

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent Application Publication

20250262681

Kind Code

A1

Publication Date

August 21, 2025

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SYSTEMS AND METHODS TO CONTROL WELDING WIRE TENSION

Abstract

An example welding wire feeder includes: a push motor configured to feed welding wire from a wire source; a first sensor configured to provide push motor velocity feedback; and control circuitry configured to control the push motor and a pull motor of a welding torch coupled to the welding wire feeder by: controlling a push motor velocity of the push motor and a pull motor velocity of the pull motor based on a target wire feed speed; and compensating each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the push motor velocity feedback and based on pull motor velocity feedback, wherein the push motor velocity and the pull motor velocity are based on a target wire tension.

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Family ID: 1000008578117

Appl. No.: 19/200218

Filed: May 06, 2025

Related U.S. Application Data

parent US continuation 17246142 20210430 parent-grant-document US 12290887 child US 19200218

Publication Classification

Int. Cl.: B23K9/133 (20060101); B23K9/12 (20060101); B65H59/38 (20060101)

U.S. Cl.:

Background/Summary

BACKGROUND

[0001] This disclosure relates generally to welding and, more particularly, to systems and methods to control welding wire tension.

[0002] When feeding aluminum welding wire through a long cable, the tension in the welding wire affects the performance and longevity of the feeding system and/or the welding torch. If the wire tension is too high, the wire may be subject to shaving along any edges in the feeder assembly, which will shorten the life of the liner and/or other consumables. Conversely, when the wire tension is too low (e.g., the wire is subject to compression), the wire may buckle, resulting in wasted time to clear a “bird's nest” of tangled wire and replacing the wire in the feeding system.

[0003] Moreover, tension that is too high or low will increase the power required by the pull motor, requiring a larger push-pull welding torch. A larger push-pull torch is generally less ergonomic for the welding operator. If the tension is too high, the pull motor has to produce more torque to keep the wire under tension. If the tension is too low, the wire may become compressed and the liner fills up with wire, which increases the liner's friction.

SUMMARY

[0004] Systems and methods to control welding wire tension are disclosed, substantially as illustrated by and described in connection with at least one of the figures, as set forth more completely in the claims.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] These and/or other aspects will become apparent and more readily appreciated from the following description of the exemplary embodiments, taken in conjunction with the accompanying drawings.

[0006] FIG. 1 is a block diagram of an example welding system to perform welding, including a welding-type power supply and a separate wire feeder in a push-pull wire feeding configuration, in accordance with aspects of this disclosure.

[0007] FIG. 2 is a block diagram of another example welding system to perform welding, in which a welding-type power supply includes an integral wire feeder in a push-pull wire feeding configuration, in accordance with aspects of this disclosure.

[0008] FIG. 3 is a block diagram of an example tension control system that may be implemented by the welding system of FIG. 1 or 2 to control a wire tension in the push-pull wire feeding configuration.

[0009] FIG. 4 is a block diagram of an example implementation of the example motion command generator of FIG. 3.

[0010] FIG. 5 is a block diagram of an example implementation of the example push motor controller of FIG. 3.

[0011] FIG. 6 is a block diagram of an example implementation of the example push motor controller of FIG. 3.

[0012] FIG. 7 is a block diagram of an example implementation of the example tension observer of FIG. 3.

[0013] FIG. 8 is a flowchart representative of example machine readable instructions which may be

executed by the example welding system of FIG. 1 or 2 to implement the tension control system of FIGS. 3-7.

[0014] The figures are not necessarily to scale. Where appropriate, similar or identical reference numbers are used to refer to similar or identical components.

DETAILED DESCRIPTION

[0015] For the purpose of promoting an understanding of the principles of this disclosure, reference will be now made to the examples illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the claims is intended by this disclosure. Modifications in the illustrated examples and such further applications of the principles of this disclosure as illustrated therein are contemplated as would typically occur to one skilled in the art to which this disclosure relates.

[0016] Disclosed systems and methods control the push motor and pull motor in a welding system to control the tension in the welding wire. In contrast with conventional, speed-based or torque-based push-pull systems, disclosed systems and methods virtually couple the push motor and the pull motor to maintain a target wire tension. In some example systems and methods, the virtual coupling mimics or serves as a virtual tuned spring that reacts to disturbances in the push motor and/or pull motor to maintain the tension in the welding wire.

[0017] As used herein, the term “velocity” generally means “linear velocity,” such as a wire feed velocity, unless otherwise stated. For example, while a wire feed push motor and/or pull motor may have an angular velocity, the angular velocity may be translated into a linear velocity, such as at the point the motor or corresponding drive rolls make contact with a welding wire, using corresponding terms such as gearbox ratios and drive roll radii.

[0018] As used herein, a welding-type power source refers to any device capable of, when power is applied thereto, supplying welding, cladding, plasma cutting, induction heating, laser (including laser welding and laser cladding), carbon arc cutting or gouging and/or resistive preheating, including but not limited to transformer-rectifiers, inverters, converters, resonant power supplies, quasi-resonant power supplies, switch-mode power supplies, etc., as well as control circuitry and other ancillary circuitry associated therewith.

[0019] Disclosed example welding wire feeders, include: a push motor configured to feed welding wire from a wire source; a first sensor configured to provide push motor velocity feedback; and control circuitry configured to control the push motor and a pull motor of a welding torch coupled to the welding wire feeder by: controlling a push motor velocity of the push motor and a pull motor velocity of the pull motor based on a target wire feed speed; and compensating each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the push motor velocity feedback and based on pull motor velocity feedback, wherein the push motor velocity and the pull motor velocity are based on a target wire tension.

[0020] In some examples, the control circuitry is configured to generate a velocity command based on the target wire feed speed and the target wire tension, and the control circuitry is configured to control the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the velocity command. In some example welding wire feeders, the control circuitry is configured to: estimate a wire slip velocity based on a push motor force and a pull motor force; estimate a wire tension in the welding wire based on the wire slip velocity, the push motor velocity feedback, and the pull motor velocity feedback; and compensate each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the estimated wire tension and the estimated wire slip velocity.

