

CLIMBING ROBOT WITH SURFACE TRANSITION AND END-TO-END WELDING CAPABILITIES FOR CONFINED-SPACE APPLICATIONS

BACKGROUND

Technical Field

5 Embodiments of the invention relate to mobile robots and more particularly to robots capable of climbing and making transitions between angled surfaces of both internal and external walls of a confined-space structure, and further capable of end-to-end welding to produce straight-line welding seam.

Description of Related Art

10 Gas Metal Arc Welding (GMAW) started its development works in the late 1940s but it was only until early 1960s that the process became more versatile and popular to be used in the steel metal fabrication industry. Later on, Flux Cored Arc Welding (FCAW) was introduced. FCAW is similar but uses a wire which contains material within its core which, when arc-heated, produces shielding gases and
15 fluxing agent. GMAW and FCAW have become the most preferred and common industrial welding processes mainly due to their versatility, productivity and, in today's technology driven industry, their ease of adapting to robotics and automated processes.

 Integration of GMAW and FCAW welding to robotics or automated carriages
20 began once it was found that there was a need to increase efficiency of welding process and at the same time promote a safer working environment. Numerous automated welding carriages which were designed to specifically perform or compliment GMAW or FCAW welding then became commercially available starting from early 1980s. Consequently, precise and uniform welds could be created
25 consistently with much higher arc on time. The development efforts have been directed towards the research on compact design of fully-autonomous robots [1].

 Certain GMAW and FCAW welding carriages that are commercially available in the market will be described below.

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Track-Guided Welding Carriage

Track-guided welding carriages run on aluminum or flexible spring steel tracks. The tracks are first mounted on the work piece with the use of magnets or vacuum system. The welding carriage is then mounted onto the tracks via roller or wheel clamps or rack and pinion system. The carriages are equipped with programmable logic controllers (PLCs) to automate certain programmable controls including travel speed, weld crater or even skip sequences for stitch welding. These carriages are designed to perform welding on all positions due to its ability to travel on different work planes where the track is mounted. Some track-guided welding carriages have tracks that are designed to be flexible and thus have the added advantage of being able to contour according to the work piece. These types of carriages are commonly used for long continuous welding seams as it is reasonable to spend more time in the set-up of the travel rails to achieve long continuous welds.

Examples of track-guided welding carriages are provided in US Patent No. 6,494,307 B1 "Track & Carriage" and US Patent No. 3,604,612 A "Track Travelling".

Due to the need to set up tracks or rails, track-guided welding carriages are not suitable for use in confined-space structures. Furthermore, existing track-guided welding carriages do not have surface transition or end-to-end welding capability.

Roller-Guided Welding Carriage

Roller-guided welding carriages are guided by adjustable wheels which track the vertical member of the fillet or lap joint that needs to be welded. These carriages travel by means of wheels that are driven by motor. These carriages, similar to track-guided welding carriages, have in-built PLCs that automate certain welding functions and controls. Roller-guided welding carriages are much more portable compared to track-guided welding carriages as set-up of tracks or rails is not required.

Examples of roller-guided welding carriages are provided in US Patent No. 8,567,466 B2 "Welding Carriage" and US Patent No. 8,487,214 B2 "Mobile Carriage".

Although roller-guided welding carriages are suitable for use in confined-space structures and can provide end-to-end welding capability, they do not provide surface transition capability.

Magnetic Wheel Welding Carriage

Magnetic wheel welding carriages are similar to roller-guided ones. Their wheels are magnetic to enable the carriages attach to and travel on ferromagnetic structures or work pieces. Their magnetic wheels may be permanent-magnet type or electromagnetic type. Similar to other carriages, magnetic wheel welding carriage have built-in PLCs that automate its functions and controls depending on the design.

Examples of magnetic wheel welding carriages are provided in US Patent Application Publication No. 2015/0041446 A1 "Welding Carriage" and US Patent No. 5,853,655 A "Magnetic Carriage".

Although magnetic wheel welding carriages are suitable for use in confined-space structures, they do not provide surface transition and end-to-end welding capability.

