(c) ascertaining a current inverse travelling speed of welding torch for a current pass based on at least a position error and the feedforward controller function;

(d) ascertaining an optimized welding input vector from the plurality of desirable welding input vectors wherein the optimized welding input vector includes the current inverse travelling speed; and

(e) performing robotic welding based on parameters of the optimized welding input vector,

wherein step (a) includes ascertaining the feedforward controller function F based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

wherein P is a low order and linear time invariant (LTI) model.

With reference to the first aspect, in a first possible implementation manner of the first aspect, the position error is ascertained based on a difference between a reference welding profile of a previous layer and the actual welding profile of the previous layer.

With reference to the first aspect, in a second possible implementation manner of the first aspect, the reference welding profile is ascertained based on the weld geometry and a count of planned layers of weld.

With reference to the first aspect, in a third possible implementation manner of the first aspect, the method, wherein after performing robotic welding, further comprises:

upon ascertaining a current layer is complete, detecting an actual welding profile of the current layer for ascertaining a next position error for a next layer subsequent to the current layer; and

repeating steps (c), (d) and (e) for the next layer.

With reference to the first aspect, in a fourth possible implementation manner of the first aspect, the method, wherein after performing robotic welding, further comprises:

upon ascertaining a current layer is incomplete, repeating steps (c), (d) and (e).

With reference to any of the first aspect, the first to the fourth possible implementation manner of the first aspect, in a fifth implementation manner of the first aspect, step (b) includes using a polyhedral machine learning algorithm for machine learning training of the plurality of welding input vectors.

With reference to any of the first aspect, the first to the fifth possible implementation manner of the first aspect, in a sixth implementation manner of the first aspect, step (c) includes ascertaining the current inverse travelling speed of welding torch for a current pass based on

$$v^{-1}(k) = e^{l-1}(k)F + {v_c}^{-1}(0)$$

wherein $v^{-1}(k)$ is the current inverse travelling speed at time sample k, $e^{l-1}(k)$ is the position error, F is the feedforward controller function, and ${v_c}^{-1}(0)$ is a constant.

~~With reference to any of the first aspect, the first to the sixth possible implementation manner of the first aspect, in a seventh implementation manner of the first aspect, step (a) includes ascertaining the feedforward controller function F based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows~~

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

~~wherein P is a low order and linear time invariant (LTI) model.~~

According to a second aspect of the invention, a robotic welding system for performing multi-pass welding on a complex welding geometry is provided, the system comprising:

a welding torch and a robot manipulator supporting the welding torch;

at least one sensor;

a computing unit communicably coupled to the robot manipulator and the sensor;

a memory storage communicably coupled to the computing unit and includes computer-executable instructions to:

(a) ascertain a feedforward controller function;

(b) using machine learning training of a plurality of welding input vectors, ascertain a plurality of desirable welding input vectors therefrom, each of the plurality of welding input vectors having parameters which include

inverse travelling speed of the welding torch, weaving width of the welding torch, and weaving length of the welding torch;

(c) ascertain a current inverse travelling speed of welding torch for a current pass based on at least a position error and the feedforward controller function; and

(d) ascertain an optimized welding input vector from the plurality of desirable welding input vectors wherein the optimized welding input vector includes the current inverse travelling speed;

(e) control the welding torch and robotic manipulator to perform robotic welding based on parameters of the optimized welding input vector,

wherein the memory storage further includes computer-executable instructions to, in step (a), to ascertain the feedforward controller function *F* based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

wherein *P* is a low order and linear time invariant (LTI) model.

With reference to the second aspect, in a first possible implementation manner of the second aspect, the memory storage further includes computer-executable instructions to ascertain position error based on a difference between a reference welding profile of a previous layer and the actual welding profile of the previous layer.

With reference to the second aspect, in a second possible implementation manner of the second aspect, the reference welding profile is ascertained based on the weld geometry and a count of planned layers of weld.

With reference to the second aspect, in a third possible implementation manner of the second aspect, the memory storage further includes computer-executable instructions to

after performing robotic welding and upon ascertaining a current layer is complete, detect an actual welding profile of the current layer for ascertaining a next position error for a next layer subsequent to the current layer; and

repeat steps (c), (d) and (e) for the next layer.