[0021] In some example welding wire feeders, the control circuitry is configured to: determine an estimated friction force in response to the push motor velocity and the pull motor velocity reaching a threshold velocity based on a velocity command; and determine the wire slip velocity based on reducing a difference in the push motor force and the pull motor force by the estimated friction force. In some example welding wire feeders, the control circuitry is configured to estimate the

wire tension based on adding the estimated wire slip velocity to a difference between the push motor velocity feedback and the pull motor velocity feedback.

[0022] In some examples, the first sensor comprises an encoder coupled to the push motor to measure at least one of an angular position or an angular velocity of the push motor. In some examples, the control circuitry is configured to, at a beginning of a welding operation, control the pull motor and the push motor to apply forces to the welding wire in opposing directions to establish a reference wire tension based on the target wire tension. In some examples, the control circuitry is configured to determine the pull motor velocity feedback based on receiving at least one of a pull motor angular velocity or a pull motor angular position from a pull motor encoder of the welding torch coupled to the welding wire feeder.

[0023] In some example welding wire feeders, the control circuitry is configured to set the target wire tension based on a type of the welding wire. In some example welding wire feeders, controlling the push motor velocity of the push motor involves generating a push motor force command, and controlling the pull motor velocity of the pull motor comprises generating a pull motor force command. In some examples, the control circuitry is configured to control the push motor velocity of the push motor by setting the push motor force command using an integrator based on a velocity command and the push motor velocity feedback. In some examples, the control circuitry is configured to control the pull motor velocity of the pull motor by setting a pull motor force using an integrator based on a velocity command and the pull motor velocity feedback.

[0024] Disclosed example methods to control welding wire tension involve: controlling a push motor velocity of a push motor of a welding wire feeder based on a target wire feed speed; controlling a pull motor velocity of a pull motor of a welding torch coupled to the welding wire feeder based on the target wire feed speed; and compensating each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on push motor velocity feedback and based on pull motor velocity feedback, wherein the push motor velocity and the pull motor velocity are based on a target wire tension.

[0025] In some example methods, the controlling of the push motor velocity of the push motor involves generating a push motor force command, and the controlling of the pull motor velocity of the pull motor comprises generating a pull motor force command. Some example methods further involve: estimating a wire slip velocity based on a push motor force and a pull motor force; estimating a wire tension in the welding wire based on the wire slip velocity, the push motor velocity feedback, and the pull motor velocity feedback; and compensating each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the estimated wire tension and the estimated wire slip velocity. Some example methods further involve determining an estimated friction force in response to the push motor velocity and the pull motor velocity reaching a threshold velocity based on a velocity command, wherein the determining of the wire slip velocity is based on reducing a difference in the push motor force and the pull motor force by the estimated friction force.

[0026] In some example methods, the estimating of the wire tension is based on adding the estimated wire slip velocity to a difference between the push motor velocity feedback and the pull motor velocity feedback. Some example methods further involve measuring at least one of an angular position or an angular velocity of the push motor with an encoder, and determining the push motor velocity feedback based on the angular position or the angular velocity.

[0027] Some example methods further involve, at a beginning of a welding operation, controlling the pull motor and the push motor to apply forces to the welding wire in opposing directions to establish a reference wire tension based on the target wire tension. Some example methods further involve setting the target wire tension based on a type of the welding wire.

[0028] FIG. 1 is a block diagram of an example welding system to perform welding, including a welding-type power supply and a separate wire feeder in a push-pull wire feeding configuration. The example welding system **100** includes a welding-type power supply **102**, a wire feeder **104**,

and a welding torch **106**. The welding system **100** powers, controls, and supplies consumables to a welding application. The example welding torch **106** is configured for gas metal arc welding (GMAW). In the illustrated example, the power supply **102** is configured to supply power to the wire feeder **104**, and the wire feeder **104** may be configured to route the input power to the welding torch **106**. In addition to supplying an input power, the wire feeder **104** supplies a filler metal to a welding torch **106** for various welding applications (e.g., GMAW welding, flux core arc welding (FCAW)).

[0029] The power supply **102** receives primary power **108** (e.g., from the AC power grid, an engine/generator set, a battery, or other energy generating or storage devices, or a combination thereof), conditions the primary power, and provides an output power to one or more welding devices in accordance with demands of the system **100**. The primary power **108** may be supplied from an offsite location (e.g., the primary power may originate from the power grid). The power supply **102** includes a power conversion circuitry **110**, which may include transformers, rectifiers, switches, and so forth, capable of converting the AC input power to AC and/or DC output power as dictated by the demands of the system **100** (e.g., particular welding processes and regimes). The power conversion circuitry **110** converts input power (e.g., the primary power **108**) to welding-type power based on a weld voltage setpoint and outputs the welding-type power via a weld circuit.

[0030] In some examples, the power conversion circuitry **110** is configured to convert the primary power **108** to both welding-type power and auxiliary power outputs. However, in other examples, the power conversion circuitry **110** is adapted to convert primary power only to a weld power output, and a separate auxiliary converter is provided to convert primary power to auxiliary power. In some other examples, the power supply **102** receives a converted auxiliary power output directly from a wall outlet. Any suitable power conversion system or mechanism may be employed by the power supply **102** to generate and supply both weld and auxiliary power.

[0031] The power supply **102** includes control circuitry **112** to control the operation of the power supply **102**. The power supply **102** also includes a user interface **114**. The control circuitry **112** receives input from the user interface **114**, through which a user may choose a process and/or input desired parameters (e.g., voltages, currents, particular pulsed or non-pulsed welding regimes, and so forth). The user interface **114** may receive inputs using any input device, such as via a keypad, keyboard, buttons, touch screen, voice activation system, wireless device, etc. Furthermore, the control circuitry **112** controls operating parameters based on input by the user as well as based on other current operating parameters. Specifically, the user interface **114** may include a display **116** for presenting, showing, or indicating, information to an operator. The control circuitry **112** may also include interface circuitry for communicating data to other devices in the system **100**, such as the wire feeder **104**. For example, in some situations, the power supply **102** wirelessly communicates with the wire feeder **104** and/or other welding devices within the welding system **100**. Further, in some situations, the power supply **102** communicates with the wire feeder **104** and/or other welding devices using a wired connection, such as by using a network interface controller (NIC) to communicate data via a network (e.g., ETHERNET, 10BASE2, 10BASE-T, 100BASE-TX, etc.).

