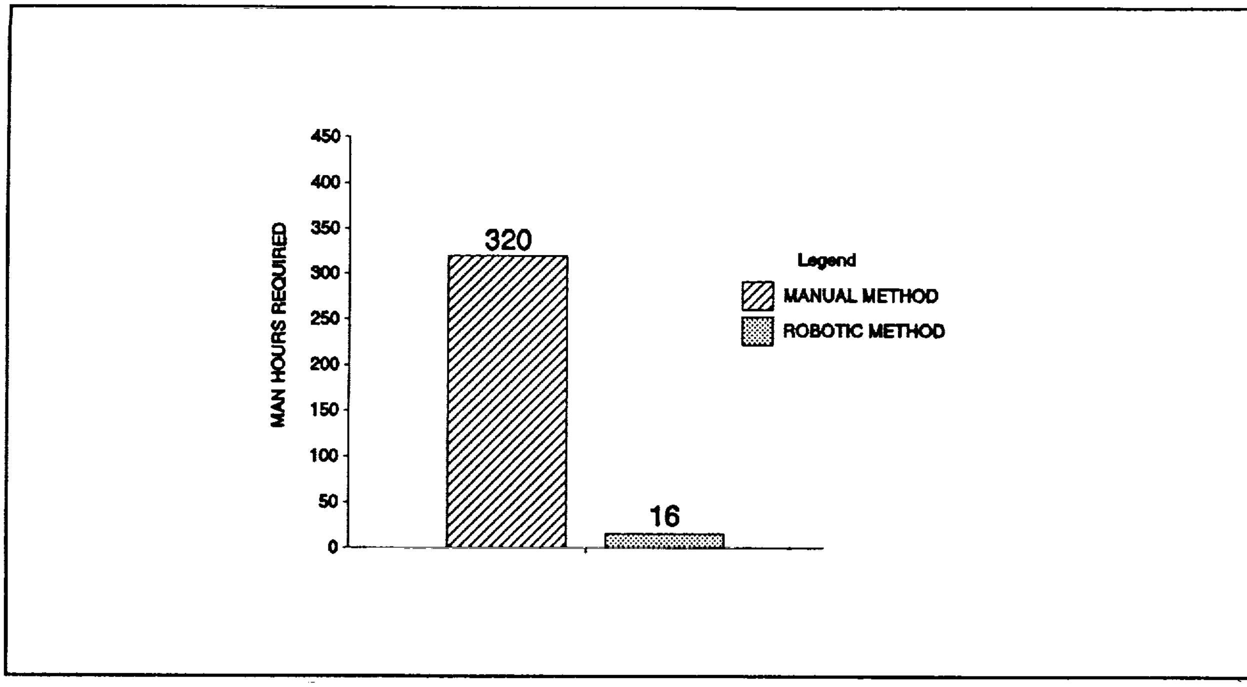


Figure 5 - Required Manhours Comparison Automated vs Manual Hole Location/Transfer

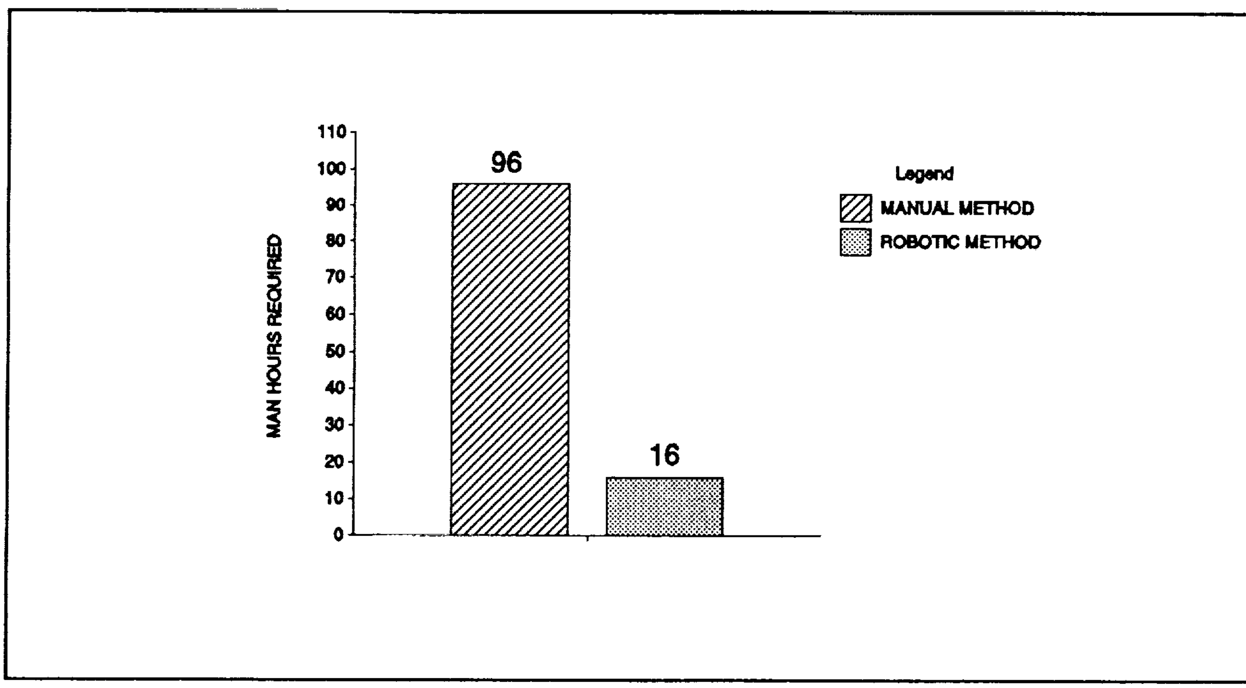


Figure 6 - Required Manhour Comparison Automated vs Manual Wing Skin Defastening