

Description

MOBILE ROBOTIC SYSTEM

Technical Field

This application relates to mobile robotic systems and, more
5 particularly, to a large mobile robotic system including a robot subsystem for delivering high pressure water to remove paint from the surface of an aircraft.

Background of the Invention

Several methods of paint removal are currently employed for large
10 aircraft, all of which are time-consuming, costly and labor-intensive. One common paint removal method is chemical stripping which typically utilizes methylene chloride based strippers which are environmentally unsound. In order to remove paint from the aircraft with a chemical stripper, a large crew of workers must first wash the aircraft to remove oil, grease and other
15 surface contamination. Components not requiring paint stripping are then removed or covered with aluminum tape before applying the chemical stripper. The chemical stripper is then either manually brushed or sprayed onto the aircraft's surface and is left for approximately 30 minutes until the paint is softened and lifts from the substrate. It should be noted that
20 chemical stripping does not generally cause substrate damage when used on aircraft constructed of metal or aluminum, but can not be used on composite structures consisting of epoxy and graphite, two materials which are being used on modern aircraft with increased frequency. After the paint has softened the excess solvent and paint is removed by the work crew
25 utilizing hard rubber scrapers, with residual solvent and paint being

removed by a water rinse. The stripping process is repeated until the chemical stripper is no longer acting to remove the paint. At that point manual scraping with wire brushes or sandpaper is used to remove the remaining paint, thereby finishing the removal process.

5 On a large aircraft chemical stripping is very labor-intensive and as a result is very time-consuming and costly.

 In addition, the chemical stripping process involves exposing the crews to potentially toxic methylene chloride based chemicals and paint dust in a closed environment, such as an aircraft hanger, for prolonged
10 periods of time. As a result, workers must wear disposable protective gearing which inhibits the workers mobility and comfort. Chemical stripping further produces large amounts of hazardous waste which must be disposed of after stripping .

 A need therefore exists for a stripping process which is reliable, non-
15 labor intensive, environmentally sound, cost-effective and which does not result in substrate damage.

 The present application provides for a mobile robotic system which is remotely operable and which delivers high pressure water to remove paint from the surface of an aircraft, without damaging the substrate.

20 Summary

 A robotic system is provided capable of stripping paint from a large aircraft and including a utility boom, a moveable transporter and robotic subsystem having a vertically extending column which interfaces with a horizontally extending arm to deliver high pressure water to the skin of the
25 aircraft.

Brief Description of the Drawings

 Various embodiments are described herein with reference to the drawings wherein:

Fig. 1 is a right side view of the robotic system of the present application in use with an aircraft;

Fig. 2 is a perspective view, partly broken away showing jacking system 20 of the transporter of the present application;

5 Fig. 3 is a right side plan view of the robotic system of the present application;

Fig. 4 is a left side plan view of the robotic system of the present application;

Fig. 5 is a rear view of the robotic system of the present application;

10 Fig. 6 is a front view of the robotic system of the present application;

Fig. 7a is an enlarged right side view showing the carriage assembly of the robotic system of the present application;

Fig. 7b is an end view taken along line 7B, 7B of Fig. 7c;

15 Fig. 7c is a front view, with robotic arm removed, showing the carriage assembly of the robotic system of the present application;

Fig. 8 shows the various degrees of freedom of the robotic system of the present application;

Fig. 9a is a right side plan view of the robotic arm with manipulator removed;

20 Fig. 9b is a side view showing the internal reinforcement of the inner robotic arm;

Fig. 9c is a side view, in partial cross section of center joint assembly of the robotic arm;

25 Fig. 9d is a top view, partially broken away of the bearing assembly of center joint assembly;

Fig. 9e is a top view illustrating the internal reinforcement of the outer robotic arm;

Fig. 10 illustrates a cross section of mapping and painting effectors;

30 Fig. 11 is a top view showing aircraft 12 and route for transporter of the robotic system of the present application;

Fig. 12 is a top view of the robotic system of the present application showing the robotic subsystem in a stowed position; and

Fig. 13 illustrates the work envelope of robotic system 10.