[0032] The control circuitry **112** includes at least one processor **120** that controls the operations of the power supply **102**. The control circuitry **112** receives and processes multiple inputs associated with the performance and demands of the system **100**. The processor **120** may include one or more microprocessors, such as one or more “general-purpose” microprocessors, one or more special-purpose microprocessors and/or ASICS, and/or any other type of processing device and/or logic circuit. For example, the processor **120** may include one or more digital signal processors (DSPs).

[0033] The example control circuitry **112** includes one or more storage device(s) **123** and one or more memory device(s) **124**. The storage device(s) **123** (e.g., nonvolatile storage) may include ROM, flash memory, a hard drive, and/or any other suitable optical, magnetic, and/or solid-state storage medium, and/or a combination thereof. The storage device **123** stores data (e.g., data

corresponding to a welding application), instructions (e.g., software or firmware to perform welding processes), and/or any other appropriate data. Examples of stored data for a welding application include an attitude (e.g., orientation) of a welding torch, a distance between the contact tip and a workpiece, a voltage, a current, welding device settings, and so forth.

[0034] The memory device **124** may include a volatile memory, such as random access memory (RAM), and/or a nonvolatile memory, such as read-only memory (ROM). The memory device **124** and/or the storage device(s) **123** may store a variety of information and may be used for various purposes. For example, the memory device **124** and/or the storage device(s) **123** may store processor executable instructions **125** (e.g., firmware or software) for the processor **120** to execute. In addition, one or more control regimes for various welding processes, along with associated settings and parameters, may be stored in the storage device **123** and/or memory device **124**, along with code configured to provide a specific output (e.g., initiate wire feed, enable gas flow, capture welding current data, detect short circuit parameters, determine amount of spatter) during operation.

[0035] In some examples, the welding power flows from the power conversion circuitry **110** through a weld cable **126** to the wire feeder **104** and the welding torch **106**. The example weld cable **126** is attachable and detachable from weld studs at each of the power supply **102** and the wire feeder **104** (e.g., to enable case of replacement of the weld cable **126** in case of wear or damage).

[0036] The example communications transceiver **118** includes a receiver circuit **121** and a transmitter circuit **122**. Generally, the receiver circuit **121** receives data transmitted by the wire feeder **104** and the transmitter circuit **122** transmits data to the wire feeder **104**. The example wire feeder **104** also includes a communications transceiver **119**, which may be similar or identical in construction and/or function as the communications transceiver **118**.

[0037] In some examples, a gas supply **128** provides shielding gases, such as argon, helium, carbon dioxide, and so forth, depending upon the welding application. The shielding gas flows to a valve **130**, which controls the flow of gas, and if desired, may be selected to allow for modulating or regulating the amount of gas supplied to a welding application. The valve **130** may be opened, closed, or otherwise operated by the control circuitry **112** to enable, inhibit, or control gas flow (e.g., shielding gas) through the valve **130**. Shielding gas exits the valve **130** and flows through a gas conduit **132** (which in some implementations may be packaged with the welding power output) to the wire feeder **104** which provides the shielding gas to the welding application. In some examples, the welding system **100** does not include the gas supply **128**, the valve **130**, and/or the gas conduit **132**. In some other examples, the valve **130** is located in the wire feeder **104**, and, the gas supply **128** is connected to the wire feeder **104**.

[0038] In some examples, the wire feeder **104** uses the welding power to power the various components in the wire feeder **104**, such as to power wire feeder control circuitry **134**. As noted above, the weld cable **126** may be configured to provide or supply the welding power. The wire feeder control circuitry **134** controls the operations of the wire feeder **104**. In some examples, the wire feeder **104** uses the wire feeder control circuitry **134** to detect whether the wire feeder **104** is in communication with the power supply **102** and to detect a current welding process of the power supply **102** if the wire feeder **104** is in communication with the power supply **102**.

[0039] A contactor **135** (e.g., high amperage relay) is controlled by the wire feeder control circuitry **134** and configured to enable or inhibit welding power to continue to flow to the weld cable **126** for the welding application. In some examples, the contactor **135** is an electromechanical device. However, the contactor **135** may be any other suitable device, such as a solid state device, and/or may be omitted entirely and the weld cable **126** is directly connected to the output to the welding torch **106**.

[0040] The example system **100** of FIG. **1** is configured as a push-pull configuration, which is used for certain welding applications such as aluminum welding. In the push-pull configuration, the wire

feeder **104** includes a push motor **136** that receives control signals from the wire feeder control circuitry **134** to drive rollers **138** that rotate to pull wire off a spool **140** of wire. The push motor **136** feeds electrode wire to the welding torch **106**. In the push-pull configuration, the example welding torch **106** of FIG. **1** is a push-pull type welding torch, which includes a pull motor **137**, which aids in maintaining proper tension on the wire to avoid buckling that might occur if only the push motor **136** were used to feed the wire.

[0041] The wire **142** is provided to the welding torch **106** through a torch cable **144**. Likewise, the wire feeder **104** may provide the shielding gas from the gas conduit **132** and combined in a torch cable **144**. The electrode wire, the shield gas, and the power from the weld cable **126** are bundled together in a single torch cable **144** and/or individually provided to the welding torch **106**.

[0042] The welding torch **106** delivers the wire, welding power, and/or shielding gas for a welding application. The welding torch **106** is used to establish a welding arc between the welding torch **106** and a workpiece **146**. A work cable **148** couples the workpiece **146** to the power supply **102** (e.g., to the power conversion circuitry **110**) to provide a return path for the weld current (e.g., as part of the weld circuit). The example work cable **148** is attachable and/or detachable from the power supply **102** for case of replacement of the work cable **148**. The work cable **148** may be terminated with a clamp **150** (or another power connecting device), which couples the power supply **102** to the workpiece **146**.