In view of the above and other issues, an improved welding carriage is highly desirable for, but not limited to, confined-space structures.

SUMMARY

According to a first aspect of the invention, a control apparatus is provided, the control apparatus comprising:

- a guiding curve module comprising a body and a guiding curve arranged on the body;

- a linkage module comprising a linkage member and a connector system which is pivotably arranged about a pivot point on the body, wherein the linkage member is movably engaged with the connector system to allow displacement of the linkage member relative to the connector system, wherein the linkage member is movably engaged with the guiding curve;

- an applicator device supported by the linkage member; and

- a drive module operably coupled to the connector system and configured to cause a rotation of the connector system about the pivot point, wherein the rotation is configured to drive the linkage member along the guiding curve and variably displace the linkage member relative to the

connection system to cause the applicator device produce a straight-line path on a target surface.

According to a second aspect of the invention, a robot is provided, the robot
5 comprising:

a carriage comprising:
at least one motor;
a plurality of wheels which are operable by the motor; and
the control device of the first aspect of the invention.

10 According to one embodiment of the second aspect of the invention, the carriage further comprises a self-alignment module which comprises:

a distance sensor configured to ascertain a plurality of distance readings from a plurality of points on the target surface; and

15 a computing unit communicably coupled to the distance sensor and the motor, wherein the computing unit is configured to compute a deviation angle of the carriage relative to the target surface based on the distance readings and send a control signal to the motor to cause rotation of the carriage by the deviation angle.

20 According to a third aspect of the invention, a method of producing straight-line path is provided, the method comprising:

having a control device which comprises:

25 a guiding curve module comprising a body and a guiding curve arranged on the body,

a linkage module comprising a linkage member and a connector system which is pivotably arranged about a pivot point on the body, wherein the linkage member is movably engaged with the connector system and with the guiding curve,

30 an applicator device supported by the linkage member, and

a drive module operably coupled to the connector system;

using the drive module, causing a rotation of the connector system about the pivot point, and resulting in driving the linkage member along the

guiding curve and variably displacing the linkage member relative to the connector system; and

using the driving of the linkage member along the guiding curve and the variable displacement of the linkage member relative to the connector system, producing, by the applicator device, a straight-line path on a target surface.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are disclosed hereinafter with reference to the drawings, in which:

Figure 1 is a perspective view of a welding robot according to one embodiment of the invention;

Figure 2 is an exploded view of the welding robot of Figure 1;

Figure 3 is an exploded view of a robot carriage;

Figure 4 is a schematic representation of a straight-line mechanism, which may be incorporated in a control apparatus, according to one embodiment of the invention;

Figure 5 is a perspective view of a straight-line mechanism according to one embodiment of the invention;

Figure 6 shows an internal view of the straight-line mechanism of Figure 5 having the cover removed therefrom;

Figure 7 shows an internal view of the straight-line mechanism of Figure 5 having the cover and base removed therefrom;

Figure 8 is an exploded view of the straight-line mechanism of Figure 5;

Figure 9A is a perspective view of a linkage member of the straight-line mechanism of Figure 5;

Figure 9B is a side view of Figure 9A;

Figure 9C is a top view of Figure 9A;

Figures 10A to AD show the straight-line mechanism with the linkage in various positions;

Figure 11 is a schematic representation of a self-alignment procedure;

Figure 12 is a flow chart describing the self-alignment procedure;

Figure 13A shows an example of wheel arrangement at a carriage;
Figure 13B shows another example of wheel arrangement at a carriage.

DETAILED DESCRIPTION

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In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all of these specific details. In
10 other instances, well known process operations have not been described in detail in order not to unnecessarily obscure pertinent aspects of embodiments being described. In the drawings, like reference numerals refer to same or similar functionalities or features throughout the several views.

Embodiments described in the context of one of the methods or devices are
15 analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other
20 embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other
25 embodiments.

