



US008989898B2

(12) **United States Patent**  
**DeVlieg**

(10) **Patent No.:** **US 8,989,898 B2**  
(45) **Date of Patent:** **Mar. 24, 2015**

(54) **ROBOTIC MANUFACTURING SYSTEM WITH ACCURATE CONTROL**

(75) Inventor: **Russell C. DeVlieg**, Woodinville, WA (US)

(73) Assignee: **Electroimpact, Inc.**, Mukilteo, WA (US)

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 159 days.

(21) Appl. No.: **12/603,851**

(22) Filed: **Oct. 22, 2009**

(65) **Prior Publication Data**

US 2011/0098852 A1 Apr. 28, 2011

(51) **Int. Cl.**  
**G06F 19/00** (2011.01)  
**B25J 13/08** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **B25J 13/088** (2013.01)  
USPC ..... **700/245**; 700/254; 700/258; 700/260;  
700/261; 318/560; 318/568.11; 318/568.16;  
318/568.17; 318/568.21

(58) **Field of Classification Search**  
USPC ..... 700/245, 254, 258, 260, 261; 900/9, 14,  
900/15; 318/560, 566, 568.11, 568.16,  
318/568.17, 568.21  
See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

3,661,051	A *	5/1972	Dunne et al. ....	700/245
4,260,941	A *	4/1981	Engelberger et al. ....	318/568.2
4,433,382	A *	2/1984	Cunningham et al. ....	700/192
4,631,689	A *	12/1986	Arimura et al. ....	700/245
5,155,423	A *	10/1992	Karlen et al. ....	318/568.11

5,373,221	A *	12/1994	McGee et al. ....	318/568.11
5,380,978	A *	1/1995	Pryor .....	219/121.64
5,410,944	A *	5/1995	Cushman .....	91/520
5,581,166	A *	12/1996	Eismann et al. ....	318/568.22
6,037,733	A *	3/2000	Genov et al. ....	318/568.11
6,121,743	A *	9/2000	Genov et al. ....	318/568.11
6,258,007	B1 *	7/2001	Kristjansson .....	477/7
6,278,902	B1 *	8/2001	Hashimoto et al. ....	700/245
6,347,259	B1 *	2/2002	Goldenberg et al. ....	700/218
6,489,741	B1 *	12/2002	Genov et al. ....	318/561
6,519,860	B1 *	2/2003	Bieg et al. ....	33/503
6,668,466	B1 *	12/2003	Bieg et al. ....	33/503
6,845,295	B2 *	1/2005	Cheng et al. ....	700/245
6,919,701	B2 *	7/2005	Nagata et al. ....	318/568.12
7,184,858	B2 *	2/2007	Okazaki et al. ....	700/254
7,264,436	B2 *	9/2007	Tillmann .....	414/744.5
7,683,565	B2 *	3/2010	Quaid et al. ....	318/568.16
8,157,155	B2 *	4/2012	Diez et al. ....	228/44.3
2002/0077721	A1 *	6/2002	Linn et al. ....	700/193
2003/0025473	A1 *	2/2003	Nagata et al. ....	318/568.18
2005/0183533	A1 *	8/2005	Tillmann .....	74/490.03

(Continued)

**OTHER PUBLICATIONS**

Bernhard Jokiel, Jr., Lothar F. X. Bieg, and Mark Ensz, Development of an Independent Real-time Position Feedback Device for CNC Machining Operations, 2000, Proc. of the American Society for Precision Engineering Winter 2000 Annual Meeting, Scottsdale, Ariz., pp. 1-4.\*