[0043] A communication cable **154** connected between the power supply **102** and the wire feeder **104**, which enables bidirectional communication between the transceivers **118**, **119**. The communications transceivers **118** and **119** may communicate via the communication cable **154**, via the weld circuit, via wireless communications, and/or any other communication medium. Examples of such communications include weld cable voltage measured at a device that is remote from the power supply **102** (e.g., the wire feeder **104**).

[0044] The example control circuitry **134** of FIG. **1** controls the push motor **136** and the pull motor **137** (e.g., via control lines **158**). The control lines **158** include conductors to provide power and/or commands to the pull motor **137**. As disclosed in more detail below, the control circuitry **134** (e.g., via the processor(s) **120** executing the instructions **125**) controls the force (e.g., the current, torque, etc.) output by the push motor **136** and the force (e.g., the current, torque, etc.) output by the pull motor **137**. For example, the control circuitry **134** may control the current provided to each of the push motor **136** and the pull motor **137** based on a tension control scheme. An example tension control scheme, as disclosed in more detail below, is based on inputs specifying a target wire feed speed and a target wire tension. The target wire tension may be based on a selected wire type and/or wire diameter.

[0045] To implement the control, the example control circuitry **134** receives angular velocity, angular position, linear velocity, and/or linear position information about the push motor **136** from a first encoder **160** (e.g., a push motor encoder, or push encoder), and receives angular velocity, angular position, linear velocity, and/or linear position information about the pull motor **137** from a second encoder **162** (e.g., a pull motor encoder, or pull encoder) in the welding torch **106** via the control lines **158**.

[0046] FIG. **2** is a block diagram of another example welding system **200** to perform welding, in which a welding-type power supply **202** includes an integrated wire feeder **204** in a push-pull wire feeding configuration. The example welding-type power supply **202** includes the power conversion circuitry **110**, control circuitry **112**, the user interface **114**, the display **116**, the processor(s) **120**, the storage devices(s) **123**, the memory **124**, the instructions **125**, and the valve **130** of the example power supply **102** of FIG. **1**.

[0047] In contrast with the example system **100**, in the example of FIG. **2** the power supply **202** includes the integrated wire feeder **204** instead being connected to a remote wire feeder. The power supply **202** of FIG. **2** outputs welding-type power and electrode wire to the torch **106**, which includes the example power selector circuit **156**.

[0048] The integrated wire feeder **204** includes the push motor **136**, the drive rollers **138**, and the wire spool **140**, and feeds the wire through a torch cable **144** to the torch **106**.

[0049] The example welding-type power supply **202** includes a communication circuit **206** to receive data via the control lines **158** from the pull encoder **162** (e.g., during a welding operation). In some examples, the communication circuit **206** converts an analog signal to a digital signal for use by the control circuitry **112** and/or receives a digital signal from the pull encoder **162**.

[0050] The control circuitry **112** may reference a synergic control scheme, such as an algorithm or a lookup table, to determine target tension and/or a target wire feed speed corresponding to the user input. A lookup table may be stored in, for example, the storage device(s) **123** and/or the memory **124** of the control circuitry **112**.

[0051] During operation, and as disclosed in more detail below, the example control circuitry **112**, **134** of FIGS. **1** and **2** control the push motor **136** and the pull motor **137** by controlling a push motor velocity $v_{sub.ps}$ of the push motor **136** and a pull motor velocity $v_{sub.pl}$ of the pull motor **137** based on a target wire feed speed $v^*_{sub.wfs}$, and compensates each of the push motor velocity $v_{sub.ps}$ of the push motor **136** and the pull motor velocity $v_{sub.pl}$ of the pull motor **137** based on the push motor velocity feedback $v_{sub.ps}$ and based on pull motor velocity feedback $v_{sub.pl}$. The control circuitry **112**, **134** controls and/or compensates the push motor velocity $v_{sub.ps}$ and the pull motor velocity $v_{sub.pl}$ based on a target wire tension $\tau^*_{sub.t}$. In particular, the control circuitry **112**, **134** controls the push motor velocity $v_{sub.ps}$ by generating a push motor force command $F^*_{sub.ps}$, and controls the pull motor velocity $v_{sub.pl}$ of the pull motor **137** comprises generating a pull motor force command $F^*_{sub.pl}$.

[0052] FIG. **3** is a block diagram of an example tension control system **300** that may be implemented by the welding system **100**, **200** of FIG. **1** or **2** to control a wire tension in the push-pull wire feeding configuration. The example tension control system **300** may be implemented by, for example, the processor(s) **120** executing the machine readable instructions **125**, by an application specific integrated circuit, and/or any combination of hardware, software, and/or firmware.

[0053] The example tension control system **300** of FIG. **3** includes a motion command generator **302**, a tension observer **304**, a push motor controller **306**, and a pull motor controller **308**. The example system **300** further includes a push current sensor **310** and a pull current sensor **312**. The push motor controller **306** controls a push motor force $F_{sub.ps}$ applied by the push motor **136**, and the pull motor controller **308** controls a pull motor force $F_{sub.pl}$ applied by the pull motor **137**. The sensors **310**, **312** measure the push motor force $F_{sub.ps}$ and the pull motor force $F_{sub.pl}$ (e.g., torque, which is based on the current through the motor) applied by the respective ones of the push motor **136** and the pull motor **137**.

[0054] The example motion command generator **302** generates a velocity command $v_{sub.vt}$ to the push motor controller **306** and the pull motor controller **308**. The example velocity command $v_{sub.vt}$ is based on a target wire feed speed $v^*_{sub.wfs}$ and force command feedback from the push motor controller **306** and the pull motor controller **308**. FIG. **4** is a block diagram of an example implementation of the example motion command generator **302** of FIG. **3**. The motion command generator **302** may be implemented by the control circuitry **112**, **134** of FIGS. **1** and/or **2**. The example motion command generator **302** includes at least one integrator (e.g., a PI controller **402**), a force limiter **404**, and integrators **406**, **408** to generate the velocity command $v_{sub.vt}$, receives the target wire feed speed $v^*_{sub.wfs}$, a push force command $F^*_{sub.ps}$ (e.g., calculated by the push motor controller **306**), and a pull force command $F^*_{sub.pl}$ (e.g., calculated by the pull motor controller **308**).