As used herein, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

30 As used herein, the terms “first,” “second,” and “third,” etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

As used therein, the term “coupled” and related terms are used in an operational sense and are not necessarily limited to a direct physical connection or coupling. Thus, for example, two devices may be coupled directly, or via one or more intermediary devices. In certain examples, devices may be suitably coupled such that information or signal can be passed therebetween, while not sharing any physical connection with each other. For example, two devices may be communicably coupled via a wired or wireless connection. Based on the present disclosure, a person of ordinary skill in the art will appreciate a variety of ways in which coupling exists in accordance with the aforementioned definition.

Figures 1 and 2 illustrate a welding robot according to one embodiment of the invention. The welding robot 1 comprises: a robot carriage 2, an end-to-end or straight-line motion-producing mechanism 3 (hereinafter straight-line mechanism), a welding torch module 4, and a self-alignment module including a distance sensor 29. The robot carriage 2 is configured to provide motion and surface transition capability to the welding robot 1, and support both the straight-line mechanism 3 and the welding torch module 4 while travelling on a target surface. The straight-line mechanism 3 is configured to enable a welding torch of the welding torch module 4 produce a straight-line motion path. The welding torch module 4 is configured to support the welding torch at least while the welding torch is performing welding. The self-alignment module is configured to adjust heading of the welding robot such that the robot is parallel to a target wall.

Carriage

Reference is made to Figure 2 showing the robot carriage 2 and Figure 3 which is an exploded view of the carriage 2. The carriage 2 comprises four motors 5, four differentially driven magnetic wheels 7. Each of the motors 5 is operably coupled to a respective one of the driving wheels 7 and configured to provide independent drive control of the corresponding wheel. The carriage 2 may further comprise a housing 6 for at least partially enclosing or housing one or more motors 5. It is to be appreciated that other embodiments of the invention may include other count or number of driving wheels and motors and/or passive wheels. In one example (see Figure 13A), a carriage may include two driven wheels 7 independently controlled by

separate motors and two free or passive wheels 7a. In another example (see Figure 13B), a carriage may include two driven wheels 7 independently controlled by separate motors and one caster wheel 7c. Other examples may include other number of passive or non-driven wheels, e.g. free or caster wheels or other motor-to-wheel ratio.

End-to-end or Straight Line Mechanism

In confined space structures, corner welding is necessary and achieved by a straight line mechanism. The conventional Hoekens Linkage is widely used in commercial welding robots, however, it cannot guarantee a perfect straight line movement.

A straight-line mechanism is provided in accordance with the invention to generate a more accurate and perfect straight line movement. This mechanism is designed as a guiding curve using rotation motor based on the desired straight line range (SLR), L_d .

Figure 4 is a schematic representation of a straight line mechanism configured to produce a straight line range or path L_d . For a given linkage parameters (L , L_1), the shape of the guiding curve of the straight line mechanism is determined based on desired L_d . The guiding curve may be represented by distance coordinates (X_c, Y_c) from point O (pivot point):

$$X_c(\theta) = L \sin(\theta) - L_1 \tan(\theta) \quad (\text{Equation 1})$$

$$Y_c(\theta) = L \cos(\theta) - L_1 \quad (\text{Equation 2})$$

where X_c is distance from point O (pivot point) in X-direction,

where Y_c is distance from point O (pivot point) in Y-direction being orthogonal to X-direction,

where L_1 is distance between point O and point E being an intermediate or mid point on the straight line path L_d , which is nearest to the pivot point,

where L is length of Linkage_1 (including linkage member 25 and applicator device 40) when it reaches mid-point of line GH or distance between point C and point E

(line C-E) (In other words, L is a distance between an intermediate point on the guiding curve and the aforementioned intermediate point on the straight-line path, which is taken through the pivot point.),

where θ is rotation angle from line C-E (In other words, θ is rotation angle of the linkage member from a line represented by L).

The maximum rotation angle θ_{max} is obtained by:

$$\theta_{max} = \text{atan}(L_d/2/L_1) \quad (\text{Equation 3})$$

The maximum rotation angle θ_{max} will take place when Linkage_1 reaches the end point G of the straight line G-H (see dash line 41 in Figure 4).