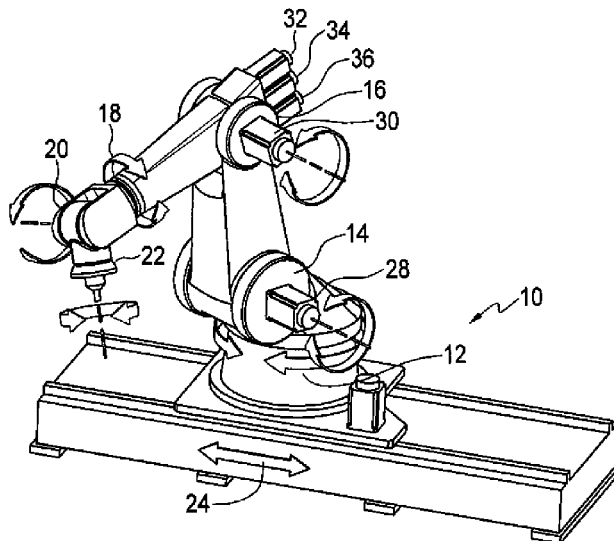
*Primary Examiner* — Khoi Tran  
*Assistant Examiner* — Jaime Figueroa

(74) *Attorney, Agent, or Firm* — Jensen & Puntigam PS

(57) **ABSTRACT**

A robot mechanism for controlling the position of a machine tool in a large-scale manufacturing assembly includes six rotary axes and one linear axis. Secondary feedback systems are included on at least several of the axes. A controller receives secondary feedback information and uses it to control the position of the machine tool within an accuracy of  $\pm 0.3$  mm.

**10 Claims, 3 Drawing Sheets**



(56)

**References Cited**

U.S. PATENT DOCUMENTS

2007/0168081	A1*	7/2007	Shin et al. ....	700/245	2009/0076655	A1*	3/2009	Blondel et al. ....	700/254
2007/0296366	A1*	12/2007	Quaid et al. ....	318/568.16	2009/0204258	A1*	8/2009	Tao et al. ....	700/248
2008/0258670	A1*	10/2008	Yoshikawa ....	318/568.22	2009/0249606	A1*	10/2009	Diez et al. ....	29/428
2009/0037022	A1*	2/2009	Teaford et al. ....	700/254	2009/0287352	A1*	11/2009	Geist et al. ....	700/254
					2010/0092032	A1*	4/2010	Boca ....	382/103
					2010/0181470	A1*	7/2010	Farley et al. ....	250/252.1
					2010/0191374	A1*	7/2010	Tsai et al. ....	700/258