Detailed Description of the Preferred Embodiments

5 Referring now in specific detail to the drawings, where like reference numerals identify similar or identical elements, referring initially to Fig. 1 there is illustrated a right side view a mobile robotic system 10 according to one embodiment of the present application. As shown in Fig. 1, the robotic system 10 is preferably adapted for use with a large aircraft 12. Referring
10 now to Fig. 3, a right side view of robotic system 10 is shown. Robotic system 10 includes transporter 20, robot subsystem 30 and utility boom 40. Robot subsystem 30 further includes column 50, a selective compliant assembly robot arm (SCARA) 70, manipulator 90 and end effector 100. In the present embodiment robotic system 10 is approximately 33 ft in height,
15 not including utility boom 40 and robot arm 70 has a horizontal reach of approximately 28 feet.

In designing a robotic system a rigid mechanical structure is needed. With conventional designs this rigid, or stiff structure can be assumed to exist because the components, especially the robot arm are small in size
20 and made of rigid material. In conventional designs if an engineer desires to increase the stiffness of the robot she would simply increase the mass which would thereby increase the stiffness. When a robot reaches the size of the present embodiment stiffness can no longer be increased by simply increasing the mass of the system. Therefore, in designing the robotic
25 system of the present invention a flexible structure was assumed and this structure was made stiff by applying general engineering principles. The factors one would consider in designing a robotic system such as system 10 include: material selection, cross-sectional area, auxiliary support, the thickness of the skin and the location of the mass of the system. The final
30 configuration of the robotic system will depend upon the dimensional

configuration of the system as well as its application. Various methods can be used to test and trade off these factors including solid modeling, finite element analysis and optimization programming, which are well known to those skilled in the art. To measure the stiffness a variety of methods may be used, including measuring the natural frequency of the system which will increase as stiffness increases. These methods are also known in the art.

With continued reference to Fig. 3, transporter 20 is a high-capacity automatic guided vehicle (AGV) which is a conventional AGV that has been modified for application with robot subsystem 30. Conventional automatic guided vehicles are available from a number of suppliers, including Mentor AGV, located in Mentor, Ohio. Transporter 20 is programmed to follow a preset guide path and operates to position robot subsystem 30 at predetermined work positions around aircraft 12. Transporter 20 has a structural stiffness sufficient to provide a stable base and support for subsystem 30 while also providing transporter 20 with mobility.

Transporter 20 preferably includes a drive system (not shown), steering system (not shown) and jacking system 22 (Fig. 2). In the present embodiment the transporter drive and steering systems are conventional designs which may be adapted and modified depending upon the application requirements. The transporter drive system includes a plurality of wheels 24 which provide transporter 20 with the capability to move from one location to another around aircraft 12. Transporter 20 travels along a predetermined path following guidewires 23 placed in floor 26 around the aircraft 12 (Fig. 1). In the present embodiment transporter 20 preferably includes ten wheels, eight of the wheels are designed as load bearing casters and two of the wheels are drive wheels which include steering components. Transporter 20 may be designed with any number of wheels, as long as robot subsystem 30 is provided with adequate support and maneuverability.

The ability to turn and maneuver transporter 20 is accomplished by a transporter steering system (not shown), as is known in the art, which

preferably includes an off-board vehicle controller (not shown) that generates a reference signal into guidewires 23 which transmit the signal to separate antennas (not shown) mounted on the leading edge of each drive wheel. The antennas provide the reference amplitude signals used by the vehicle controller in commanding forward and reverse motion of transporter 20. Other steering systems including direct drive torque hubs and laser guidance vehicle controllers may alternatively be utilized with transporter 20.

Referring now to Fig. 2, jacking system 22 of transporter 20 is illustrated. Jacking system 22 is designed to provide robot subsystem 30 with a stable, level platform and as such is preferably designed according to the dimensional configurations of robot subsystem 30 along with the preferred application for subsystem 30. Jacking system 22 includes a plurality of jacks 22a which operate to raise transporter 20 off the floor thereby providing robot subsystem 30 with a level working platform. In the present embodiment jacking system 22 preferably includes four, independently driven hydraulic jacks which raise transporter 20 approximately 1/2" off the floor.