Footprint size (FS) of the straight-line mechanism (see the dash box 42 in Figure 4) is determined by the maximum variation of the guiding curve in the X-direction ΔX_{max} and is obtained by:

$$FS = \Delta X_{max}(L - L_1) \quad (\text{Equation 4})$$

As there exists infinite combinations of the linkage parameters which can meet a desired SLR, particle swarm optimization (PSO) method may be adopted to optimize the linkage parameters to minimize the FS while meeting some constraints which include: (i) the acceptable SLR of the mechanism satisfies desired SLR; (ii) the distance from the welding torch to the mechanism has enough clearance distance C_d during the welding process for safety consideration; (iii) pushing force F_p should be larger than the resistance or friction force F_f which is determined by normal force F_n and friction force coefficient, wherein F_n and F_f are force vector components of total force F.

In one example, optimal linkage parameters are $L=280\text{mm}$ and $L_1=200.87\text{mm}$, based on the friction force coefficient 0.4, clearance distance C_d 30mm, desired SLR 200mm, and the range of each linkage of (1, 280) mm. Range of each linkage refers to the smallest and largest length of each linkage.

In another example, performance of the straight line mechanism of the invention is compared against a conventional Hoekens linkage. Particularly, optimal parameters for each mechanism are searched using PSO method based on the constraints in Table 1, i.e. minimize the footprint size of each mechanism based on specified or desired straight line error (SLE), straight line range (SLR) and safety distance. Comparison of the two mechanisms is shown in Table 2.

TABLE 1: CONSTRAINTS

SLE(mm)	Acceptable SLR(mm)	C_d (mm)	Linkage range (mm)
0.5	100	30	(1, 200)

TABLE 2: COMPARISON BETWEEN TWO MECHANISMS

Mechanism	FS (mm ²)	No. of linkage	Fabrication cost	Straightness
Hoekens linkage	746.25	3	Low	Not Perfect
Straight-line mechanism of the invention	113.53	2	High	Perfect

As would be appreciated from the above, the straight-line mechanism of the invention has better performance than a Hoekens linkage, i.e. requires a smaller footprint size and number of linkages, but produces a more accurate straight line range or path.

Figures 5 to 8 show a straight-line mechanism according to one embodiment of the invention. The straight-line mechanism comprises a drive module, a guide curve module and a linkage module. The drive module is configured to actuate or

drive the linkage module. The guide curve is configured to define the motion path of the linkage module. The linkage module is configured to actuate or move an applicator device 40, e.g. welding torch module, which is coupled thereto to produce a straight-line path.

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The drive module comprises a motor 24, a first bevel gear 26a rotatably coupled to the motor, a second bevel gear 26b rotatably coupled to the first bevel gear 26a, a first timing pulley 29a rotatably coupled to the second bevel 26b, a second timing pulley 29b, and a timing belt 30 movably coupling the timing pulleys 29a, 29b.

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The guiding curve module comprises a body, e.g. plate or base 28, and a guiding curve 28a arranged on/in the body. The guiding curve 28a is defined by Equations 1 and 2. The guiding curve 28a may be provided as an opening formed in the body as shown in Figure 5 or as a projection attached to the body (not shown).

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The linkage module (see also Figures 9A to 9C) comprises a linkage member 25 and a connector system movably coupled thereto and configured to produce a varying or adjustable relative displacement between the linkage member 25 and connector system.

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The connector system comprises a first (upper) connector 23 and a second (lower) connector 27. The second (lower) connector 27 may be provided as an elongate member having opposed ends wherein a first end is provided with two or a plurality of short pins 27a extending therefrom in a first direction while the second end is provided with a long pin 27b extending therefrom in a second direction opposite to the first direction. The first (upper) connector 23 may be provided as an elongate member having opposed ends wherein a first end is provided with two or a plurality of openings configured to receive and/or engage with the short pins of the second (lower) connector 25 while a second end is provided with a long pin 23b extending therefrom, which is configured to be received through the linkage member 25 and the long pin 27b of the second (lower) connector 27.

