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FOREARM EXOSKELETON FOR TREMOR ALLEVIATION

Abstract

The embodiments described herein are directed to a non-invasive wearable forearm exoskeleton that provides condition monitoring, tremor alleviation, and movement assistance at the human forearm joints in activities of daily living. The rigid linkages in the exoskeleton can adapt to different forearm profiles, allowing the user to perform natural forearm motions and transmit forces and torques efficiently. The exoskeleton can be worn by the user comfortably through soft interfacing. Encoders and inertia measurement units provide accurate measurements of the forearm motions. Through signal processing, a tremor signal is separated from voluntary motion for assessment and control. The motors produce safe actuations based on adaptive control and motion planning algorithms that simultaneously suppress tremors and assist voluntary motions.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims the benefit of and priority to U.S. Provisional Application Ser. No. 63/363,876, titled “Forearm Exoskeleton For Tremor Alleviation,” filed Apr. 29, 2022, the entire contents of which is hereby incorporated herein by reference.

BACKGROUND
[0002] A tremor is an involuntary quivering movement or shake in the limbs of the body of an individual. Tremors are common in individuals afflicted with Parkinson's disease, among other conditions. The slow, rhythmic tremor of Parkinson's disease can start in one hand, foot, or leg and can eventually affect both sides of the body. The resting tremor of Parkinson's disease can also occur in the jaw, chin, mouth, or tongue. Some people with Parkinson's disease can also experience a feeling of internal tremor. Tremors can be particularly frustrating for motor planning. Tremors also attract attention, and individuals with Parkinson's disease tend to keep tremoring hands in pockets.
SUMMARY OF THE INVENTION
[0003] The embodiments described herein are directed to a non-invasive wearable forearm exoskeleton that provides condition monitoring, tremor alleviation, and movement assistance at the human forearm joints in activities of daily living. The rigid linkages in the exoskeleton can adapt to different forearm profiles, allowing the user to perform natural forearm motions and transmit forces and torques efficiently. The exoskeleton can be worn by the user comfortably through soft interfacing. Encoders and inertia measurement units provide accurate measurements of the forearm motions. Through signal processing, a tremor signal is separated from voluntary motion for assessment and control. The motors produce safe actuations based on adaptive control and motion planning algorithms that simultaneously suppress tremors and assist voluntary motions.
[0004] In one example, a forearm exoskeleton for an arm includes a plurality of attachment modules, a plurality of pivotable linkages between the plurality of attachment modules, a plurality of motors mechanically coupled between the attachment modules and the pivotable linkages, feedback sensors that provide position feedback for the exoskeleton, and a controller configured to direct one or more of the motors to suppress tremors in and assist with voluntary motions of the arm based on the position feedback. The pivotable linkages can include a first link, a second link, a pivot point between the first link and the second link, and a position encoder at the pivot point in one example.
[0005] In other aspects, the controller is further configured to direct one or more of the motors of the forearm exoskeleton based on one or more kinematic models for the arm, one or more kinematic models for the forearm exoskeleton, and a motion planning algorithm using the position feedback and the models. The controller is also configured to isolate involuntary movement from voluntary movement in the arm based on a frequency analysis performed on the position feedback. The controller is also configured to direct the motors of the forearm exoskeleton based on a motion

planning algorithm to suppress the involuntary movement and assist with the voluntary movement in the arm.

[0006] The feedback sensors can include at least one inertial measurement unit, at least one positional encoder in at least one of the plurality of motors, and at least one positional encoder in at least one of the plurality of pivotable linkages. At least one pivotable linkage among the plurality of pivotable linkages can include an Euler-type joint. The attachment modules can include an attachment module for a bicep of the arm, an attachment module for a proximal end of a forearm of the arm, an attachment module for a distal end of the forearm, and an attachment module for a dorsum of a hand of the arm.