With reference to the second aspect, in a fourth possible implementation manner of the second aspect, the memory storage further includes computer-executable instructions to

after performing robotic welding and upon ascertaining a current layer is incomplete, repeating steps (c), (d) and (e).

With reference to any of the second aspect, the first to the fourth possible implementation manner of the second aspect, in a fifth implementation manner of the second aspect, the memory storage further includes computer-executable instructions to, in step (b), use a polyhedral machine learning algorithm for machine learning training of the plurality of welding input vectors.

With reference to any of the second aspect, the first to the fifth possible implementation manner of the second aspect, in a sixth implementation manner of the second aspect, the memory storage further includes computer-executable instructions to, in step (c), ascertain the current inverse travelling speed of welding torch for a current pass based on

$$v^{-1}(k) = e^{l-1}(k)F + {v_c}^{-1}(0)$$

wherein $v^{-1}(k)$ is the current inverse travelling speed at time sample k, $e^{l-1}(k)$ is the position error , F is the feedforward controller function, and ${v_c}^{-1}(0)$ is a constant.

~~With reference to any of the second aspect, the first to the sixth possible implementation manner of the second aspect, in a seventh implementation manner of the second aspect, the memory storage further includes computer-executable instructions to, in step (a), to ascertain the feedforward controller function *F* based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows~~

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

~~wherein *P* is a low order and linear time invariant (LTI) model.~~

BRIEF DESCRIPTION OF THE DRAWINGS

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

Fig. 1 shows a complex weld geometry of a thick wall pipe-to-pipe joint prior to welding;

Fig. 2A shows a physical arrangement of a robotic welding system;

Fig. 2B shows a schematic arrangement of a robotic welding system;

Fig. 3 shows multi-pass planning for a thick wall pipe-to-pipe weld geometry;

Fig. 3 shows a weld geometry of a brace-to-chord joint;

Fig. 4A shows a torch tracking a previous seam boundary for each pass;

Fig. 4B shows a top view from the standing pipe;

Fig. 5 shows multi-pass filling of each layer using a robotic welding system;

Fig. 6 shows Zig-Zag weaving motion for robotic welding at each time sample (cycle);

Fig. 7A shows a block diagram for a welding profile control system according to one embodiment;

CLAIMS

1. A method of robotic multi-pass welding on a complex weld geometry by a welding torch, the method comprising:

(a) ascertaining a feedforward controller function;

(b) using machine learning training of a plurality of welding input vectors, ascertaining a plurality of desirable welding input vectors therefrom, each of the plurality of welding input vectors having parameters which include inverse travelling speed of the welding torch, weaving width of the welding torch, and weaving length of the welding torch;

(c) ascertaining a current inverse travelling speed of welding torch for a current pass based on at least a position error and the feedforward controller function;

(d) ascertaining an optimized welding input vector from the plurality of desirable welding input vectors wherein the optimized welding input vector includes the current inverse travelling speed; and

(e) performing robotic welding based on parameters of the optimized welding input vector,

wherein step (a) includes ascertaining the feedforward controller function *F* based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

wherein *P* is a low order and linear time invariant (LTI) model.

2. The method of claim 1, wherein the position error is ascertained based on a difference between a reference welding profile of a previous layer and the actual welding profile of the previous layer.

3. The method of claim 2, wherein the reference welding profile is ascertained based on the weld geometry and a count of planned layers of weld.

4. The method of claim 1, wherein after performing robotic welding, the method further comprising:

upon ascertaining a current layer is complete, detecting an actual welding profile of the current layer for ascertaining a next position error for a next layer subsequent to the current layer; and

repeating steps (c), (d) and (e) for the next layer.

5. The method of claim 1, wherein after performing robotic welding, the method further comprising:

upon ascertaining a current layer is incomplete, repeating steps (c), (d) and (e).

6. The method of any one of claims 1 to 5, wherein step (b) includes using a polyhedral machine learning algorithm for machine learning training of the plurality of welding input vectors.