[0055] The example PI controller **402** includes at least one integrator and may include one or more proportional terms, and is tuned so that the push motor **136** and the pull motor **137** can follow the velocity command $v_{sub.vt}$. The force limiter **404** affects or limits a combined acceleration of the motors **136**, **137**, and filters the output of the PI controller **402** to avoid commanding a velocity

change that would require more force (e.g., current) than allowed for the push motor **136** and the pull motor **137**. The push force command $F^*.sub.ps$ and a pull force command $F^*.sub.pl$ are input as feedback of the commanded, unconstrained forces $F^*.sub.ps$ and $F^*.sub.pl$ from the push motor controller **306** and the pull motor controller **308**. The motion command generator **302** scales the push force command $F^*.sub.ps$ and a pull force command $F^*.sub.pl$ by the respective virtual gear ratios $g.sub.ps$ and $g.sub.pl$ of the push motor **136** and the pull motor **137** for input to the control loop. The virtual gear ratios $g.sub.ps$ and $g.sub.pl$ may be set to match or balance the powers of the push motor **136** and the pull motor **137** so that perturbations in one of the push motor **136** or the pull motor **137** appropriately affects the response by the other of the motors **136**, **137**.

[0056] If either the push motor **136** or the pull motor **137** runs into its force limits and the corresponding PI regulator of the push motor controller **306** or the pull motor controller **308** will wind up, the motion command generator **302** decreases the velocity command $v.sub.vt$ so that the tension in the wire does not become too large or too small relative to the target tension $\tau.sub.t$. The velocity command $v.sub.vt$ is also fed back to the control loop of the motion command generator **302**.

[0057] The resulting force $F.sub.vt$ following the scaled push force command $F^*.sub.ps$ and a pull force command $F^*.sub.pl$ feedback is converted to the velocity command $v.sub.vt$ by integrators **406**, **408**. The velocity command $v.sub.vt$ is output to the push motor controller **306** and to the pull motor controller **308**.

[0058] The example push motor controller **306** controls a push motor velocity $v.sub.ps$ of the push motor **136** based on the target wire feed speed $v^*.sub.wfs$ and the target wire tension τ^* . FIG. 5 is a block diagram of an example implementation of the example push motor controller **306** of FIG. 3. In a similar manner, the pull motor controller **308** controls a pull motor velocity $v.sub.pl$ of the pull motor **137** based on the target wire feed speed $\tau^*.sub.wfs$ and the target wire tension τ^* . FIG. 6 is a block diagram of an example implementation of the example pull motor controller **308** of FIG. 3.

[0059] The example push motor controller **306** and the pull motor controller **308** each include at least one integrator, and may include one or more proportional terms. In the examples of FIGS. 5 and 6, the push motor controller **306** and the pull motor controller **308** each include respective PII controllers **502**, **602**.

[0060] The PII controller **502** of FIG. 5 receives a compensated velocity command $v.sub.vt$, which is compensated by subtracting the push motor velocity feedback $v.sub.ps$ and adding the estimated slip velocity $\{\text{circumflex over } (v)\}.sub.slip$. The motion command generator **302** can be considered as a virtual motor, which has a corresponding velocity (e.g., the velocity command $v.sub.vt$). The proportional terms of the PII controllers **502**, **602** each control the difference in velocity between the respective motor (e.g., $v.sub.ps$, $v.sub.pl$) and the velocity $v.sub.vt$ of the motion command generator **302** as a virtual motor. The proportional terms add damping between the physical motors **136**, **137** and motion command generator **302** as the virtual motor.

[0061] The PII controller **502** further receives a wire position term based on the integrated velocity error (e.g., via integrator **504**) and a position offset Δp^* . The position offset Δp^* is based on the target wire tension and a tuned spring constant K , one or both of which may be selected based on the selected wire type. The position offset Δp^* may be substantially constant over the course of a welding operation. In the example of FIG. 5, the PII controller **502** includes a second integrator to reduce or eliminate steady state error in the PII controller **502**.

[0062] The PII controller **502** outputs a commanded push motor force $F^*.sub.ps$ to a force limiter **506**, which limits the force (e.g., current) command that is output to the push motor **136**. The resulting push motor force $F.sub.ps$ is output to the push motor **136** (e.g., as the corresponding current or power to drive the push motor **136**). The example push current sensor **310** measures the push motor force $F.sub.ps$ and provides the measured push motor force $F.sub.ps$ as feedback to the tension observer **304**. The push motor controller **306** also outputs the commanded push motor force $F^*.sub.ps$ to the motion command generator **302** as feedback, as described above.

[0063] The example pull motor controller **308** of FIG. 6 includes a PII controller **602**, which may be similar to the PII controller **502** of FIG. 5, except that the PII controller **602** is tuned to the characteristics of the pull motor **137** instead of the push motor **136**. For example, the PII controller **602** receives a compensated velocity command $v_{sub.vt}$, which is compensated by subtracting the pull motor velocity feedback $v_{sub.pl}$ and subtracting the estimated slip velocity $\{\text{circumflex over } (v)\}_{sub.slip}$. The PII controller **602** further receives a wire position term based on the integrated velocity error (e.g., via integrator **604**) and the position offset Δp^* . The PII controller **602** also includes a second integrator to reduce or eliminate steady state error in the PII controller **602**.

[0064] The PII controller **602** outputs a commanded push motor force $F^*_{sub.pl}$ to a force limiter **606**, which limits the force (e.g., current) command that is output to the pull motor **137**. The resulting pull motor force $F_{sub.pl}$ is output to the pull motor **137** (e.g., as the corresponding current or power to drive the pull motor **137**). The example pull current sensor **312** measures the pull motor force $F_{sub.pl}$ and provides the measured pull motor force $F_{sub.pl}$ as feedback to the tension observer **304**. The pull motor controller **308** also outputs the commanded pull motor force $F^*_{sub.pl}$ to the motion command generator **302** as feedback, as described above.