Transporter 20 is preferably made of a material such as steel, but may be constructed of any material which would allow robot subsystem 30 to be both stable and mobile. In the present embodiment the approximate combined weight of subsystem 30 and transporter 20 is about 60,000 lbs. Transporter 20 can travel at speeds up to about 75 ft/min in a straight line, with 40 ft/min being the preferred operating speed, and up to about 20 ft/min while turning, with 15-18 ft/min being the preferred turning speed in the present embodiment. The width of transporter 20 is preferably between approximately 8-12 feet, with 10 feet being the most preferred width. The overall length of the transporter is between about 18-28 feet, with approximately 23 1/2 feet being the most preferred length. The height of transporter 20 is preferably between about 2-4 feet with approximately 3 feet being the most preferred height. Since transporter 20 is designed according to the dimensional configurations of robot subsystem 30, along with the

preferred application for subsystem 30, the exact dimensional configurations of transporter 20 may vary from one robot subsystem 30 design to another and from one application to another.

5 With continuing reference to Figs. 2 and 3, transporter 20 also preferably includes a collision avoidance system (not shown). In the present embodiment the collision avoidance system preferably includes front and rear opposing bumpers 28a and 28b respectively, side edge sensors 27a, 27b and front and rear detection sensors 29a, 29b (Figs. 5-6). Bumpers 28a, b are preferably hoop-type bumpers which begin
10 approximately 2-5 inches above the floor and extend to between 10-14 inches in height. In the present embodiment bumpers 28a, b are about 3.5 inches above the floor and approximately 12 inches in height. An object contacting bumpers 28 will cause the transporter 20 to stop within approximately 4 inches of initial contact with the object, when the transporter
15 20 is traveling at a rate of about 40 ft/min.

In the present embodiment side edge sensors 27a, 27b are preferably photoelectric sensors having both transmitting and receiving capabilities. Interruption of a beam emitted from the sensors will cause the transporter 20 to stop within 4 inches of interruption when the transporter is
20 traveling at about 40 ft/min.

Referring now to Figs. 5-6 transporter detection sensors 29, 29b are preferably dual range, infra red obstacle detection sensors of a type known in the art, which can detect objects from a predetermined range. According to the present embodiment, the detection sensors are preferably configured
25 such that an object detected approximately 8 feet away from transporter 20 will cause the transporter 20 to slow down, while an object detected approximately 3 feet away will cause the transporter to come to a controlled stop. The transporter detection sensors are also preferably travel direction sensitive and are inactive when transporter 20 is stationary.

30 With continued reference to Fig. 2, robot subsystem 30 is mounted to transporter 20 by a turntable 52 which provides support for subsystem 30

while also allowing the subsystem 30 to rotate about vertical axis "A". This rotation provides the subsystem 30 with a first degree of freedom as illustrated in Fig. 8 by arrows "B" and "C". Turntable 52 includes a rotatable column mount plate 52a which is mounted to column 50 and a bearing mount structure 52b which is mounted to deck 25 of transporter 20 in any suitable manner, e.g. bolts. Turntable 52 is electrically connected to a pair of drive motors (not shown) which are housed within cover 54. The drive motors provide the power to drive turntable 52. Rotation of column mount plate 52a is mechanically accomplished by gearing (not shown), which can drive robot subsystem 30 to a rotation speed of approximately 3 rpm, with the preferred operating speed being below about 1 rpm. Although robot subsystem 30 is mounted to turntable 52 in the present embodiment, subsystem 30 may be mounted to transporter 20 in any suitable manner which would provide support for robot subsystem 30 while allowing for rotation of subsystem 30.

Referring again to Fig. 3, column 50 extends substantially vertically from transporter 20, approximately 24 - 36 feet, as measured from the interface 55 with transporter 20 to the top 56 of the column 50, with about 30 feet being the preferred height in the present embodiment. In the present embodiment column 50 is constructed of steel, but it may be constructed of any alternative material which will provide the column with structural stability, while allowing it to be mobile. Column 50 is preferably rectangular in shape and includes first and second, generally parallel, opposing sides 57a and 57b (Fig. 4) respectively, which are joined at approximately 90° to third and fourth generally parallel, opposing sides 58a (Fig. 5) and 58b (Fig. 6), respectively. In the present embodiment sides 57a, b and 58a, b are preferably joined by bolts, but may be joined or fabricated in any suitable manner.

