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(54) Title: ROBOTIC SYSTEM INCLUDING FOLDABLE ROBOTIC ARM

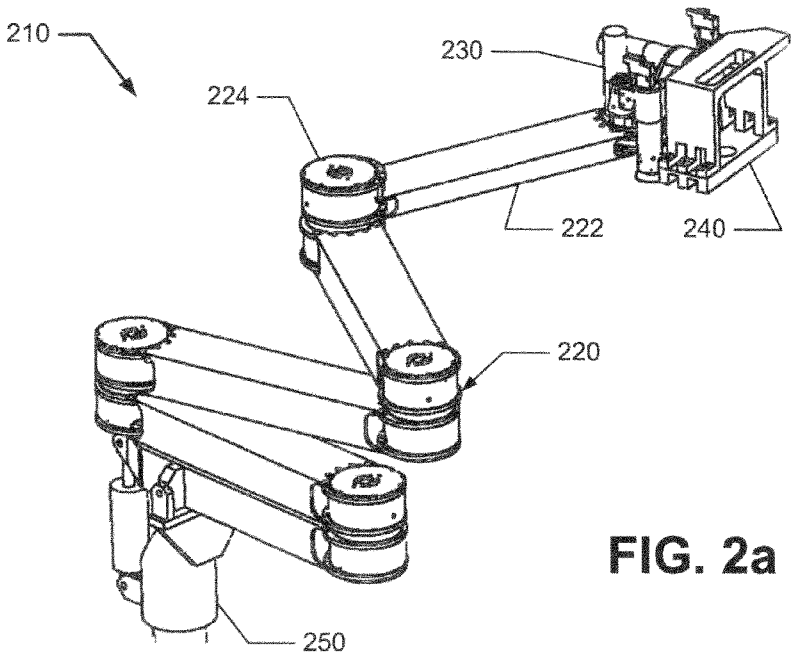


FIG. 2a

(57) Abstract: A system includes an end effector (110), a robotic wrist (120) for orienting the end effector (110); and a robotic arm (130) for positioning the end effector. The robotic arm (130) is foldable into a stack. The robotic wrist (120) is mounted to a last link of the robotic arm.

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ROBOTIC SYSTEM INCLUDING FOLDABLE ROBOTIC ARM

BACKGROUND

There is a need for a robotic system that can precisely position an end effector against a work surface within a confined work space. There is also a need for the robotic system to maneuver the end effector past an access port and into the confined work space.

SUMMARY

In one embodiment, a system includes an end effector, a robotic wrist for orienting the end effector; and a robotic arm that is foldable into a stack. The robotic wrist is mounted to a last link of the robotic arm.

In another embodiment, a system includes a robotic arm having multiple links and a parallel-axis joint layout such that the links can be folded into a compact configuration with links stacked on top of each other. The system further includes a robotic wrist mounted to a last link of the robotic arm, and an end effector mounted to the robotic wrist. The robotic arm is used to position the end effector, and the robotic wrist is used to orient the end effector.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure **1** is a block diagram of a robotic system.

Figures **2a** and **2b** are illustrations of an embodiment of a robotic system.

Figure **3** is an illustration of an end effector and a robotic wrist.

Figure **4** is an illustration of a structure having a confined work space and an access port to the confined work space.

Figure **5** is an illustration of a method of using the robotic system of Figures **2a** and **2b**.

DETAILED DESCRIPTION

Reference is made to Figure **1**, which illustrates a robotic system **100**. The system **100** includes an end effector **110**. The design of the end effector **110** depends on the task for which it is intended. For example, the end effector may be designed to support tooling for inspection (e.g., with cameras or other sensors), cutting operations (e.g., drilling, punching or milling), fastening operations (e.g., with rivets or screws), or other assembly operations.

The system **100** also includes a robotic wrist **120** for orienting the end effector **110**. The robotic wrist **120** is not limited to any particular type. The range of motion and degrees of freedom in the wrist **120** is determined by how many orientations the different work surfaces

have. As but one example, a spherical wrist having three degrees of freedom may be used to orient the end effector **110**.