\* cited by examiner

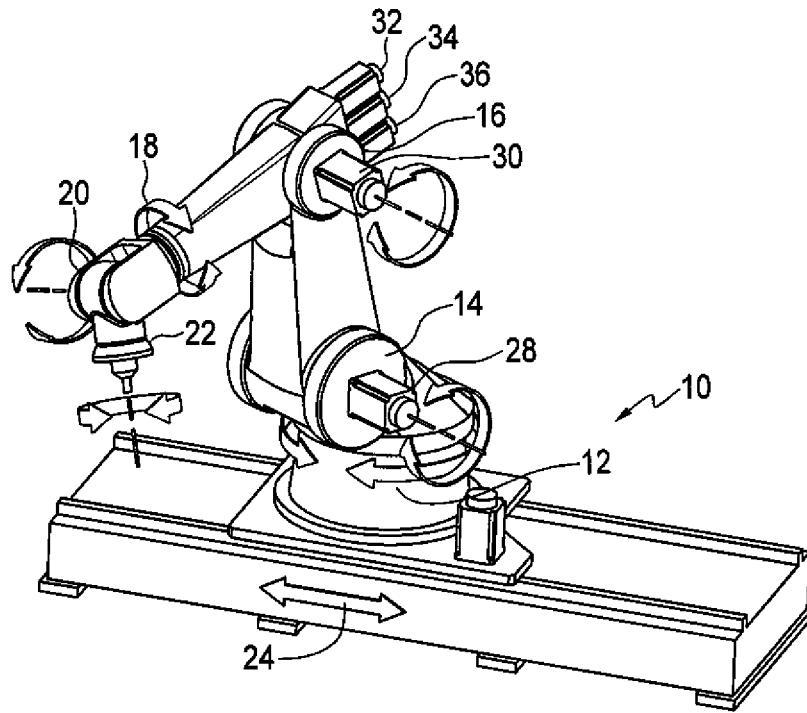


FIG. 1

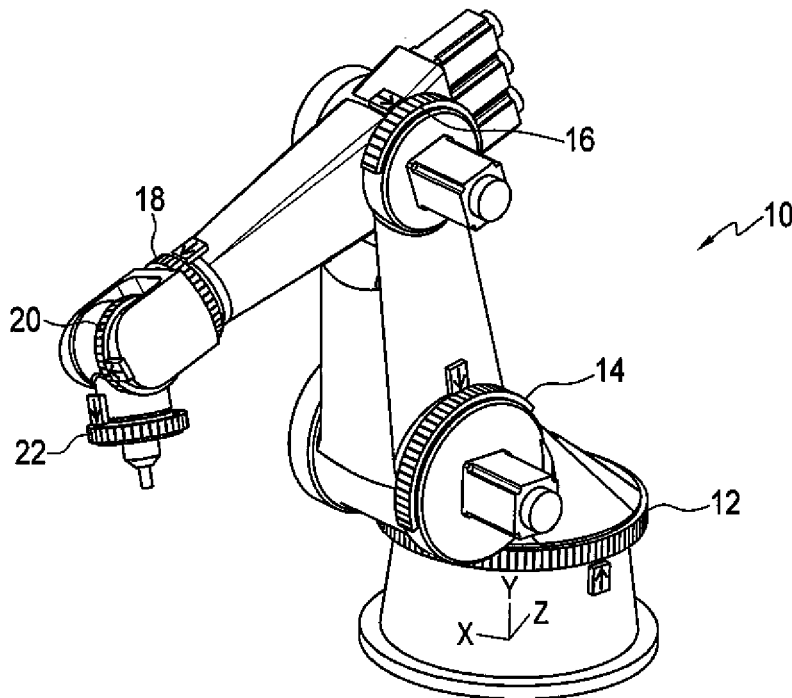


FIG. 2

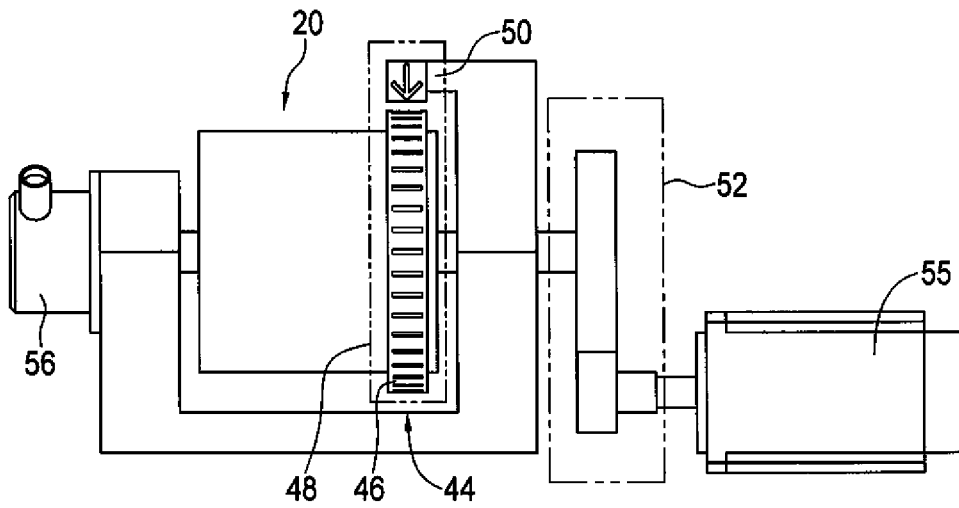


FIG. 3A

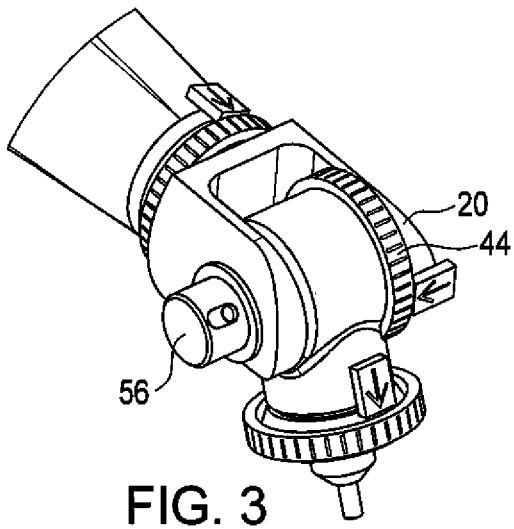


FIG. 3

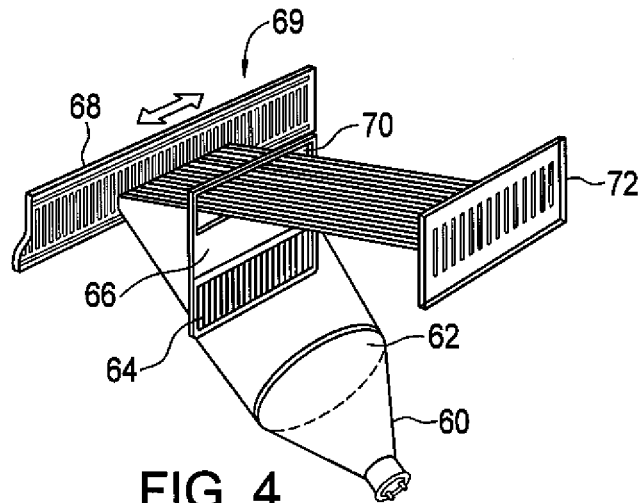


FIG. 4

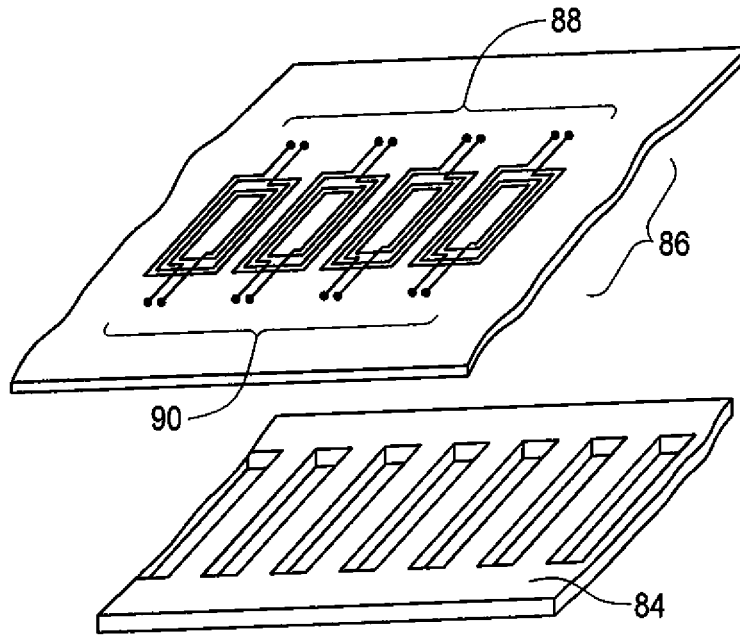


FIG. 5

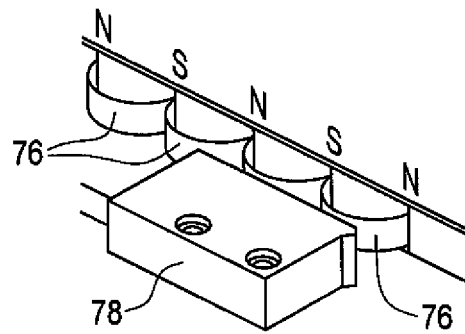


FIG. 6

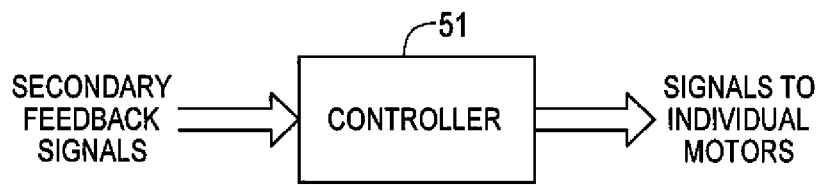


FIG. 7

1

## ROBOTIC MANUFACTURING SYSTEM WITH ACCURATE CONTROL

### TECHNICAL FIELD

This invention relates generally to robots used in the manufacture of large-scale assemblies, such as commercial airplanes and/or components for those assemblies, and more particularly concerns such a system for accurate control of the position of the work tool/end effector portion of the robot.