With continuing reference to Fig. 3, mounted to first side 57a are end effector racks 59. In the present embodiment, approximately four different end effectors can be stored in these racks for use with manipulator 90. End

effector racks 59 are an optional storage element of robot subsystem 30. Also disposed on side 57a is cable carrying track 60. Utilities which are fed from the utility boom 40 are inserted through a slip ring assembly 62, through carrying track 60 and into robot arm 70. Also disposed on side 57a are access bays 1a and 6a which provide access to the lower and upper chambers (not shown) respectively, disposed within column 50. The upper chamber of column 50 houses electrical junction boxes and other connections while the lower chamber houses electrical connections to the transporter 20 and to turntable drive motors.

Referring now to Fig. 4, there is illustrated a left side view of robot subsystem 30 showing second side 57b. Side 57b preferably includes an upper access bay 6b for access to the upper chamber and a lower access bay 1b for access to the lower chamber of column 50. Side 57b further preferably includes intermediate access bays 2b, 3b, 4b and 5b disposed between upper and lower access bays 6b, 1b. Access bay 4b provides access to a chamber disposed in column 50 which contains a process controller. Access bays 2b and 3b provide access to a chamber containing robot controller which is disposed within column 50. Finally, access bay 5b provides access to a hydraulic unit for nozzle rotation disposed within column 50. The number and location of the access bays will vary depending upon the design of column 50 and the location of the various electrical connections and controls within the column.

Referring now to Fig. 5, there is illustrated a rear view of robot subsystem 30 showing third side 58a. Side 58a supports electrical wireway, conduit and pneumatic piping (none shown) to column 50. Side 58a preferably includes a cover which shields the electrical wireway, conduit and pneumatic piping from the working environment.

Referring now to Fig. 6, there is illustrated a front view of robot subsystem 30 showing fourth side 58b. Extending vertically along substantially the length of side 58b is gear rack 64. Gear rack 64 includes a plurality of gear teeth 65 which are disposed along gear rack 64. Located on

either side of gear rack 64 are bearing rails 66a, b. Gear rack 64 and bearing rails 66a, b are mounted to side 58b of column 50 in any suitable manner, e.g. bolts.

Referring now to Figs. 7a-7c, there is illustrated a carriage assembly 5 68 which includes a plate member 72, pinions 74a, b, bearing tracks 76a, b and dual direct drive motors 78a, b. Bearing rails 66a, b of column 50 interface with carriage bearing tracks 76a, b to guide carriage assembly 68 vertically along gear rack 64. Gear rack 64 meshes with pinions 74a, b in a conventional rack and pinion arrangement which is driven by the power 10 supplied by motors 78a, b through a gear reducer to move carriage assembly 68 vertically along gear rack 64. Motors 78a, b are enclosed within housing 65 as shown in Fig. 9a. As illustrated in Fig. 8 by arrows "D" and "E", vertical movement of carriage assembly 68 provides robot subsystem 30 with a second degree of freedom.

Referring again to Fig. 3 in conjunction with Fig. 7a-c, subsystem 30 15 includes rack covers 77a, b which extend over gear rack 64 and bearing rails 66a, b. Covers 77a, b protect the gear rack 64 and bearing rails 66a, b from environmental conditions which could cause damage to the rack and pinion assembly during operation. Cover 77a is attached at one end to 20 upper canister 79a and is attached at an opposing end to a first end 68a of carriage assembly 68. Cover 77b is attached at one end to lower canister 79b and is attached at an opposing end to a second end 68b of carriage assembly 68. As carriage assembly 68 moves vertically in the direction of arrow "Z" cover 77a unwinds from canister 79a and follows carriage 25 assembly 68 while cover 77b winds around canister 79b, thereby allowing gear rack 64 and bearing rails 66a, b to remain covered during movement of the carriage assembly. Likewise, as carriage assembly 68 moves vertically in the direction of arrow "Y" cover 77b unwinds from canister 79b and follows carriage assembly 68 while cover 77a winds around canister 79a, 30 thereby allowing gear rack 64 and bearing rails 66a, b to remain covered during movement.