7. The method of any one of claims 1 to 6, wherein step (c) includes ascertaining the current inverse travelling speed of welding torch for a current pass based on

$$v^{-1}(k) = e^{l-1}(k)F + {v_c}^{-1}(0)$$

wherein $v^{-1}(k)$ is the current inverse travelling speed at time sample k, $e^{l-1}(k)$ is the position error, F is the feedforward controller function, and ${v_c}^{-1}(0)$ is a constant.

~~8. The method of any one of claims 1 to 7, wherein step (a) includes ascertaining the feedforward controller function F based on a H infinity (H∞) controller which satisfies a minimisation problem as follows~~

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

~~wherein P is a low order and linear time invariant (LTI) model.~~

~~9~~8. A robotic welding system for performing multi-pass welding on a complex welding geometry, the system comprising:

a welding torch and a robot manipulator supporting the welding torch;

at least one sensor;

a computing unit communicably coupled to the robot manipulator and the sensor;

a memory storage communicably coupled to the computing unit and includes computer-executable instructions to:

(a) ascertain a feedforward controller function;

(b) using machine learning training of a plurality of welding input vectors, ascertain a plurality of desirable welding input vectors therefrom, each of the plurality of welding input vectors having parameters which include inverse travelling speed of the welding torch, weaving width of the welding torch, and weaving length of the welding torch;

(c) ascertain a current inverse travelling speed of welding torch for a current pass based on at least a position error and the feedforward controller function; and

(d) ascertain an optimized welding input vector from the plurality of desirable welding input vectors wherein the optimized welding input vector includes the current inverse travelling speed;

(e) control the welding torch and robotic manipulator to perform robotic welding based on parameters of the optimized welding input vector,

wherein the memory storage further includes computer-executable instructions to, in step (a), to ascertain the feedforward controller function F based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

wherein P is a low order and linear time invariant (LTI) model.

~~10~~9. The robotic welding system of claim ~~9~~8, wherein the memory storage further includes computer-executable instructions to ascertain position error based on a difference between a reference welding profile of a previous layer and the actual welding profile of the previous layer.

~~11~~10. The robotic welding system of claim ~~10~~9, wherein the reference welding profile is ascertained based on the weld geometry and a count of planned layers of weld.

~~12~~11. The robotic welding system of claim ~~9~~8, wherein the memory storage further includes computer-executable instructions to

after performing robotic welding and upon ascertaining a current layer is complete, detect an actual welding profile of the current layer for ascertaining a next position error for a next layer subsequent to the current layer; and

repeat steps (c), (d) and (e) for the next layer.

~~13~~12. The robotic welding system of claim ~~9~~8, wherein the memory storage further includes computer-executable instructions to

after performing robotic welding and upon ascertaining a current layer is incomplete, repeating steps (c), (d) and (e).

~~14~~13. The robotic welding system of any one of claims ~~9~~8 to ~~13~~12, wherein the memory storage further includes computer-executable instructions to, in step (b), use a polyhedral machine learning algorithm for machine learning training of the plurality of welding input vectors.

~~15~~14. The robotic welding system of any one of claims ~~9~~8 to ~~14~~13, wherein the memory storage further includes computer-executable instructions to, in step (c), ascertain the current inverse travelling speed of welding torch for a current pass based on

$$v^{-1}(k) = e^{l-1}(k)F + {v_c}^{-1}(0)$$

wherein $v^{-1}(k)$ is the current inverse travelling speed at time sample k, $e^{l-1}(k)$ is the position error , F is the feedforward controller function, and ${v_c}^{-1}(0)$ is a constant.

~~16. The robotic welding system of any one of claims 9 to 15, wherein the memory storage further includes computer-executable instructions to, in step (a), to ascertain the feedforward controller function F based on a H-infinity (H∞) controller which satisfies a minimisation problem as follows~~

$$\min_{F} \left\| \frac{1}{FP} \right\|_{\infty}$$
$$s.t. \ \left\| 1 - FP \right\|_{\infty} < 1$$

~~wherein P is a low order and linear time invariant (LTI) model.~~