[0007] In other aspects, the controller is also configured to perform a first kinematic identification algorithm for elbow flexion-extension (EFE) motion of the arm using the position feedback, perform a second kinematic identification algorithm for forearm pronation-supination (FPS) motion of the arm using the position feedback, perform a third kinematic identification algorithm for wrist flexion-extension (WFE) motion of the arm using the position feedback, and perform a fourth kinematic identification algorithm for wrist radial-ulnar deviations (RUD) motions of the arm using the position feedback. The controller can develop a model for the arm based on a combination of the first, the second, the third, and the fourth kinematic identification algorithms, and direct the motors based on the model for the arm using the position feedback. The controller is also configured to recursively update the models for the arm, the models for the forearm exoskeleton, or both in real-time.

[0008] In other examples, the controller is also configured to perform trajectory tracking of an intended motion of the arm based on the position feedback, forecast a trajectory of the intended motion of the arm based on the position feedback, and direct the plurality of motors based on a motion planning algorithm to suppress involuntary movement in the arm and to assist with voluntary movement in the arm based on the forecast of the trajectory of the intended motion.

[0009] In another example, a method for control of a forearm exoskeleton for an arm includes analyzing movement data of the forearm exoskeleton based on position feedback from feedback sensors of the forearm exoskeleton, generating a model for the forearm exoskeleton based on the analyzing, planning motion for the arm and the exoskeleton based on the model, and directing at least one motor of the forearm exoskeleton based on the motion planning.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, with emphasis instead being placed upon clearly illustrating the principles of the disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0011] FIG. **1** illustrates an example forearm exoskeleton for tremor alleviation according to various embodiments described herein.

[0012] FIG. **2** illustrates a top-down view of the forearm exoskeleton shown in FIG. **1** according to various embodiments described herein.

[0013] FIG. **3** illustrates a side view of the forearm exoskeleton shown in FIG. **1** according to various embodiments described herein.

[0014] FIG. **4** illustrates example pivot points of the pivotable linkage in the exoskeleton shown in FIG. **1** according to various embodiments described herein.

[0015] FIG. **5** illustrates example pivot points of another pivotable linkage in the exoskeleton shown in FIG. **1** according to various embodiments described herein.

[0016] FIG. **6** illustrates example pivot points of another pivotable linkage in the exoskeleton shown in FIG. **1** according to various embodiments described herein.

[0017] FIG. **7** illustrates an example method of tremor alleviation and voluntary movement assistance using an exoskeleton according to various embodiments described herein.

DETAILED DESCRIPTION

[0018] The embodiments described herein are directed to a non-invasive wearable forearm exoskeleton that provides condition monitoring, tremor alleviation, and movement assistance at the human forearm joints in activities of daily living. The 6-degree-of-freedom (DOF) rigid linkages can adapt to different forearm profiles, allowing the user to perform natural forearm motions and transmit forces and torques efficiently. The exoskeleton is worn by the user comfortably through soft interfacing. Encoders and inertia measurement units provide accurate measurements of forearm motions. Through signal processing, the tremor signal is separated from voluntary motion for assessment and control. The servo motors produce safe actuations based on adaptive control and motion planning algorithms that simultaneously suppress tremors and assist voluntary motions.

[0019] The exoskeleton embodiments described herein do not require skin-contacting sensors (e.g., EMG sensors, Goniometers, etc.) for control. Encoders and inertia measurement units in the exoskeleton provide accurate measurements of forearm motions. Through signal processing, feedback data representative of tremors can be separated from voluntary motions by a control system of the exoskeleton, for assessment and control. A number of motors in the exoskeleton produce safe actuations based on adaptive control and motion planning algorithms that simultaneously suppress tremors and assist with voluntary motions. Overall, the embodiments aim to provide non-invasive, compliant, and stable tremor rehabilitation, as well as movement assistance at the forearm for individuals experiencing tremors. The embodiments are also applicable to reduce fatigue in manual laborers tasked with repetitive and dexterous tasks through continual assistance, among other uses.

[0020] The exoskeleton embodiments described herein can actively suppress tremors for the elbow flexion-extension (EFE), the forearm pronation-supination (FPS), the wrist flexion-extension (WFE), and the wrist radial-ulnar deviations (RUD) motion in the arm. The exoskeleton includes rigid linkage mechanisms extending between attachment modules located at the lateral side of upper arm or bicep, the proximal end of forearm, the distal end of the forearm, and the dorsum of the hand, respectively. The attachment modules can be adapted (e.g., sized or fitted) to different bicep, forearm, wrist, and hand profiles of users and allow fully natural arm movements. The motors in the exoskeleton can provide a wide range of actuations or movements of the arm. For tremor suppression and partial movement assistance, the maximum torques of the motors are approximately 2 N-m for the WFE and RUD motions, and 4 N-m for the WPS and EFE motions in one example. However, the motors can provide other maximum torques in other cases, depending on various factors such as the desired power efficiency and loading safety of the exoskeleton.