The system **100** further includes a robotic arm **130** having a plurality of links that are foldable into a stack. The robotic arm **130** may be a SCARA-type arm having multiple links and a parallel-axis joint layout (the acronym SCARA refers to a Selective Compliant Articulated Robot Arm). These joint axes may be nominally parallel to the gravity vector, thereby minimizing gravitational torques on the joints. The multiple links can be folded into a compact configuration with links stacked on top of each other.

The robotic arm **130** positions the end effector **110**. The wrist **120** allows the end effector **110** to reach orientations that the robotic arm **130** might not be able to reach on its own.

The system **100** may further include an external apparatus **140** for positioning, lifting and tilting the base of the arm **130**. The apparatus **140** has particular utility for a structure having a confined work space and an access port that leads to the work space. The apparatus **140** can maneuver the folded arm **130** through the access port and into the confined work space. For example, the apparatus **140** may include a base having three degrees of freedom for translating the arm **130** along a vertical axis (that is, adjusting the height of the arm **130**), rotating the arm **130** about the vertical axis, and pitching to swing the entire **130** arm up and down. Once within the work space, the arm **130** can be unfolded and used to position the end effector **110** against a work surface within the work space.

Additionally, the robotic system **100** may ride on a carriage assembly **150**. The carriage assembly may be used to move the system **100** along a floor to locate the system **100** with respect to the access port.

Reference is now made to Figure **2a**, which illustrates an example of a robotic system **210**. The robotic system **210** includes a robotic arm **220** having a plurality of links **222** connected by joints **224**. The joints **224** are oriented with parallel axes. Although five links **222** of equal length are illustrated in Figure **2a**, a robotic arm described herein is not so limited.

The joints **224** may include bearings and actuators (e.g., electric motors) for folding and unfolding the arm **220**. These joint axes may be nominally parallel to the gravity vector. Such an arrangement of joints can minimize gravitational torques on the joints **224**. If all of the main load bearing joints are parallel to gravity, the actuator size and power requirements drop sharply.

The robotic system **210** further includes a robotic wrist **230** and an end effector **240**. The robotic wrist **230** is mounted to the end of the last link. An actuator system **250** for positioning, lifting and tilting and the robotic arm **220** is also shown.

Reference is now made to Figure **2b**, which illustrates the robotic arm **210** in a compact configuration with its links **222** stacked on top of each other. The configuration of links **222** illustrated in Figure **2b** is referred to as a "coextensive stack." Figure **2b** also shows the robotic wrist **230** oriented so it and the end effector **240** are in a stowed position on the last link, making the robotic system **210** even more compact.

Reference is made to Figure **3**, which illustrates an example of an end effector **300** and a robotic wrist **310**. The robotic wrist **310** mimics the kinematics of a spherical wrist having three degrees of freedom. The wrist **310** includes first, second and third revolute joints **320**, **330** and **340** for controlling pitch, yaw and roll of the end effector **300**.

The third revolute joint **340** allows the end effector **300** to be rotated about a B-axis. The B-axis passes near the middle of the end effector **300** to minimize the volume swept by the end effector **300** as the third joint **340** rotates.

The second revolute joint **330** allows the end effector **300** to revolve about an A-axis. The first revolute joint **320** allows the end effector **300** to revolve about a C-axis.

The three axes intersect at a common point (i.e., an epicenter) CP, which eliminates any axis offset. Having all three axes intersecting simplifies the kinematic calculations, increases compactness and reduces the complexity of controls.

The wrist **310** further includes motors **325**, **335** and **345** for driving the end effector **300** with respect to the A, B and C axes. The motors **325**, **335** and **345** may be brush-type gear motors having built-in gearing such as planetary gear reducers. Placing such motors **325**, **335** and **345** in the wrist **310** allows for greater modularity and serviceability of the entire robotic system. The wrist **310** is modular and self-contained. To install or remove the wrist, it need only be attached to or detached from the last link **305** of the robotic arm.