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The connector system is pivotably arranged about a pivot point which is positioned at a fixed distance from the guiding curve 28a. In one example, the pivot point may be positioned on the body of the guiding curve module.

5 The linkage member 25 may be provided as an elongate member having greater length dimensions than the connectors 23, 27. A slot 25a or opening is formed partially along the length of linkage member 25, and configured to receive the long pin 23b of the first (upper) connector 23. Also along the length of linkage member 25, an applicator support pin 31 may extend from the linkage member 25 in
10 a first direction and configured to support an applicator device 40, e.g. weaving torch or other tools. At one end or along the length of linkage member 25, an engagement pin 32 may extend from the linkage member 25 in a second direction opposite to the first direction, and configured to engage with the guiding curve. In the linkage module, the support pin 31 is suitably arranged or located between the engagement
15 pin 32 and the slot 25a.

When assembled, the linkage member 25 is movably engaged with both the guiding curve module and the connector system. This movable engagement of the linkage member 25 and connector system allows varying or adjustable displacement,
20 e.g. slidable displacement, of linkage member 25 relative to the connector system while the connectors 23, 27 are rotatably driven about the pivot point by the second timing pulley 29b. Particularly, the linkage member 25 is interposed between the first (upper) connector 23 and the second (lower) connector 27 by a pin arrangement that couples the pair of connectors 23, 27 and is received through an opening on the
25 linkage member 25, particularly by engaging short pins 27a of the second (lower) connector 27 with the first end of the first (upper) connector 23, and also by passing long pin 23b of the first (upper) connector 23 through the slot 25a and engaging with the long pin 27b of the second (lower) connector 27. Both the long pins 23b, 27b are rotatably coupled to the second timing pulley 29b. Furthermore, the engagement pin
30 32 of the linkage member 25 is movably engaged with the guiding curve.

With the above-described arrangement of linkage member 25 and connection system, the drive module or motor 24 thereof is operably coupled to the connector system and configured to cause a rotation of the connector system about the pivot

point. The rotation of the connector system is configured to drive the linkage member 25 along the guiding curve 28a and displace the linkage member 25 relative to the connection system to cause the applicator device 40 produce a straight-line range or path on a target surface.

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In operation, rotation movement or driving torque produced by the motor 24 is outputted by the first bevel gear 26a and then transferred to the second bevel gear 26b. As the second bevel gear 26b is coupled to a first timing pulley 29a, the rotation movement is transferred from the first timing pulley 29a by timing belt 30 to the
10 second timing pulley 29b. The second timing pulley 29b is linked or rotatably coupled to the connector system. The second timing pulley 29b drives the connector system which in turn rotates or drives the linkage member 25. As the motion path of the linkage member 25 is constrained by the guiding curve due to coupling of the engagement pin 32 with the guiding curve 28a, driving the linkage member 25
15 between ends of the guiding curve 28a causes the pin arrangement e.g. long pins 23b, 27b, to slide or move along the slot 25a, thereby variably displacing the linkage member 25 relative to the connection system. Due to the driving of the linkage member 25 along the guiding curve 28a and the variable displacement of the linkage member 25 relative to the connector system, the applicator device 40, which is
20 supported by the linkage member 25 is caused to produce a straight-line range or path on a target surface (e.g. wall represented by GH in Figure 4).

Following from the above, in welding applications for example, the applicator support pin 31 of linkage member 25 may be coupled to a welding tool e.g. welding
25 torch module 4 comprising a welding torch and possibly a weaving mechanism supporting the torch. It is to be appreciated that a weaving mechanism may be required for certain welding orientation, e.g. vertically upward and overhead welding, while optional in other welding orientations. The welding torch, driven by the linkage member 25, whether directly or indirectly driven, would produce a straight line range
30 to enable straight-line end-to-end welding as illustrated in Figures 10A to 10D, e.g. depositing a weld material along a straight-line seam.