[0021] To improve ergonomics (e.g., non-invasiveness, compliance, and stability) of the design, the exoskeleton embodiments described herein can be worn using soft and non-binding interfaces, including gloves, arm bands, and hook and loop fastener strips. The battery and controller of the exoskeleton can be located at the upper arm to reasonably distribute weight. Cables run through the mechanisms to avoid entanglements. The sensors of the exoskeleton include IMUs and encoders, which provide full measurements of forearm kinematics as described herein. The controller employs advanced techniques in signal processing, robotics, and motion planning to ensure safe and compliant operations. A touch-screen user interface can also be coupled, either by wired or wireless communications, to directly configure the settings of the exoskeleton. The controller can also include fail-safe systems that detect anomalies, such as electric malfunctions and hardware damage.

[0022] FIG. **1** illustrates an example forearm exoskeleton **100** for tremor alleviation according to various embodiments described herein. The exoskeleton **100** is illustrated as a representative example of one type of system that can help an individual with both tremor suppression and to completely voluntary, intended motions. The tremor suppression and motion assistance concepts described herein are not limited to use with any particular type of exoskeleton or related device. The exoskeleton **100** is not exhaustively illustrated and may include other features or components that are not shown. In some cases, one or more of the components of the exoskeleton **100**, as shown and described below, can be omitted. Additionally, the concepts described herein can be extended to exoskeletons and related devices that can be worn or fitted to the leg, neck, torso, or other areas of the body.

[0023] The exoskeleton **100** is shown attached to an arm **110** of an individual in FIG. **1**. Among other components, the exoskeleton **100** includes attachment modules **120-123** for attachment to the arm **110**, attachments platforms **120**A-**123**A and straps **120**B-**123**B of the attachment modules **120-123**, pivotable linkages **130-132** between the attachment modules **120-123**, attachment anchors **135** and **136**, and motors **140-142** mechanically coupled between the attachment modules **120-123** and the pivotable linkages **130-132**. The exoskeleton **100** also includes an embedded controller **150**, a battery **150**A, a number of signaling and power cables, such as the cable **170**, positional encoders **160-164**, inertial measurement units (IMUs) **166-168**, and other components described herein. The cable **170** can be routed through the pivotable linkages **130-132** as shown in FIG. **1** to avoid entanglements. Additional components of the exoskeleton **100** are also illustrated in FIGS. **4-6**.

[0024] The exoskeleton **100** provides both active and passive suppression of tremors or involuntary movement in the arm **110**. As for passive suppression of involuntary movement, the kinematic chain formed by the motors **140-142** and the pivotable linkages **130-132** between the attachment modules **120-123** is elastic and provides resistance against involuntary motion to some extent, even without model-based control of the motors **140-142**. As for active suppression of involuntary movement, the motors **140-142** are directed by the motor drivers **153** and the robot control system **156** to suppress (e.g., counterbalance against) the involuntary movements of the arm **110**. Additionally, the exoskeleton **100** provides active assistance to the voluntary movement of the arm **110**. These and other aspects of the exoskeleton **100** are described below.

[0025] The attachment modules **120-123** can be formed from any suitable materials, including fabric, rubber, neoprene, plastic, other materials, and combinations thereof. The attachment modules **120-123** can be formed to any suitable size and shape depending on the size of the arm to which the exoskeleton **100** is fitted. The attachment modules **120-123** can also be held in place, in part, by bands, strips of hook and loop fastener, ties, or other means as described below.