Two fine positioner modules **350** may be mounted to opposite sides of the end effector **300**. The fine positioner modules **350** perform fine adjustment of the end effector **300**. The length and number of links in the robotic arm can affect stiffness and positioning accuracy. The fine positioning is performed to correct for position errors of the X-Y(-Z) position of the end effector **300**. Orientation errors in the wrist can also induce some position error at the end effector **300**. The fine positioning can also correct for such position error. Embodiments of the fine positioner modules **350** are disclosed in U.S. Serial No. 12/119,513 filed May 13, 2008, which is incorporated herein by reference.

A robotic system described herein is not limited to any particular application. However, it is especially useful for maneuvering an end effector through an access port of a structure and

into a confined space.

Figure **4** is an illustration of a structure **410** having a confined space and an access port **420** to the confined space. For example, dimensions of a small confined space might be 1'x3'x3' while the dimensions for a large confined space might be 3'x10'x4'. Dimensions of the access port **420** to both spaces might be 9"x18".

Reference is now made to Figure **5**, which illustrates a method of positioning an end effector over a target within the confined space. For example, the method can be used to position a tool center point of an end effector with respect to a hole in a work surface.

At block **510**, the robotic arm is folded so that the links are compactly stacked on top of each other. In addition, the robotic wrist may be oriented so it and the end effector are stowed on the last link of the folded robotic arm. As such, the folded arm is compact enough to move though an access port.

At block **520**, the folded arm is maneuvered through the access port and into the confined space. For example, the folded arm can be positioned horizontally, lifted and tilted. The arm carries the robotic wrist, fine positioner modules, and end effector inside the confined space.

At block **530**, the robotic arm is at least partly unfolded once inside the confined space. Depending on the geometry of the confined space, some or all of the links may be extended.

At block **540**, the robotic arm is used for coarse x-y-z positioning of the end effector with respect to a work surface, and the robotic wrist is used to place the end effector in a proper orientation. The coarse positioning may be based on measured joint angles and geometry of the arm, along with knowledge of the location and orientation of the target in space. An open loop control can determine the joint angles that place the end effector in the desired position and orientation. With knowledge of the confined space, and knowledge of the configuration and location of the robotic system, the control can predict the location of the end effector in the confined space, within the limits of component accuracy, backlash and rigidity, and servocontrol errors. Various calibration procedures may be implemented to minimize some of these errors. At the end of the coarse positioning, the end effector is coarsely positioned on the work surface, near its target position.

At block **550**, the fine positioner modules adjust the position of the end effector to correct for remaining positioning errors. In some embodiments, fine control of the position of the end effector uses an image of the work surface to locate a target. Once the target has been located, the fine positioning process is invoked to move the tooling center over the target. The

fine positioner modules move the end effector by momentarily breaking contact between the end effector and the work surface, while moving the end effector along the work surface. Contact members of multiple end effectors may be moved synchronously to achieve and maintain fine positioning of the end effector along the work surface. To achieve synchronous motion, the fine positioner modules may receive commands simultaneously and a generate paths locally on a precision clock.

CLAIMS

1. A system comprising:
an end effector;
a robotic wrist for orienting the end effector; and
a robotic arm for positioning the end effector, the robotic arm being foldable into a stack, the robotic wrist mounted to a last link of the robotic arm.

2. The system of claim 1, wherein the arm includes multiple links and a parallel-axis joint layout such that the links can be folded into a compact configuration with links stacked on top of each other.

3. The system of claim 2, wherein the robotic arm is foldable into a coextensive stack.

4. The system of claim 2, wherein the robotic wrist and end effector are in a stowable position on the last link of the robotic arm.

5. The system of claim 1, further comprising means for positioning, lifting and tilting the robotic arm to fit through an access port.

6. The system of claim 5, further comprising a carriage assembly for moving the system to the access port.

7. The system of claim 1, wherein the wrist allows the end effector to reach orientations that the arm cannot reach on its own.

8. The system of claim 1, wherein the robotic wrist mimics a spherical wrist having three degrees of freedom; and wherein all rotational axes of the wrist intersect at a common point.

9. The system of claim 1, further comprising at least one fine positioner module attached to the end effector for performing fine adjustment of the end effector.