As illustrated in Figures 10A to 10D, a welding torch module 4 or applicator device 40 for other applications, as represented by dashed lines, is coupled to or

supported by the linkage member 25, e.g. pin 30. The applicator device 40 includes one end, which is distal from the linkage member 25 and moves along point A and point B to produce a straight line range therebetween when the linkage member 25 is driven from one end of the guiding curve to the other. Applying Figures 10A to 10D to welding applications, the distal end of the elongate member as shown in dash lines is representative of the welding torch. Weaving mechanism and any other welding components are not shown to simplify the drawings. Clearance distance C_d is provided to improve safety in the welding process. In one example, the elongate member as shown in dashed lines or applicator device 40 may be about 280 mm to produce a straight line range of about 200 mm.

The term “applicator device” 40 refers to any device of any suitable shape that is attached to or supported by the linkage member 25 and of suitable length to produce a straight-line trajectory at its end-point. In some examples, an “applicator device” may be integrally formed, e.g. formed into a single piece, with the linkage member 25.

In the welding robot, the straight-line mechanism may be provided in a housing comprising a base 28 and a cover 22 supported on the base 28 (see Figures 5 to 8). The guiding curve may be formed as an opening in the base 28 which is supported by the carriage 2. The cover 22 may support the welding torch module 4 and may be provided with an opening 22a therein to allow movement of the support pin of the linkage module. The opening 22a in the cover 22 may be defined by Equations 1 and 2, however, the opening 22a may take other shapes as appropriate.

Self-Alignment Module

The welding robot may be provided with a self-alignment module configured to adjust heading of the robot such that a linear parameter of the robot is parallel to a target wall ($\alpha=0$) where α is a deviation angle between the linear parameter of robot and target wall. Reference is made to Figure 11 which is a schematic representation of a self-alignment procedure. In the example of Figure 11, the linear parameter is defined as by its wheels 7, e.g. front wheels.

The self-alignment module comprises a distance sensor 29, a sensor holder, a computing unit which is communicably coupled to the distance sensor 29, a memory storage which is communicably coupled to the computing unit and/or distance sensor 29.

The distance sensor 29 may be provided as laser sensor, an infrared proximity sensor, an optical sensor or other suitable sensor which is capable of determining distance from a target object or wall 150.

The sensor holder is mounted on the carriage and supports the distance sensor 29 and is configured to turn or pivot the distance sensor 29 about a centre position.

The computing unit is configured to receive readings or data from the distance sensor 29, compute an angle relative to the target wall 150 based on the received data, determine whether self-alignment is required and the extent required, and generates and send control signals to the motor or motor controller driving the wheels 7 to adjust the wheels based on the control signals.

A self-alignment procedure is described with reference to the flow chart of Figure 12.

In block 1601, the distance sensor determines distance readings based on a plurality of points on the target wall, i.e. relative distance between the robot and different points on the target wall (block 1601). Particularly, the sensor 29 determines three distance readings (L_1 , L_2 , L_3) from three different points (P_1 , P_2 , P_3) on the target wall 150. For this purpose, the sensor 29 may be pivotally moved or displaced to its left and right at predetermined angles (0 , θ and $-\theta$ respectively) relative to its centre position.

In block 1603, the computing unit computes or determines the value of deviation angle α based on the distance readings obtained in block 1601. The value of α may computed using either one of the following equations:

$$\alpha = \text{atan}\left(\frac{L1 - L2 * \cos(\vartheta)}{L2 * \sin(\vartheta)}\right) \quad (\text{Equation 5})$$

$$\alpha = \text{atan}\left(\frac{L3 * \cos(\vartheta) - L1}{L3 * \sin(\vartheta)}\right) \quad (\text{Equation 6})$$

In block 1605, the computing unit compares whether the computed α value is greater than a predetermined threshold value or falls within a predetermined range, which defines an acceptable deviation angle. If not, the self-alignment procedure stops (block 1607). If the computed α value is an unacceptable deviation angle value, e.g. greater than a predetermined threshold value or falls within a predetermined range, the self-alignment procedure proceeds to block 1609.