[0065] While example PII controllers **502**, **602** are disclosed above, the motor controllers **306**, **308** may include more or fewer proportional and/or integral terms. In some examples, the PII controllers **502**, **602** include one or more differential terms, such as when position feedback is received from the encoders **160**, **162**. Such position feedback may be processed by a differential term in the controllers **502**, **602** (e.g., now PID controllers) to determine velocity.

[0066] As shown above, the example motor controllers **306**, **308** are each controlled independently, but are also virtually coupled via the motion command generator **302** which incorporates feedback from both motor controllers **306**, **308**.

[0067] The example motion command generator **302** and the motor controllers **306**, **308** of FIGS. 3-6 control the motors **136**, **137** based on velocity feedback. However, in practical systems, controlling the differential position of the motor is not sufficient to maintain the desired tension. Over time, the drive rolls coupled to the wire will slip relative to the wire, so the motor velocity will not equal the wire velocity. The difference in velocity causes a reduction in the tension in the wire over time. However, it may take time on the order of seconds until the reduction in tension due to slip is noticeable in the motor force feedback. The example tension observer **304** estimates the wire tension in the wire based on feedback from the push motor force $F_{sub.ps}$ (e.g., from the push current sensor **310**), the pull motor force $F_{sub.pl}$ (e.g., from the push current sensor **310**), the push motor velocity $v_{sub.ps}$, the pull motor velocity $v_{sub.pl}$, and the velocity command $v_{sub.vt}$.

[0068] The example tension observer **304** uses the difference in force between the push motor **136** and the pull motor **137** to estimate the wire slip velocity. However, the motor force difference contains the wire tension, the difference in motor friction, and the acceleration forces in the motors **136**, **137**. Since the motors **136**, **137** accelerate only for a short period, the acceleration forces are filtered out by tuning a PI regulator **704** of the tension observer **304** to be slower than the motor controllers **306**, **308**.

[0069] In the example of FIG. 6, the tension observer **304** first determines an estimated friction force $F_{sub.\mu,m}$. The friction force $F_{sub.\mu,m}$ represents both motor friction and wire friction within the length of the cable. To estimate the friction force $F_{sub.\mu,m}$, the tension observer **304** samples and holds **702** a force difference $F_{sub.ps} - F_{sub.pl}$ in response to the push motor velocity $v_{sub.ps}$ and/or the pull motor velocity $v_{sub.pl}$ reaching a threshold, which may be based on the velocity command $v_{sub.vt}$. At the time the push motor velocity $v_{sub.ps}$ and/or the pull motor velocity $v_{sub.pl}$ reach the threshold, it may be assumed that the force difference contains only the tension and the friction terms. Under the further assumption that there has been little slip up to the point that the sample and hold **702** is triggered, and the force difference $F_{sub.ps} - F_{sub.pl}$ is mainly the frictional losses, the sample and hold element **702** will decouple the frictional forces from the tension estimation by subtracting the frictional force $F_{sub.\mu,m}$ from the

force difference $F_{sub.ps} - F_{sub.pl}$.

[0070] The tension observer **304** estimates a wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ based on the push motor force $F_{sub.ps}$ and a pull motor force $F_{sub.pl}$, and removes the wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ from the motor velocity difference (e.g., $v_{sub.ps} - v_{sub.pl}$). The tension observer **304** receives the velocity feedback from the push encoder **160** and the pull encoder **162**. The resulting velocity is integrated at integrator **706** and multiplied by the spring constant K **708** to estimate the wire tension $\{\text{circumflex over (}\tau)\}$. The estimated wire tension $\{\text{circumflex over (}\tau)\}$ may be used as feedback to estimate the wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$. The estimated wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ is further provided to the motor controllers **306**, **308**.

[0071] In some examples, the control circuitry **134** performs a tension initialization at the beginning of each welding operation (e.g., when the motors **136**, **137** are first accelerated). During the tension initialization, the control circuitry **134** commands the forces of the push motor **136** and the pull motor **137** in opposing directions to establish an initialization tension. The control circuitry **134** (e.g., the tension control system **300**) may use the initialization tension as the reference tension or “zero” tension, with respect to the target tension $v_{sub.t}$.

[0072] The example tension observer **304** estimates a wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ between the push motor **136** and the wire and/or the pull motor **137** and the wire, and estimates the tension in the wire to determine the wire slip velocity.

[0073] FIG. **8** is a flowchart representative of example machine readable instructions **800** which may be executed by the example welding system **100**, **200** of FIG. **1** or **2** to implement the tension control system **300** of FIGS. **3-7**. The example instructions **800** may be executed by the example control circuitry **112**, **134** (e.g., via the processor(s) **120**) of FIGS. **1** and/or **2**.

[0074] At block **802**, the control circuitry **134** determines whether a wire type has been selected. For example, an operator may select a wire type, a wire size, and/or other characteristics of the wire via a user interface (e.g., the user interface **114**). If a wire type has been selected (block **802**), at block **804** the control circuitry **134** sets a target wire tension $\tau^*_{sub.t}$. For example, the control circuitry **134** may look up the target wire tension $\tau^*_{sub.t}$ in a look up table stored in the memory **124** and/or the storage device(s) **123**.

[0075] After setting the target wire tension $\tau^*_{sub.t}$ (block **804**), or if a wire type has not been selected (block **802**), at block **806** the control circuitry **134** determines whether welding has started. If welding has not started (block **806**), control returns to block **802**.

[0076] If welding has started (block **806**), at block **808** the control circuitry **134** initializes the push motor **136** and the pull motor **137** to apply the target wire tension $\tau^*_{sub.t}$. For example, the control circuitry **134** may command the forces of the push motor **136** and the pull motor **137** in opposing directions to establish an initialization tension.

[0077] At block **810**, the control circuitry **134** sets a wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ and a friction force $F_{sub.\mu,m}$ to predetermined values. For example, the predetermined values may be estimated values, values that do not substantially affect the control loops prior to determining updated values of wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ and the friction force $F_{sub.\mu,m}$.