10. The system of claim 9, wherein each fine positioner module includes:
a contact member for making contact with a work surface
a position adjustor for causing the contact member to move the end effector along the work surface; and
an actuator for relieving pressure of the end effector against the work surface while the

contact member is used to move the end effector along the work surface.

11. A method of operating the robotic system of claim 1 to position the end effector within a structure having a confined space, comprising:

folding the robotic arm such that its links are stacked on top of each other;

maneuvering the folded arm through an access port to the confined space;

at least partially unfolding the arm within the confined space; and

using the arm to position the end effector over a target within the confined space.

12. The method of claim 12, further comprising stowing the robotic wrist and end effector on a last link of the folded robotic arm.

13. A system comprising:

a robotic arm having multiple links and a parallel-axis joint layout such that the links can be folded into a compact configuration with links stacked on top of each other;

a robotic wrist mounted to a last link of the robotic arm; and

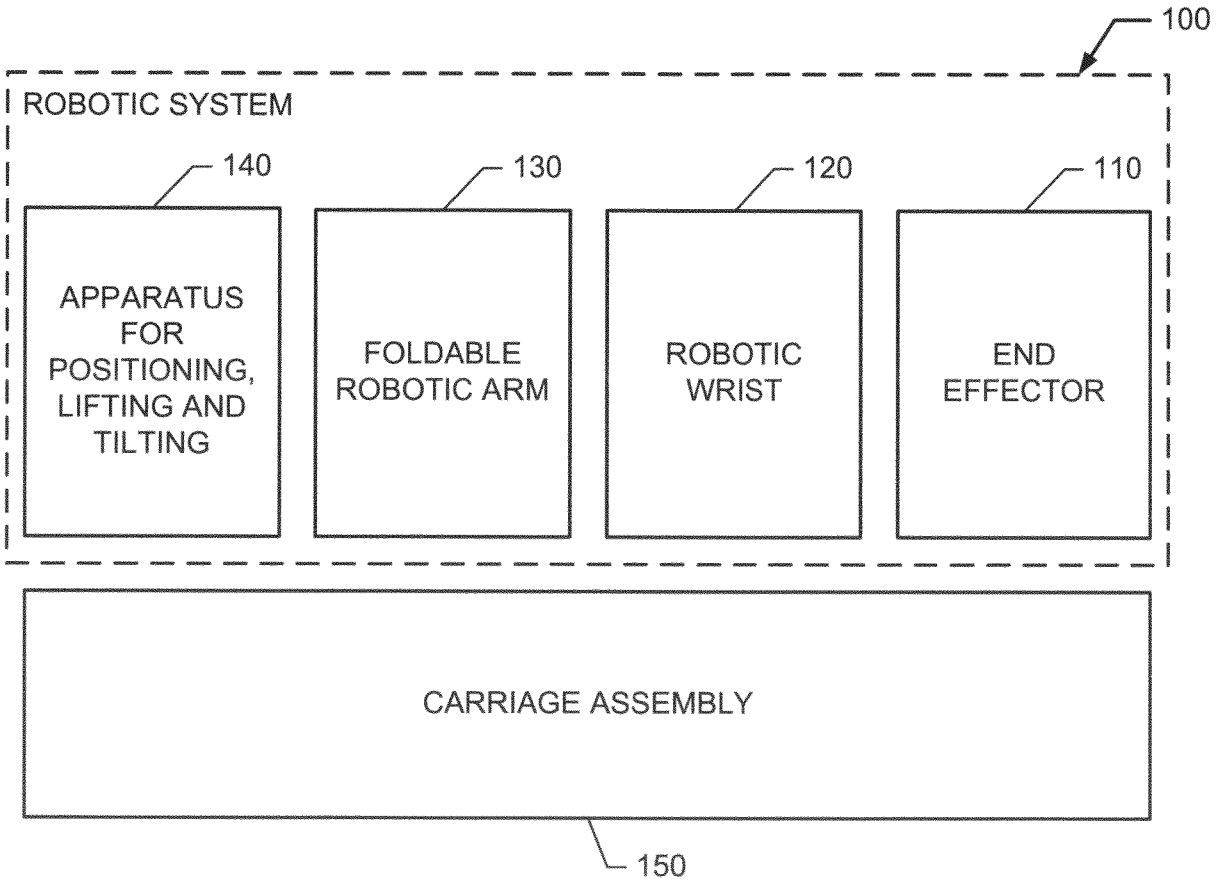
an end effector mounted to the robotic wrist;

the robotic arm for positioning the end effector, the robotic wrist for orienting the end effector.