Referring now to Figs. 9a-c, there is illustrated a side view of robot arm 70 with partial cut-aways. Robot arm 70 transports utilities and services from cable carrying track 60 (Fig. 3) to manipulator 90, provides support for manipulator 90 and selectively positions manipulator 90 about aircraft 12 (Fig. 1). Robot arm 70 includes an inner arm 80, center joint assembly 82 and an outer arm 84. Inner arm 80 is mounted to carriage assembly 68 at a first end 80a and is mounted to the center joint assembly 82 at a second end 80b. In the present embodiment inner arm 80 is approximately 25 inches in length and 25 inches in width, with a constant cross-section, and includes an internal angle reinforcement 83. Internal angle reinforcement 83 aids in providing inner arm 80 with structural stiffness. Inner arm 80 is preferably made of steel, but may be made of any material which does not appreciably reduce the natural frequency of robot subsystem 30 and which has the structural stiffness to support and position manipulator 90 within the parameters of the particular application. In the present embodiment inner arm 80 weighs approximately 1200 lbs, center joint assembly 82 weighs approximately 1100 lbs, outer arm weighs approximately 400 lbs and manipulator 90 weighs approximately 860 lbs.

With continued reference to Figs. 9a-c, center joint assembly 82 includes an upper fitting assembly 82a, a lower fitting assembly 82b and a middle joint assembly 82c. In the present embodiment upper fitting assembly 82a is mounted at one end to inner arm 80. Likewise, lower fitting assembly 82b is mounted at one end to outer arm 84. Upper and Lower fitting assemblies 82a, b are preferably attached to inner and outer arms 80, 84 respectively, by bolts. Upper and Lower fitting assemblies may alternatively be attached in any manner which would provide a sufficient structural stiffness to support outer arm 84, manipulator 90 and end effector 100 while maintaining the operational parameters for the given application.

Referring now to Fig. 9c in conjunction with Fig. 9d, upper fitting assembly 82a is connected at a second end to middle joint assembly 82c, likewise lower fitting assembly 82b is connected at a second end to middle

joint assembly 82c. Upper fitting assembly 82a is connected to bearing 86 of middle joint assembly 82c. In the present embodiment, bearing 86 includes a plurality of gear teeth 86a which meshingly engage pinions 88 in a conventional arrangement that is driven by the power supplied by direct drive motors (not shown) through a gear reducer (not shown) to provide rotation to lower fitting assembly 82b and outer arm 84. As illustrated in Fig. 8 by arrows "F" and "G", rotation of outer arm 84 provides robot subsystem 30 with a third degree of freedom.

Referring now to Figs. 9a-9e, outer arm 84 is mounted at one end to middle joint assembly 82 and is connected at an opposing end to manipulator mount 88. In the present embodiment outer arm 84 is approximately 20 inches in length and 20 inches in width, with a constant cross-section, and includes an internal angle reinforcement 89. Internal angle reinforcement 89 aids in providing outer arm 84 with structural stiffness. Outer arm 84 is preferably made of steel, but may be made of any material which does not appreciably reduce the natural frequency of robot subsystem 30 and which has the structural stiffness to support and position manipulator 90 within the parameters of the particular application. In the present embodiment outer arm 84 weighs approximately 400 lbs.

With continuing reference to Fig. 9a, manipulator 90 is rotatably mounted to robot arm 70 via manipulator mount 92. Manipulator mount 92 includes gearing (not shown) to provide robot subsystem 30 with a fourth degree of freedom as illustrated in Fig. 8 by arrows "H" and "I". Manipulator 90 utilizes conventional manipulator technology but is specifically designed for aircraft stripping/painting applications. Manipulator 90 is available from GMFanuc Robotics and is designed for electrical use in Class I Division I at temperatures between 33 - 109 degrees Fahrenheit. In the present embodiment manipulator 90 has a payload capacity of approximately 75 lbs plus 50 lbs of back thrust. Manipulator 90 also includes a large capacity hollow wrist 94 and outer arm 96 for process line routing to end effector 100. In the present embodiment manipulator 90 preferably includes an elbow 98

which is double jointed and a multiple turn faceplate 93. Elbow 98 and manipulator faceplate 93 provide manipulator 90 with six degrees of freedom, as illustrated in Fig. 8 by arrows "J, K"; "L,M" and "N,O"; "P, Q"; "R, S", respectively. Manipulator 90 can reach below the base of transporter 20 and can extend vertically approximately 30 feet which enables robotic system 10 to easily reach aircraft wings and fuselage.