[0078] At block **812**, the control circuitry **134** determines whether a friction force $F_{sub.\mu,m}$ has been estimated. For example, the control circuitry **134** may determine whether the sample and hold clement **702** has been triggered. If the friction force $F_{sub.\mu,m}$ has been estimated (block **812**), at block **814** the control circuitry **134** determines a wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$ based on the push motor force $F_{sub.ps}$, the pull motor force $F_{sub.pl}$, and the friction force $F_{sub.\mu,m}$. For example, the control circuitry **134** may implement the tension observer **304** of FIG. **7** to determine the wire slip velocity $\{\text{circumflex over (v)}\}_{sub.slip}$.

[0079] If the friction force $F_{sub.\mu,m}$ has not been estimated (block **812**), at block **816** the control circuitry **134** determines whether a push motor velocity $v_{sub.ps}$ and a pull motor velocity $v_{sub.pl}$

is at least a threshold velocity. The threshold velocity may be, for example, the velocity command $v_{sub.vt}$ and/or the commanded wire feed speed $v^*_{sub.wfs}$. In some examples, the threshold velocity may be different velocities (e.g., different linear velocity thresholds, different angular velocity thresholds). If the push motor velocity $v_{sub.ps}$ and the pull motor velocity $v_{sub.pl}$ is at least the threshold velocity (block **816**), at block **818** the control circuitry **134** estimates the friction force $F_{sub.\mu,m}$. For example, the sample and hold element **702** of the tension observer **304** may hold a force difference $F_{sub.ps} - F_{sub.pl}$ captured at the time the push motor velocity $v_{sub.ps}$ and the pull motor velocity $v_{sub.pl}$ reach or exceed the threshold velocity. After estimating the friction force $F_{sub.\mu,m}$, control returns to block **814** to determine the wire slip velocity $\{\text{circumflex over } (v)\}_{sub.slip}$.

[0080] After determining the wire slip velocity $\{\text{circumflex over } (v)\}_{sub.slip}$ (block **814**), or if the push motor velocity $v_{sub.ps}$ and the pull motor velocity $v_{sub.pl}$ are less than the threshold velocity (block **816**), at block **820** the control circuitry **134** generates a velocity command $v_{sub.vt}$ based on the target wire feed speed $v^*_{sub.wfs}$ and the target wire tension $\tau^*_{sub.t}$. For example, the control circuitry **134** may implement the motion command generator **302** of FIG. 4 to generate the velocity command $v_{sub.vt}$.

[0081] At block **822**, the control circuitry **134** generates a push motor force command $F^*_{sub.ps}$ based on the velocity command $v_{sub.vt}$, push motor velocity feedback $v_{sub.ps}$, and the wire slip velocity $\{\text{circumflex over } (v)\}_{sub.slip}$. For example, the control circuitry **134** may implement the push motor controller **306** of FIG. 5 to generate the push motor force command $F^*_{sub.ps}$.

[0082] At block **824**, the control circuitry **134** generates a pull motor force command $F^*_{sub.pl}$ based on the velocity command $v_{sub.vt}$, pull motor velocity feedback $v_{sub.pl}$, and the wire slip velocity $\{\text{circumflex over } (v)\}_{sub.slip}$. For example, the control circuitry **134** may implement the pull motor controller **308** of FIG. 6 to generate the pull motor force command $F^*_{sub.pl}$.

[0083] At block **826**, the control circuitry **134** controls the push motor **136** based on the push motor force command $F^*_{sub.ps}$ and controls the pull motor **137** based on the pull motor force command $F^*_{sub.pl}$. For example, the control circuitry **134** may apply respective force limiters **506**, **606** to the push motor force command $F^*_{sub.ps}$ and the pull motor force command $F^*_{sub.pl}$, and output corresponding push force $F_{sub.ps}$ (e.g., current, torque) to the push motor **136** and pull force $F_{sub.pl}$ (e.g., current, torque) to the pull motor **137**.

[0084] At block **828**, the control circuitry **134** compensates the velocity command $v_{sub.vt}$ based on the push motor force command $F^*_{sub.ps}$ and the pull motor force command $F^*_{sub.pl}$. For example, the control circuitry **134** may implement the motion command generator **302** of FIG. 4 to compensate the velocity command $v_{sub.vt}$ based on the push motor force command $F^*_{sub.ps}$ and the pull motor force command $F^*_{sub.pl}$ (e.g., based on respective virtual gear ratio factors $g_{sub.ps}$ and $g_{sub.pl}$).

[0085] At block **830**, the control circuitry **134** determines whether welding has ended. If welding is ended, control returns to block **802**. If welding is ongoing, control returns to block **812** to continue the closed-loop control and compensation.

[0086] The present devices and/or methods may be realized in hardware, software, or a combination of hardware and software. The present methods and/or systems may be realized in a centralized fashion in at least one computing system, processors, and/or other logic circuits, or in a distributed fashion where different elements are spread across several interconnected computing systems, processors, and/or other logic circuits. Any kind of computing system or other apparatus adapted for carrying out the methods described herein is suited. A typical combination of hardware and software may be a processing system integrated into a welding power source with a program or other code that, when being loaded and executed, controls the welding power source such that it carries out the methods described herein. Another typical implementation may comprise an application specific integrated circuit or chip such as field programmable gate arrays (FPGAs), a programmable logic device (PLD) or complex programmable logic device (CPLD), and/or a

system-on-a-chip (SoC). Some implementations may comprise a non-transitory machine-readable (e.g., computer readable) medium (e.g., FLASH memory, optical disk, magnetic storage disk, or the like) having stored thereon one or more lines of code executable by a machine, thereby causing the machine to perform processes as described herein. As used herein, the term “non-transitory machine readable medium” is defined to include all types of machine readable storage media and to exclude propagating signals.

[0087] An example control circuit implementation may be a microcontroller, a field programmable logic circuit and/or any other control or logic circuit capable of executing instructions that executes weld control software. The control circuit could also be implemented in analog circuits and/or a combination of digital and analog circuitry.