In block 1609, based on the computed α value, the computing unit generates and sends a control signal to one or more motors or motor controllers of carriage 2, which are configured to rotate the robot or carriage about its centre point by the computed α value.

Various modifications may be made to the self-alignment module. Possible modifications include any one or more of the following: providing the computing unit and/or memory storage at other parts of the robot, communicably coupling the computing unit and/or memory storage to other modules or mechanisms of the robot, using other linear parameter of the robot for the self-alignment procedure.

While the foregoing describes a carriage, a straight-line mechanism, a welding torch module and a self-alignment module which are combined to provide a welding robot, it is to be appreciated that the aforementioned modules or mechanism may be appropriately combined with other components. For example, the self-alignment module may be optional, the welding torch module may be replaced by other applications or tools, the carriage may be replaced with other appropriate driving carriage with similar or different surface transition capability, or the straight-line mechanism may be combined with other appropriate tool and/or driving carriage with similar or different capabilities.

Embodiments of the invention may include at least one robot control unit which is communicably coupled to the motor(s) 5 driving the robot carriage 2 and/or straight line mechanism, e.g. drive module. The robot control unit may comprise at least one computing unit, e.g. microprocessor, at least one memory storage
5 communicably coupled thereto, and executable instructions stored in the memory storage, which are executable by the microprocessor to cause transmission of control signals to the motor(s) 5 to move or orientate the wheel(s) and/or to the drive module to actuate the straight-line mechanism and the applicator device produce a straight line path. It is to be appreciated that transmission of these control signals to
10 may take place over wired and/or wireless connection between the control unit and the motor(s) and/or drive module.

Embodiments of the invention provide several advantages including, but not limited to, the following:

- Only one setup is required to weld surfaces with different orientations as the
15 carriage of the welding robot is designed to climb ferromagnetic structures, bi-directionally transit between ferromagnetic surfaces and/or turn on the spot. These capabilities are due to its wheel parallel to wheel structure and are useful for confined space structures, e.g. cubic structure where each surface of the structure is assumed to be orthogonal to an adjacent surface. As such,
20 welding of various seams in the entire confined structure requires only a single setup by operator, thus resulting in reduced setup time and increased efficiency. Furthermore, the wheel parallel to wheel structure allows gradual decrease of magnetic force during surface transition.
- The end-to-end or straight-line mechanism has higher accuracy than
25 conventional Hoekens linkage and provides a perfect straight line motion path. The straight-line mechanism will enable the welding robot to perform full length fillet welding that is needed to ensure that complete weld is achieved for a given seam and that follows a straight line path.
- The self-alignment module provides self-localization ability which is useful in a
30 cubic environment since it requires less human interaction.

- The robot according to the invention is suitable for use in welding in confined spaces of ship construction, ship repair, and other related and related industrial applications, such as inspection, non-destructive test (NDT) operations, welding seam blasting, welding seam cleanings, and application of strip coating, spray painting and other related industrial operations. These operations may be employed in the construction, aerospace and other industries outside of marine, offshore, oil & gas industries.

Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments of the invention.

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Claims

1. A control apparatus comprising:

a guiding curve module comprising a body and a guiding curve arranged on
5 the body;

a linkage module comprising a linkage member and a connector system
which is pivotably arranged about a pivot point on the body, wherein the linkage
member is movably engaged with the connector system to allow displacement of the
linkage member relative to the connector system, wherein the linkage member is
10 movably engaged with the guiding curve;

an applicator device supported by the linkage member; and

a drive module operably coupled to the connector system and configured to
cause a rotation of the connector system about the pivot point, wherein the rotation
is configured to drive the linkage member along the guiding curve and variably
15 displace the linkage member relative to the connection system to cause the
applicator device produce a straight-line path on a target surface.