[0026] More particularly, the attachment module **120** can include a sleeve formed from a flexible fabric, rubber, neoprene, plastic, other related material, or combinations thereof, sized to fit around the bicep **111** of the arm **110**. The attachment module **120** can be formed to any suitable size and shape depending on the size of the bicep **111**. The attachment module **120** includes the attachment platform **120**A. The attachment platform **120**A can be formed from a more rigid material, such as a firm plastic or metal material. The motor **140** can be secured to a surface region of the attachment platform **120**A using adhesives, mechanical fasteners, mechanical interferences or interlocks, other attachment means, or combinations thereof. A number of straps, such as the strap **120**B, extend through mounting apertures in the attachment platform **120**A and around the sleeve of the attachment module **120** and the bicep **111**. The strap **120**B can be embodied as an elastic strap and, in some cases, include one or more fasteners, such as hook-and-loop fasteners, hooks, ties, or other means, to secure the attachment platform **120**A around the sleeve and hold the attachment module **120** in place around the bicep **111**.

[0027] The attachment module **121** can include a sleeve formed from a flexible fabric, rubber, neoprene, plastic, other related material, or combinations thereof, sized to fit around the forearm **112** of the arm **110**. The attachment module **121** can be formed to any suitable size and shape depending on the size of the forearm **112**. The attachment module **121** includes the attachment platform **121**A. The attachment platform **121**A can be formed from a more rigid material, such as a firm plastic or metal material. The motor **141** can be secured to a first region of the attachment platform **121**A using adhesives, mechanical fasteners, mechanical interferences or interlocks, other attachment means, or combinations thereof. The attachment anchor **135** can be formed integrally with or be secured to another region of the attachment platform **121**A. The attachment anchor **135** includes a joint for interfacing with one end of the pivotable linkage **130**. A number of straps, such as the strap **121**B, extend through mounting apertures in the attachment platform **121**A and around the sleeve of the attachment module **121** and the forearm **112**. The strap **121**B can be embodied as an elastic strap and, in some cases, include one or more fasteners, such as hook-and-loop fasteners, hooks, ties, or other means, to secure the attachment platform **121**A around the sleeve and hold the attachment module **121** in place around the forearm **112**.

[0028] The attachment module **122** can include a sleeve formed from a flexible fabric, rubber, neoprene, plastic, other related material, or combinations thereof, sized to fit around the wrist **113** of the arm **110**. The attachment module **122** can be formed to any suitable size and shape depending on the size of the wrist **113**. The attachment module **122** includes the attachment platform **122**A. The attachment platform **122**A can be formed from a more rigid material, such as a firm plastic or metal material. A hub of the motor **142** can be secured to the attachment platform **122**A, as described in further detail below with reference to FIG. **6**. A number of straps, such as the strap **122**B, extend through mounting apertures in the attachment platform **122**A and extend around the sleeve of the attachment module **122** and the wrist **113**. The strap **122**B can be embodied as an elastic strap and, in some cases, include one or more fasteners, such as hook-and-loop fasteners, hooks, ties, or other means, to secure the attachment platform **122**A around the sleeve and hold the attachment module **122** in place around the wrist **113**.

[0029] The attachment module **123** can include a glove, possibly with open fingers, formed from a flexible fabric, rubber, neoprene, plastic, other related material, or combinations thereof, sized to fit around the hand **114** of the arm **110**. The attachment module **123** can be formed to any suitable size and shape depending on the size of the hand **114**. The attachment module **123** includes the attachment platform **123**A, which can be formed from a more rigid material, such as a firm plastic or metal material. The attachment platform **123**A includes a joint for interfacing with one end of the pivotable linkage **132**. A number of straps, such as the strap **123**B, extend through mounting apertures in the attachment platform **123**A and around the glove of the attachment module **123**. The strap **123**B can be embodied as an elastic strap and, in some cases, include one or more fasteners, such as hook-and-loop fasteners, hooks, ties, or other means, to secure the attachment platform **123**A around the glove and hold the attachment module **123** in place around the hand **114**.

[0030] The motors **140-142** are secured to the rigid platforms of the attachment modules **120-123**. The motors **140-142** can be embodied as any suitable motors, such as servo motors, brushless motors, or other motors, and the motors **140-142** can incorporate positional encoders in some cases. The motors **140** and **141** include a single motor shaft and degree of freedom with respect to the shaft. The motor **142** includes two separate motors. The motors **140-142** are mechanically coupled to other components in the kinematic chain of the exoskeleton **100** at a number of joints, as described in detail below with reference to FIGS. **4-6**. The motors **140-142** can be powered and driven by the motor drivers **153** in the embedded controller **150** at the direction of the robot control system **156**, as described herein.