### BACKGROUND OF THE INVENTION

High accuracy is required for certain manufacturing functions with respect to various parts of commercial airplanes, including drilling and riveting functions. It is desirable that the end tool location be accurate to within  $\pm 0.1$  to  $\pm 0.3$  mm, or in some cases, even more precise. However, the machines to carry out those manufacturing functions are quite expensive and, although necessary to accomplish the desired accuracy, can be commercially burdensome for a manufacturer of such large-scale assemblies.

On the other hand, typical bent-arm, multi-axis type robots used typically in the manufacture of vehicles and similar articles do not require such high accuracy (typical accuracy of  $\pm 0.6$  mm) but are significantly less expensive than the machines described above used in aircraft manufacture and the like. The robots use a plurality of rotary axes for tool positioning. The controller for the robot determines the desired position/angle of the robot's end tool/end effector and runs an algorithm to determine the angle of each rotary joint, to properly position the tool. The positioning of the tool is produced by a feedback system using the position of the robot motor/motors. The best possible angular accuracy for such robots is determined by the backlash of the gearbox (at best 0.5 arcminute) and shaft windup, which refers to power transfer components such as shafts and belts. When this is multiplied by the large radial distance to the tool point, 200-1600 mm, a significant error, typically 0.03 to 0.25 mm, results from each joint. With such a positioning system, the overall accuracy of such a robot machine is not sufficient for the aircraft applications noted above and other manufacturing operations requiring high accuracy, such as medical device positioning, welding and machining operations, for example.

In the world of high accuracy machine tools, the XYZ position of the tool is accomplished through the use of linear axes, with secondary feedback. Zero, one or two rotary axes are used in the head of the machine tool, but secondary feedback is not typically used for the rotary axes. The distance to the tool point is quite short, so there is only a small effect in the XYZ positioning of the tool point from the rotary axes and secondary feedback on these axes has a negligible effect on improving accuracy.

Accordingly, it is desirable to be able to control the position of the tool/end effector of a typical multi-rotary axis manufacturing robot with a significantly higher degree of accuracy than is presently possible with existing robots.

### SUMMARY OF THE INVENTION

Accordingly, the system for controlling the position of an end tool in a large-scale manufacturing assembly comprising of a robot mechanism which includes at least three cascaded rotary axes of movement; a secondary feedback system on at least one of the rotary axes; and a controller for receiving secondary feedback information from said secondary feed-

2

back system or systems and using said secondary feedback information to control the position of the end tool.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a general schematic diagram of an articulated machine robot having six rotary axes and one linear axis.

FIG. 2 is a schematic diagram similar to FIG. 1, showing secondary feedback assemblies on six rotary axes (linear axis not shown.)

FIGS. 3 and 3A are diagrams showing one robot axis using the feedback system described herein for increased robot accuracy.

FIGS. 4-6 are diagrams showing various embodiments of secondary feedback assemblies used for a robot manufacturing system.

FIG. 7 is a simple block diagram showing the feedback control system.

### BEST MODE FOR CARRYING OUT THE INVENTION

FIGS. 1 and 2 show a manufacturing robot having six rotary axes with a joint following each axis. FIG. 1 also includes a linear axis. The robot, shown generally at 10, includes a first rotary axis 12, a second rotary axis 14, a third rotary axis 16, a fourth rotary axis 18, a fifth rotary axis 20 and a sixth rotary axis 22. The robot also includes a linear axis 24, as shown specifically in FIG. 1. The operation of the individual axes, allows the working end tool/end effector to be accurately positioned within an XYZ Cartesian coordinate system (FIG. 2), and if sufficient additional axes exist, roll, pitch and yaw can also be controlled. FIGS. 1 and 2 show motors 28, 30, 32, 34 and 36 which separately operate axes 14, 16, 18, 20 and 22, respectively. The motor for axis 12 is not shown.