2. The control apparatus of claim 1, wherein the guiding curve is defined on
the body by a set of distance coordinates (X_c, Y_c) wherein $X_c(\theta) = L \sin(\theta) - L_1 \tan(\theta)$
20 and $Y_c(\theta) = L \cos(\theta) - L_1$,

where X_c is a distance from the pivot point in an X-direction,

where Y_c is a distance from the pivot point in a Y-direction being orthogonal to
the X-direction,

where L_1 is a distance between the pivot point and an intermediate point on
25 the straight-line path, which is nearest to the pivot point,

where L is a distance between an intermediate point on the guiding curve and
the intermediate point on the straight line path, and taken through the pivot point,
and

where θ is a rotation angle of the linkage member from a line represented by

30 L.

3. The control apparatus of any one of claim 1 to claim 2, wherein the connector system comprises a pin arrangement and a pair of connectors, wherein an opening is formed partially along a length of the linkage member which is interposed between the pair of connectors, wherein the pin arrangement couples the pair of connectors and is received through the opening on the linkage member to allow variable displacement of the linkage member relative to the connector system along the length of the linkage member.

4. The control apparatus of any one of claim 1 to claim 3, wherein the applicator device includes a welding tool and/or a weaving mechanism.

5. The control apparatus of any one of claim 1 to claim 4, wherein the applicator device is integrally formed with the linkage member.

6. A robot comprising:
a carriage comprising:
at least one motor;
a plurality of wheels which are operable by the motor; and
the control device of any one of claim 1 to claim 5.

7. The robot of claim 7 wherein the carriage further comprises a self-alignment module which comprises:

a distance sensor configured to ascertain a plurality of distance readings from a plurality of points on the target surface; and

a computing unit communicably coupled to the distance sensor and the motor, wherein the computing unit is configured to compute a deviation angle of the carriage relative to the target surface based on the distance readings and send a control signal to the motor to cause rotation of the carriage by the deviation angle.

8. A method of producing straight-line path, the method comprising:

having a control device which comprises:

a guiding curve module comprising a body and a guiding curve arranged on the body,

5 a linkage module comprising a linkage member and a connector system which is pivotably arranged about a pivot point on the body, wherein the linkage member is movably engaged with the connector system and with the guiding curve,

an applicator device supported by the linkage member, and

a drive module operably coupled to the connector system;

10 using the drive module, causing a rotation of the connector system about the pivot point, and resulting in driving the linkage member along the guiding curve and variably displacing the linkage member relative to the connector system; and

15 using the driving of the linkage member along the guiding curve and the variable displacement of the linkage member relative to the connector system, producing, by the applicator device, a straight-line path on a target surface.

9. The method of claim 8, wherein

20 wherein the guiding curve is defined on the body by a set of distance coordinates (X_c, Y_c) wherein $X_c(\theta) = L \sin(\theta) - L_1 \tan(\theta)$ and $Y_c(\theta) = L \cos(\theta) - L_1$,

where X_c is a distance from the pivot point in an X-direction,

where Y_c is a distance from the pivot point in a Y-direction being orthogonal to the X-direction,

25 where L_1 is a distance between the pivot point and an intermediate point on the straight-line path, which is nearest to the pivot point,

where L is a distance between an intermediate point on the guiding curve and the intermediate point on the straight line path, and taken through the pivot point, and

where θ is a rotation angle of the linkage member from a line represented by

30 L .

10. The method of any one of claim 8 to claim 9, further comprising:
depositing, by the applicator device, weld material along the straight-line path on the target surface.

5 11. The method of any one of claim 8 to claim 10, wherein having the control device includes:

 having a robot which comprises:

 a carriage comprising:

 at least one motor;

10 a plurality of wheels which are operable by the motor; and
 the control device.

 12. The method of claim 11, wherein the carriage comprises a self-alignment module which comprises: a distance sensor and a computing unit communicably
15 coupled to the distance sensor and the motor, the method further comprising:

 ascertaining, by the distance sensor, a plurality of distance readings from a plurality of points on the target surface;

 computing, by the computing unit, a deviation angle of the carriage relative to the target surface based on the distance readings;

20 sending, by the computing unit, a control signal to the motor; and
 rotating, by the motor, the carriage by the deviation angle.

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