[0031] The motors **140-142** can incorporate positional encoders. Thus, the motors **140-142** can provide feedback signals or data to the embedded controller **150**, with the feedback signals identifying the absolute or relative positions of the shafts or other internal moving parts of the motors **140-142**. As described in further detail below, the embedded controller **150** can calculate information related to the positions, orientations, and movement of the attachment modules **120-123** and the pivotable linkages **130-132** of the exoskeleton **100** based in part on the feedback signals from the motors **140-142**. The embedded controller **150** can also calculate information related to the position of the arm **110**, including the positions and orientations of the bicep **111**, the forearm **112**, the wrist **113**, and the hand **114** of the arm **110**.

[0032] The arm **110** may experience involuntary quivering movement due to Parkinson's disease, for example. The arm **110** may also move, at least in part, in an intended direction or directions based on the intentions of an individual. The embedded controller **150** is configured to analyze and monitor the motion of the arm **110** based on the feedback signals and data provided from the positional encoders in the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168** (also referenced herein collectively as “feedback sensors”). More particularly, the embedded controller **150** is configured to identify, isolate, and analyze the portion of the movement in the arm **110** that is attributed to involuntary quivering movements or shakes (e.g., the tremor motion) through a frequency or related analysis of the feedback data. The embedded controller **150** is also configured to identify, isolate, and analyze the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the individual through a frequency or related analysis of the feedback data. The embedded controller **150** can also calculate and determine the trajectory of the intended motion of the arm **110** based in part on the feedback signals.
[0033] Based on the analysis of the feedback data, the embedded controller **150** is configured to direct the motors **140-142** to help suppress the involuntary movements in the arm **110** while, at the same time, direct the motors **140-142** to assist with the intended motion of the arm **110**. Thus, the embedded controller **150** is capable of separately identifying the involuntary and voluntary movements in the arm **110**. The embedded controller **150** can also process or execute adaptive control algorithms to learn the intended movements or motions of the individual and the arm **110** over time. These and other aspects of the embedded controller **150** are described below.
[0034] The pivotable linkages **130-132** provide mechanical linkages between the attachment modules **120-123** and the motors **140-142**. The pivotable linkages **130-132** include one or more links and joints, as described in further detail below. The motors **140-142** can provide external forces to the pivotable linkages **130-132**, both to aid in the intended movement of the arm **110** and to dampen involuntary motions or tremors in the arm **110**. The pivotable linkages **130-132** can be formed from plastic, metal, other suitable materials, and combinations thereof. Examples of the links and pivot points or joints in the pivotable linkages **130-132** are described in further detail below with reference to FIGS. **4-6**.
[0035] The positional encoders **160-164** are fitted and positioned at pivot points in the pivotable linkages **130-132**. The positional encoders **160-164** can be embodied as angular position encoders. The positional encoders **160-164** can provide feedback signals to the embedded controller **150**, with the feedback signals identifying the absolute or relative positions (e.g., angular positions) of links in the pivotable linkages **130-132** with respect to other links in the pivotable linkages **130-132**, with respect to shafts of the motors **140-142**, with respect to the rigid platforms in the attachment modules **120-123**, or with respect to other points or frames of reference in the exoskeleton **100**.
[0036] The embedded controller **150** can calculate information related to the positions, orientations, and movement of the attachment modules **120-123** and the pivotable linkages **130-132** of the exoskeleton **100** based in part on the feedback signals from the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168**. The embedded controller **150** can also calculate information related to the position of and movement in the arm **110**, including the positions, orientations, and movements of the bicep **111**, the forearm **112**, the wrist **113**, and the hand **114** of the arm **110** based in part on the feedback data. The embedded controller **150** can also calculate, determine, and monitor the motion of the arm **110** based in part on the feedback signals. The embedded controller **150** is configured to direct the motors **140-142** to help suppress the involuntary movements in the arm **110** while, at the same time, direct the motors **140-142** to assist with the intended motion of the arm **110**.
[0037] The embedded controller **150** can be embodied as a controller or microcontroller system. The embedded controller **150** can include one or more processors, one or more memory devices, and one or more motor driver circuits, among other components. The embedded controller **150** can