The inventor has discovered the significance of using secondary feedback on one or more of the rotary axes of robots to significantly improve the accuracy of otherwise conventional robots. Previously, it has been known from machine tools to use linear scales (with secondary feedback) on multiple axes to achieve high accuracy XYZ tool positioning. Secondary feedback for the one or two rotary axes (the head or tipping axis) of machine tools is not typically used and is not understood to add measurably to the accuracy of the machine tool. Hence, machine tool techniques for producing high tool accuracy do not provide significant insight relative to improving accuracy of robots with their relative long links (up to 2 meters in some cases) and their rotary axes. In robots, a link refers to the distance from one axis center to the next axis center. Machine tools typically have relatively short links, defined by the distance from the center of rotation of the rotary axis to the tool point. With robots, there has been no use or understanding to date of using secondary feedback from individual rotary axes to improve linear (XYZ) accuracy of the tool position.

In the embodiment shown, each separate axis includes a secondary feedback assembly, which could be a scale on an external portion of the axis or coupled to the pivot portion of the axis. An example of a secondary feedback assembly is shown on one rotary axis 20 in FIGS. 3 and 3A. Similar secondary feedback assemblies are shown on axes 12, 14, 16, 18 and 22 in FIG. 2. The particular secondary feedback assembly shown is an external scale, shown generally at 44, mounted on the rotary joint of axis 20. The external scale 44 is a linear tape scale wrapped around the axis joint. The scale can also be enclosed in a ring-like member 48. A detector 50

reads the rotary position of the axis by counting the lines in the scale which pass by the detector. The secondary feedback assembly could also be coupled to the axis pivot **56** in FIG. **3**. The information from the detector is then applied to a feedback system, which uses the information to control the motors for the axes to locate the tool to the desired accuracy, at least  $\pm 0.25$  mm for robots with a reach of  $3\frac{1}{2}$  meters. The accuracy will be even better with robots having shorter reaches.

FIG. **3A** also illustrates the structural arrangement for one axis **20**. Axis **20** has a motor **55** associated therewith to provide the controlled movement of the rotary axis, as well as a power transmission **52** which connects the motor **50** to the axis. The power transmission is hidden within the external robot structure, and comprises couplings, shafts, U-joints, gears, belts and gear boxes, etc., to connect the motor **50** to the rotary joint. Although the arrangement of FIGS. **1** and **2** shows a separate motor for each rotary axis; with a separate short power transmission connecting each motor to separate axis joints, it is possible that a robot could have fewer motors, with power transmissions connecting motors to more than one axis joint.

FIG. **7** shows a simplified feedback arrangement involving signals from the secondary feedback assemblies on one or more of the axes to the robot controller **51**. The controller then sends control signals to the motors as required to position the tool with the desired accuracy.

The encoders described above, either a linear tape is applied around the axis or a system coupled to the axis pivot can be implemented with a variety of position-detecting arrangements, including, but not limited to, optical, magnetic and inductive, as shown in FIGS. **4-6**.

Referring to FIG. **4**, an optical encoder assembly **69** includes a light source **60**, such as an LED, the light being directed through a condenser lens **62** and then through an index grating **64** with a scanning reticle **66** onto encoder scale **68**. Light is reflected off of the scale and back through a window **70** to a detector **72**, which counts the number of lines as the axis is rotated. The information from the detector, referring to FIG. **7**, is provided to the controller **51**, which then provides corresponding signals back to the individual robot motors to position the robot tool with the desired accuracy to the preselected position for accomplishing the manufacturing function (drilling, riveting, etc.).

An inductive arrangement is shown in FIG. **5**, and includes a measuring scale **84** and a microstructure **86** which includes primary windings **88** and secondary windings **90**, so that as the measuring scale moves past the microstructure by movement of the axis joint, a pattern of electrical signals is developed on the secondary windings **90** indicative of the scale (and joint) movement. The information from the secondary windings is then applied to the controller for location of the robot tool, as with the other arrangements.

A magnetic arrangement is shown in FIG. **6**. In this arrangement, the external scale includes a sequence of magnetic elements **76** with alternating north/south poles. Also included is a magnetic reader **78**. As the rotary axis joint turns, the magnetic reader produces information which is forwarded to the controller **51**, which in turn generates the motor signals necessary to accurately locate the robot tool.