Referring now to Fig. 10, there is illustrated mapping and paint removal end effectors 102 and 104, respectively. Both mount to a manipulator face plate 93 through a quick change interface system. In the present embodiment, the mapping end effector maps the surface of aircraft 12 for input into a controller (not shown) and transmission to robot system 10. Mapping end effector 102 consists of a laser contour sensor which returns a range measurement from a line equation produced by the intersection of the beam and the aircraft surface. In the present embodiment the paint removal end effector 104 consists of a high pressure water quick change, rotary swivel housing and nozzle. Depending upon the application, a variety of end effectors can be designed for use with robotic system 10.

Referring again to Fig. 1, robotic system 10 further includes utility boom 40. Utility boom 40 routes utilities from the roof 42 of the hangar enclosing aircraft 12 to the robotic subsystem 30. In the present embodiment boom 40 is supported at three points, the facility center swivel 44, the monorail attach point 46 and the top of the column 56. Boom 40 is not a controlled degree of freedom, but acts as a slave, following robot subsystem 30 from position to position about aircraft 12 along a monorail 48. In the present embodiment boom 40 carries high pressure water, electrical power, control and data lines and air and vacuum lines.

The operation of robotic system 10 will now be described. Robotic system 10 may be used in a variety of applications. One such application is as a paint removal system for use on large aircrafts as depicted in Fig. 1. Aircraft paint removal system consists of robot system 10 which interfaces with a computer subsystem, a sensor subsystem, a guidance subsystem, a

paint removal subsystem and facility subsystem (none shown). The computer subsystem includes operator's station access terminals and peripheral devices. The system operator interfaces primarily through the operator's terminal. Most computer equipment is located in an operator's control room and adjacent computer room. The sensor subsystem includes the process controller, which monitors the stripping pressure and nozzle rotation rate.

Prior to stripping aircraft 12, mapping end effector maps the surface of aircraft 12 for input into a controller (not shown). Guidewires 23 are then placed in floor 26 around aircraft 12 corresponding to the path transporter 20 will follow (Fig. 11). Utilities are routed through boom 40 as described hereinabove, and transporter 20 is positioned over guidewires 23. The transporter can stow in any of four quadrants as depicted in Fig. 12 which allows for optimum flexibility in movement of the transporter from position to position around the aircraft 12, especially through limited clearance areas between the aircraft and facility. After transporter 20 is placed in its starting location, robot arm 70 is extended to a predetermined position. Stripping is now ready to commence.

Robot system 10 delivers high pressure water above approximately 20,000 psi to the aircraft surface to commence stripping of aircraft 12. Robot system 10 will strip one area and then transporter 20 will travel to a second predetermined position, stop, jack to a level platform and continue to strip, as described hereinabove. In the present embodiment robot system 10 has a static repeatability of approximately plus or minus 0.010 inches, 3 sigma with a 100lb payload. The dynamic straight line repeatability of robot system 10 of the present embodiment is approximately plus or minus 0.1 inches at 15 inches/second with a 24 lb payload and 0.030 at 2 inches/second with 100 lb payload. Static Repeatability is the amount of error or deviation resulting from a device (in this case a robot) moving to a single fixed static location. In the robotic industry, this is usually measured at maximum payload and at maximum approach speed.

Straight Line Dynamic Repeatability is the amount of error or deviation resulting from a device (in this case a robot) moving along a straight line path (trajectory). This error has two components; straight line error and location error. This error will be correlated to the robot's velocity. The work envelope of system 10 is shown in Fig. 13.

Robotic system 10 and its operation is described in a paper entitled "The Large Aircraft Robotic Paint Stripping (LARPS) System" which is herein incorporated by reference.

It will be understood that various modifications may be made to the embodiments disclosed herein. For example, robotic system 10 may be used in a variety of applications, e.g. applying paint to an aircraft. Therefore, the above description should not be construed as limiting, but merely as exemplifications of preferred embodiments. Those skilled in the art will envision other modifications within the scope and spirit of the claims appended hereto.



Claims

1. A mobile robotic system having nine degrees of freedom including:

a) a transporter having a jacking system;

5 b) a column extending substantially vertically from the transporter;

c) a robotic arm extending substantially horizontally from the column and having a horizontal reach of at least 15 feet; and

d) a utility boom for transporting utilities to the robotic arm;
10 wherein the robotic system delivers high pressure water above approximately 15,000 psi to the surface of the aircraft to strip paint therefrom.