be embodied as an embedded single-board microcontroller processing system, such as a Raspberry Pi, Arduino, or related single-board microcontroller. The embedded controller **150** can also be embodied as a type of programmable logic controller (PLC) system. The embedded controller **150**, however, is not limited to any type or style of controller or microcontroller system. The embedded controller **150** is configured to receive and store data, such as the feedback data described herein. The embedded controller **150** is also configured to execute computer-readable code or instructions (e.g., software) to develop the models described below, to direct the operation of the exoskeleton **100**, and to communicate or interface with other devices in some cases. These and other aspects of the embedded controller **150** are described in further detail below.

[0038] As shown in FIG. **1**, the embedded controller **150** includes a data store **152**. The data store **152** stores data for use and execution by the one or more processors of the embedded controller **150**, including the control information **152**A, the model parameters **152**B, the motion trajectories **152**C, and other data. The embedded controller **150** also includes motor drivers **153**, a communications interface **154**, and a robot control system **156** in the example shown. The robot control system **156** includes a model identifier **157**, a motion planner **158**, and a motion controller **159**. The operation of the robot control system **156** is described in additional detail below.

[0039] In the data store **152**, the control information **152**A includes the feedback data provided by the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168**, among feedback data provided from other sensors and systems of the exoskeleton **100**. The control information **152**A can be organized and stored in any suitable format for evaluation and processing by the robot control system **156**. For example, the feedback data provided by the motors **140-142** can be stored separately from the feedback data provided by the positional encoders **160-164** and the IMUs **166-168**. Similarly, the feedback data provided by the positional encoders **160-164** can be stored separately from that provided by the IMUs **166-168**. The feedback data from the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168** can also be correlated or organized together in the data store **152**. Additionally, the control information **152**A can be correlated, organized, and processed in connection with the model parameters **152**B, as described below.

[0040] The model parameters **152**B include data related to the mechanical structure of the exoskeleton **100**, such as the size of the exoskeleton **100**, the positions of the attachment modules **120-123** on the arm **110**, the characteristics (e.g., types, forces applied by) of the motors **140-142**, the degrees of freedom in the pivot points or joints in the exoskeleton **100**, the mechanical arrangements of the pivotable linkages **130-132**, and other mechanical characteristics of the exoskeleton **100**. The model parameters **152**B can be organized and stored in any suitable format for evaluation and processing by the robot control system **156**. In addition to feedback and model parameter data, the data store **152** can also store executable code (e.g., executable software) for execution by the one or more processors of the embedded controller **150**. The executable code can be relied upon to implement the robot control system **156**, for example, among other functional components of the embedded controller **150**.

[0041] The motion trajectories **152**C include data related to the movement of the arm **110**. The motion trajectories **152**C can include a historical database of the movements undertaken by the arm **110** during the performance of various tasks. The motion trajectories **152**C can also include forecasted or estimated trajectories of the arm **110**, as those forecasted trajectories are generated by the motion planner **158**. The historical and forecasted motion trajectories **152**C can be maintained in any suitable format with reference to any suitable coordinate or dimensionality reference or system. The motion trajectories **152**C can also be developed in connection with kinematic models of the exoskeleton **100**, kinematic models of the arm **110**, and other models. The kinematic models of the exoskeleton **100** may be defined, in part, based on the model parameters **152**B. The kinematic models of the arm **110** can be defined based on evaluations of the arm **110** performed by the model identifier **157**, as described below.

[0042] The embedded controller **150** can also provide a type of user interface for the exoskeleton

100. To that end, the embedded controller **150** can include a user interface **151**, which can be embodied as a capacitive touch screen or other type of display. A user of the exoskeleton **100** can interface with the user interface **151** to direct certain operations of the exoskeleton **100**. In some cases, the embedded controller **150** can also include additional input/output (I/O) interfaces, such as one or more buttons, indicator lights, speakers, haptic feedback systems, and related I/O peripherals.