14. The system of claim 13, wherein the robotic wrist mimics a spherical wrist having three degrees of freedom; and wherein all rotational axes of the wrist intersect at a common point.

15. The system of claim 13, further comprising at least one fine positioner module attached to the end effector for performing fine adjustment of the end effector.

FIG. 1


100
ROBOTIC SYSTEM
140
130
120
110
APPARATUS FOR POSITIONING, LIFTING AND TILTING
FOLDABLE ROBOTIC ARM
ROBOTIC WRIST
END EFFECTOR
CARRIAGE ASSEMBLY
150

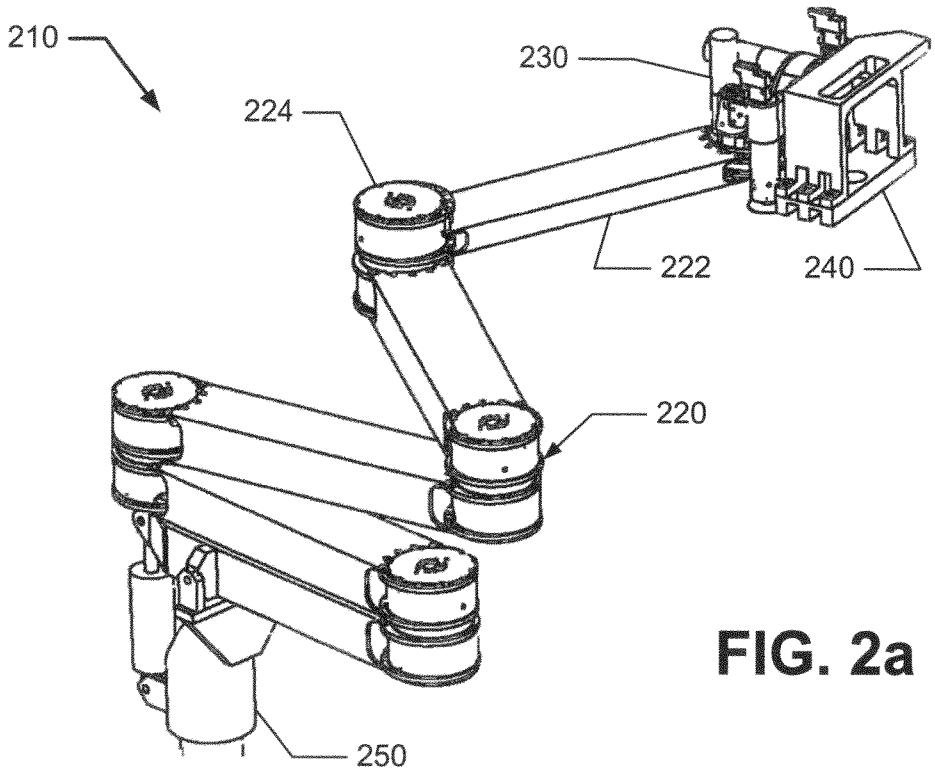