[0088] As utilized herein the terms “circuits” and “circuitry” refer to physical electronic components (i.e. hardware) and any software and/or firmware (code) that may configure the hardware, be executed by the hardware, and/or otherwise be associated with the hardware. As used herein, for example, a particular processor and memory may comprise a first “circuit” when executing a first set of one or more lines of code and may comprise a second “circuit” when executing a second set of one or more lines of code. As utilized herein, “and/or” means any one or more of the items in the list joined by “and/or”. As an example, “x and/or y” means any element of the three-element set {(x), (y), (x, y)}. In other words, “x and/or y” means “one or both of x and y.” As another example, “x, y, and/or z” means any element of the seven-element set {(x), (y), (z), (x, y), (x, z), (y, z), (x, y, z)}. In other words, “x, y, and/or z” means “one or more of x, y and z”. As utilized herein, the term “exemplary” means serving as a non-limiting example, instance, or illustration. As utilized herein, the terms “e.g.” and “for example” set off lists of one or more non-limiting examples, instances, or illustrations. As utilized herein, circuitry is “operable” to perform a function whenever the circuitry comprises the necessary hardware and code (if any is necessary) to perform the function, regardless of whether performance of the function is disabled or not enabled (e.g., by an operator-configurable setting, factory trim, etc.).

[0089] While the present method and/or system has been described with reference to certain implementations, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the present method and/or system. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the present disclosure without departing from its scope. For example, block and/or components of disclosed examples may be combined, divided, re-arranged, and/or otherwise modified. Therefore, the present method and/or system are not limited to the particular implementations disclosed. Instead, the present method and/or system will include all implementations falling within the scope of the appended claims, both literally and under the doctrine of equivalents.

Claims

1. A welding wire feeder, comprising: a push motor configured to feed welding wire from a wire source; and control circuitry configured to control the push motor and a pull motor of a welding torch coupled to the welding wire feeder by: controlling a push motor velocity of the push motor and a pull motor velocity of the pull motor based on a target wire feed speed; determine an estimated friction force in response to at least one of the push motor velocity or the pull motor velocity; estimating a wire slip velocity based on a push motor force and a pull motor force; estimating a wire tension in the welding wire based on the wire slip velocity, the push motor velocity, and the pull motor velocity, based on reducing a difference in the push motor force and the pull motor force by the estimated friction force; and compensating each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the estimated wire tension and the estimated wire slip velocity, wherein the push motor velocity and the pull motor velocity

are based on a target wire tension.

2. The welding wire feeder as defined in claim 1, wherein the control circuitry is configured to generate a velocity command based on the target wire feed speed and the target wire tension, and the control circuitry is configured to control the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the velocity command.
3. The welding wire feeder as defined in claim 1, further comprising a sensor configured to provide push motor velocity feedback.
4. The welding wire feeder as defined in claim 3, wherein the control circuitry is configured to estimate the wire tension based on push motor velocity feedback.
5. The welding wire feeder as defined in claim 3, wherein the control circuitry is configured to estimate the wire tension based on adding the estimated wire slip velocity to a difference between the push motor velocity feedback and pull motor velocity feedback.
6. The welding wire feeder as defined in claim 3, wherein the sensor comprises an encoder coupled to the push motor to measure at least one of an angular position or an angular velocity of the push motor.
7. The welding wire feeder as defined in claim 1, wherein the control circuitry is configured to, at a beginning of a welding operation, control the pull motor and the push motor to apply forces to the welding wire in opposing directions to establish a reference wire tension based on the target wire tension.
8. The welding wire feeder as defined in claim 1, wherein the control circuitry is configured to determine the pull motor velocity feedback based on receiving at least one of a pull motor angular velocity or a pull motor angular position from a pull motor encoder of the welding torch coupled to the welding wire feeder.
9. The welding wire feeder as defined in claim 1, wherein the control circuitry is configured to set the target wire tension based on a type of the welding wire.
10. The welding wire feeder as defined in claim 1, wherein controlling the push motor velocity of the push motor comprises generating a push motor force command, and controlling the pull motor velocity of the pull motor comprises generating a pull motor force command.
11. The welding wire feeder as defined in claim 10, wherein the control circuitry is configured to control the push motor velocity of the push motor by setting the push motor force command using an integrator based on a velocity command and push motor velocity feedback.
12. The welding wire feeder as defined in claim 10, wherein the control circuitry is configured to control the pull motor velocity of the pull motor by setting a pull motor force using an integrator based on a velocity command and the pull motor velocity feedback.
13. A method to control welding wire tension, the method comprising: controlling, via control circuitry, a push motor velocity of a push motor of a welding wire feeder based on a target wire feed speed; controlling, via the control circuitry, a pull motor velocity of a pull motor of a welding torch coupled to the welding wire feeder based on the target wire feed speed; determining, via the control circuitry, an estimated friction force in response to the push motor velocity and the pull motor velocity reaching a threshold velocity based on a velocity command; estimating, via the control circuitry, a wire slip velocity based on a push motor force and a pull motor force; estimating, via the control circuitry, a wire tension in the welding wire based on the wire slip velocity, the push motor velocity, and the pull motor velocity, based on reducing a difference in the push motor force and the pull motor force by the estimated friction force; and compensating, via the control circuitry, each of the push motor velocity of the push motor and the pull motor velocity of the pull motor based on the estimated wire tension and the estimated wire slip velocity, wherein the push motor velocity and the pull motor velocity are based on a target wire tension.
14. The method as defined in claim 13, wherein the controlling of the push motor velocity of the push motor comprises generating a push motor force command, and the controlling of the pull motor velocity of the pull motor comprises generating a pull motor force command.

15. The method as defined in claim 13, wherein the estimating of the wire tension is based on adding the estimated wire slip velocity to a difference between push motor velocity feedback and pull motor velocity feedback.

16. The method as defined in claim 13, further comprising measuring at least one of an angular position or an angular velocity of the push motor with an encoder, and determining push motor velocity feedback based on the angular position or the angular velocity.

17. The method as defined in claim 13, further comprising, at a beginning of a welding operation, controlling the pull motor and the push motor to apply forces to the welding wire in opposing directions to establish a reference wire tension based on the target wire tension.

18. The method as defined in claim 13, further comprising setting the target wire tension based on a type of the welding wire.