The determination of axis position with a rotary/angle encoder on the axis pivot can also be accomplished with a resolver, which comprises a rotary transformer where the magnitude of the energy through the windings varies in a sinusoidal fashion as the shaft rotates. Typically, a resolver control transmitter will have one primary winding, referred to as the reference winding, and two secondary windings, referred to as the SIN and COS windings. The signal from the

secondary windings provides a reliable, accurate indication of the change of position of the axis.

The above arrangements are examples of scale-type encoders which provide accurate positional information, typically within  $\pm 0.25$  mm for robots which is suitable for many large-scale manufacturing operations with a reach in the range of  $3\frac{1}{2}$  meters.

The above system is advantageous, in that it permits the use of a multi-rotary axis and one linear axis robot which is significantly less expensive than apparatus which has heretofore been used to produce assembly operations requiring high accuracy, such as required in aircraft manufacture.

Each of the axes of the robot, as indicated above, will typically have a secondary feedback arrangement. This includes all of the rotary axes, as well as the linear axis. It should be understood, however, that it is not necessary that every axis have such a capability in order to provide significant advantages over the prior art systems. In fact, even having an encoder scale arrangement for secondary feedback on one axis, such as for instance the rotary axis **12**, can result in an advantage in accuracy of the overall system.

Although a preferred embodiment has been disclosed for purposes of illustration, it should be understood that various changes and modifications and substitutions could be made in the preferred embodiment without departing from the spirit of the invention as defined by the claims which follow:

What is claimed is:

1. A system for accurate large-scale manufacturing assembly operations, comprising:
  - a robot mechanism which includes more than three cascaded rotary axes of movement, wherein each rotary axis has a motor associated therewith for controlled movement of the axis, wherein the robot mechanism includes an end tool to accomplish large-scale manufacturing assembly operations;
  - a secondary feedback system mounted in relation to the rotary joint of each of a plurality of the rotary axes, separate from and not connected to the motors associated with the axes, so as to read directly the rotary position of each axis; and
  - an integrated controller in a feedback arrangement for receiving secondary feedback information from each of said secondary feedback systems and using said secondary feedback information to directly control the motors for each of said axes to accurately position the end tool to specified 3-dimensional linear Cartesian coordinates from the controller relative to a large-scale assembly and to produce at least one of roll, pitch and yaw angles of the end tool to accomplish the large-scale manufacturing operations.
2. The system of claim **1**, wherein the system has an angular accuracy of 0.05 arcminute relative to a desired angle for each axis joint having secondary feedback.
3. The system of claim **1**, wherein the robot mechanism has six rotary axes, at least two of which include secondary feedback systems.
4. The system of claim **1**, wherein the manufacturing assembly is an aerospace assembly.
5. The system of claim **1**, wherein the robot mechanism includes six rotary axes and one linear axis, all of which have secondary feedback systems.
6. The system of claim **1**, wherein the secondary feedback system is an optical encoder.
7. The system of claim **1**, wherein the secondary feedback system is an inductive encoder.
8. The system of claim **1**, wherein the secondary feedback system is a magnetic encoder.

9. The system of claim 1, wherein the secondary feedback system is a rotary or angle encoder using a resolver.

10. A system for accurate large-scale manufacturing assembly operations, comprising:

a robot mechanism which includes more than three cascaded rotary axes of movement, wherein each rotary axis has a motor associated therewith for controlled movement of the axis, wherein the robot mechanism includes an end tool to accomplish large-scale manufacturing assembly operations;

a secondary feedback system mounted on the rotary joint of or at the output of each of a plurality of the rotary axes, without any gears or other transmission elements therebetween so as to read directly the rotary position of each axis; and

an integrated controller in a feedback arrangement for receiving secondary feedback information from each of said secondary feedback systems and using said secondary feedback information to directly control the motors for each of said axes to accurately position the end tool to specified 3-dimensional linear Cartesian coordinates from the controller relative to a large-scale assembly and to produce at least one of roll, pitch and yaw angles of the end tool to accomplish the large-scale manufacturing operations.

\* \* \* \* \*