FIG. 2a

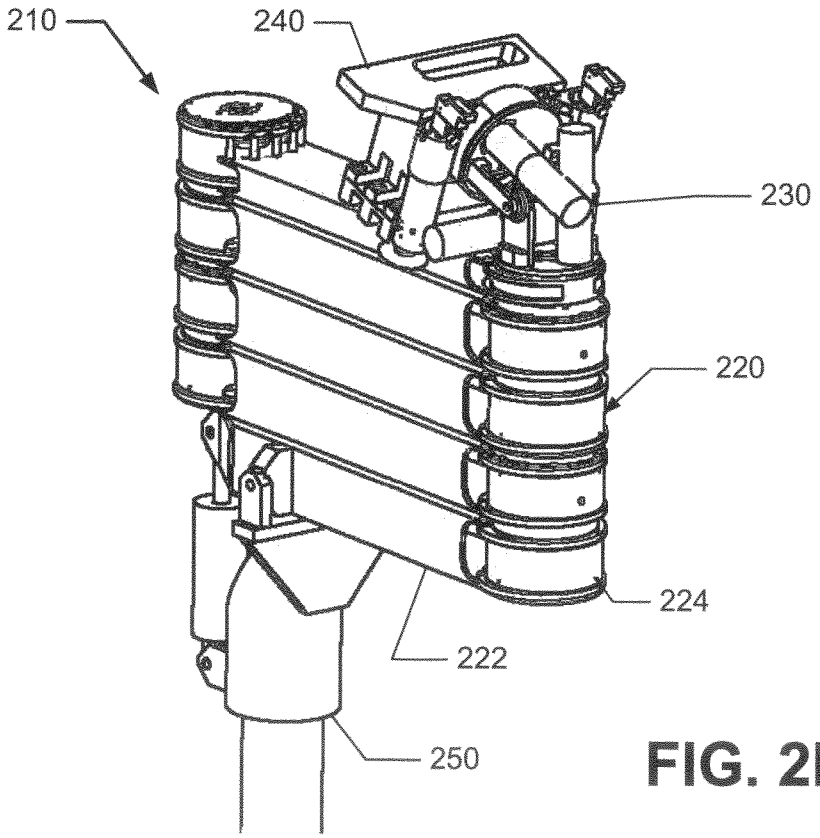


FIG. 2b

FIG. 3

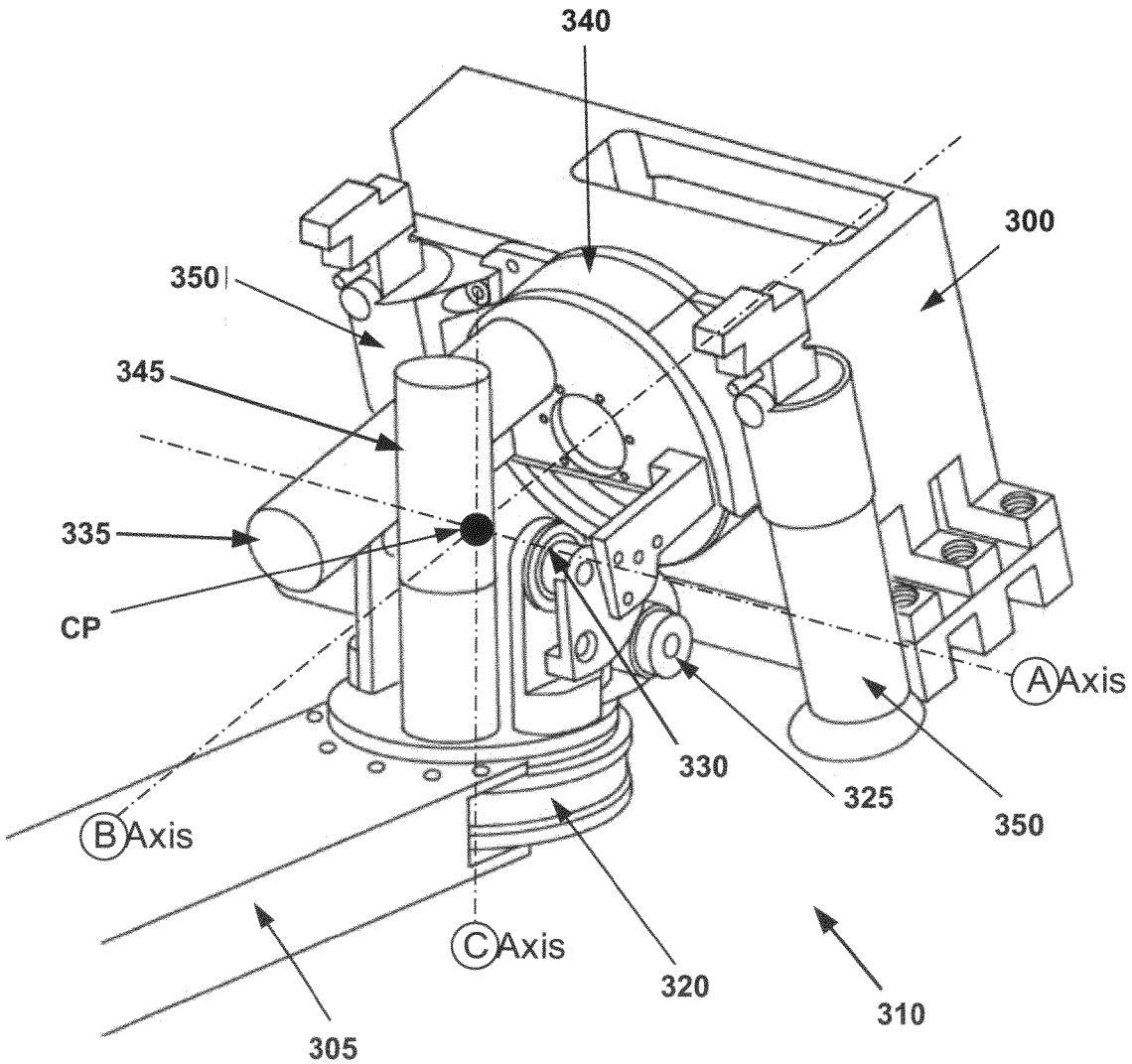

340
300
350
345
335
CP
A Axis
330
325
350
B Axis
C Axis
320
310
305

FIG. 4

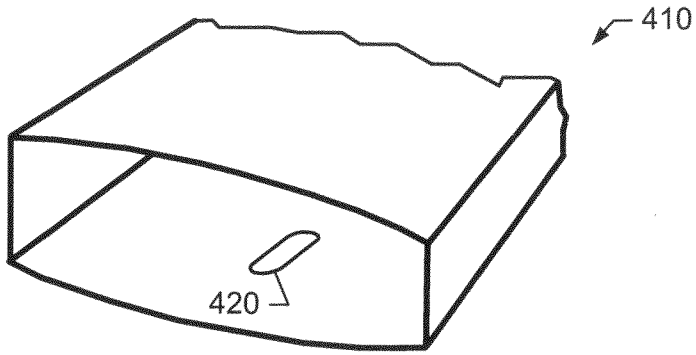
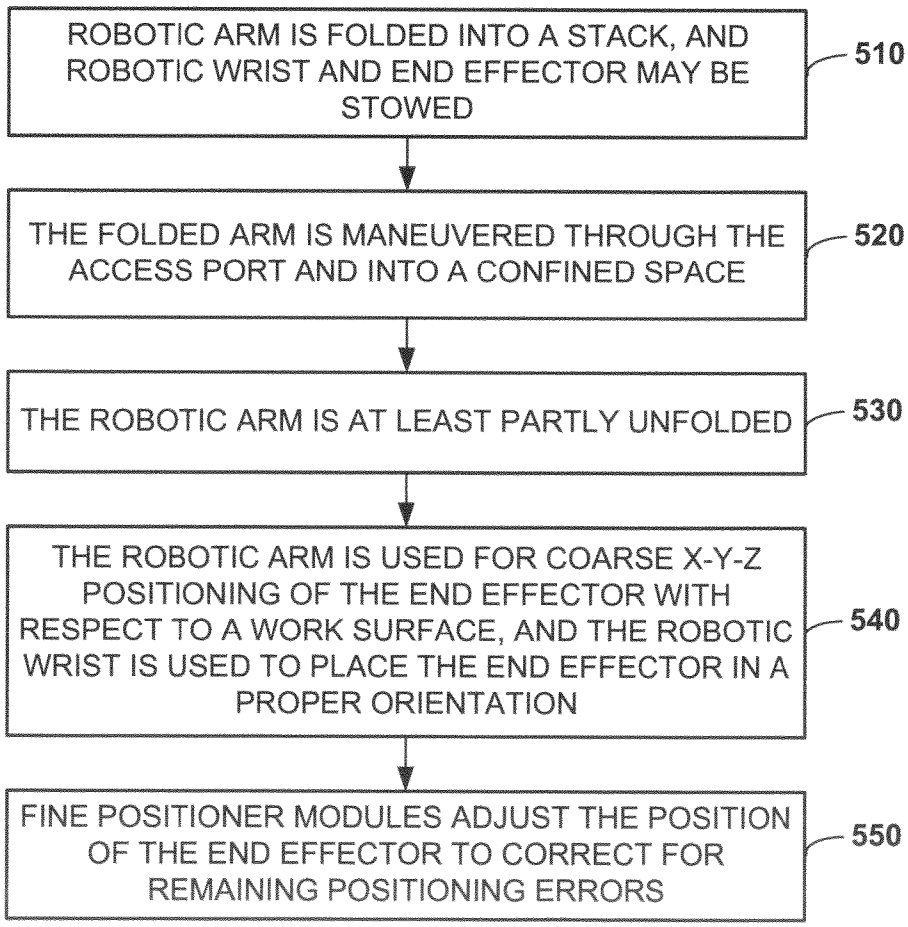

410
420

FIG. 5


ROBOTIC ARM IS FOLDED INTO A STACK, AND ROBOTIC WRIST AND END EFFECTOR MAY BE STOWED
510
THE FOLDED ARM IS MANEUVERED THROUGH THE ACCESS PORT AND INTO A CONFINED SPACE
520
THE ROBOTIC ARM IS AT LEAST PARTLY UNFOLDED
530
THE ROBOTIC ARM IS USED FOR COARSE X-Y-Z POSITIONING OF THE END EFFECTOR WITH RESPECT TO A WORK SURFACE, AND THE ROBOTIC WRIST IS USED TO PLACE THE END EFFECTOR IN A PROPER ORIENTATION
540
FINE POSITIONER MODULES ADJUST THE POSITION OF THE END EFFECTOR TO CORRECT FOR REMAINING POSITIONING ERRORS
550

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/044032

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J9/04 B25J9/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JASON GEIST, HOWIE CHOSET, BRANKO SARH, BEN BROWN: "The Development of an Adaptive Jacobian Method for Dynamic Constraint Handling in Inverse Kinematics" PROCEEDINGS OF CMU MECHANICAL ENGINEERING DEPARTMENT BENNETT TECHNICAL CONFERENCE, [Online] 21 April 2006 (2006-04-21), XP002535525 Pittsburgh, USA Retrieved from the Internet: URL:http://www.cs.cmu.edu/{biorobotics//projects/wing/Bennet_Paper.pdf> [retrieved on 2009-07-06]	1-3,5,7, 9,11,13, 15
Y	abstract; figure 7 page 5, right-hand column, paragraph 3 - page 6, right-hand column, paragraph 2	4,6,12

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 July 2009	20/07/2009

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lumineau, Stéphane

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/044032

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	JP 09 309083 A (KOKUSAI ELECTRIC CO LTD) 2 December 1997 (1997-12-02) abstract; figures 1,6,7,8	1 4,12
X Y	BINAYAK ROY, HARRY ASADA: "Design of a Reconfigurable Robot Arm for Assembly Operations inside an Aircraft Wing-Box" ROBOTICS AND AUTOMATION, 2005. PROCEEDINGS OF THE 2005 IEEE INTERNATIONAL CONFERENCE ON BARCELONA, SPAIN 18-22 APRIL 2005, PISCATAWAY, NJ, USA,IEEE, 18 April 2005 (2005-04-18), pages 590-595, XP010872144 ISBN: 978-0-7803-8914-4 abstract; figures 1,3,8a-8d,9,12 page 591, left-hand column, last paragraph - right-hand column, paragraph 2	1,5 6
A	JP 2002 137181 A (TEN AROOZU KK) 14 May 2002 (2002-05-14) abstract; figures 2,3,4	1-15
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2009/044032

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