[0043] The motor drivers **153** can be embodied as semiconductor motor drivers for the motors **140-142**. Based on control commands, signals, or other direction provided by the robot control system **156**, the motor drivers **153** can provide power from the battery **150**A to power and control the operation (e.g., the movement) of the motors **140-142** and the pivotable linkages **130-132** between the attachment modules **120-123**, respectively.

[0044] The communications interface **154** can be embodied as one or more wired or wireless physical layer communications devices, such as a serial or parallel wired interface, a Bluetooth®, WiFi®, or other wireless interface, or a related data communications interface. The embedded controller **150** can interface with one or more external devices, such as the device **250**, using the communications interface **154**. Examples of the device **250** include those in the form of a desktop computer, laptop computer, personal digital assistant, cellular telephone, tablet computer, or other related computing device or system. The device **250** can be used to interface with the exoskeleton **100**. For example, a user of the device **250** can monitor and control certain operations of the exoskeleton **100** through a user interface presented on the device **250** based on one or more applications executing on the device **250**. In some cases, the device **250** can perform the operations of the robot control system **156**, in whole or in part, as described herein. In that case, the device **250** can perform the operations of the robot control system **156** and direct the motor drivers **153** via data communications over the communications interface **154**.

[0045] The battery **150**A can be embodied as any suitable battery capable of storing power to operate the embedded controller **150**, the motors **140-142**, and other parts of the exoskeleton **100**. As examples, the battery **150**A can be embodied as one or more alkaline, lithium-ion, nickel-cadmium, nickel-metal hydride, or other types of batteries. The battery **150**A can be rechargeable and, in some cases, include a recharging controller and other control circuitry to monitor the current level of charge and discharge rate of the battery **150**A.

[0046] The IMUs **166-168** can be embodied as inertial measurement units capable of measuring orientation, velocity, acceleration, and other inertial information related to the exoskeleton **100**. The IMUs **166-168** can provide feedback related to the motion, orientation, and position of components in the exoskeleton **100** in three-dimensional space. The IMUs **166-168** can include one or more accelerometers, gyroscopes, magnetometers, and other types of sensors to calculate inertial and position information for the exoskeleton **100**. The IMU **166** is positioned at or on the attachment anchor **135** over the forearm **112**. The IMU **167** is positioned at or on the housing of the motor **142** over the wrist **113**. The IMU **168** is positioned at or on the attachment platform **123**A over the hand **114**. IMUs **166-168** can provide feedback signals or data to the embedded controller **150**, with the feedback signals identifying the orientation, velocity, acceleration, and other inertial and position information for the exoskeleton **100**. The embedded controller **150** can also include an additional IMU in some cases, and the exoskeleton **100** can incorporate additional IMUs at other locations. Additionally, in some cases, one or more of the IMUs **166-168** can be omitted from the exoskeleton **100**.

[0047] The feedback data from the IMUs **166-168** can be stored in the data store **152** as the control information **152**A for further processing by the embedded controller **150**. Based in part on the feedback data from the IMUs, the embedded controller **150** can calculate the position and movement of the arm **110** over time, including the movement of the bicep **111**, the forearm **112**, the wrist **113**, and the hand **114** of the arm **110**. The embedded controller **150** can also calculate, determine, and monitor the motion of the arm **110** based on the control information **152**A. The embedded controller **150** is also configured to identify, isolate, and analyze the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the individual through a frequency or related analysis of the control information **152**A. The embedded controller **150** can also calculate and determine the trajectory of the intended motion of the arm **110** based in part on the control information **152**A.

[0048] FIG. **2** illustrates a top-down view of the forearm exoskeleton **100** shown in FIG. **1** according to various embodiments described herein. The exoskeleton **100** can actively suppress tremors in four upper limb degrees of freedom (DOFs) of the arm **110**. The exoskeleton **100** can actively suppress tremors for the EFE, the FPS, the WFE, and the RUD motions in the arm **110**. Referring to FIG. **2**, the pivotable linkage **130** extends between a joint connection at the motor **140** and a joint connection at the attachment anchor **135**. The motor **140** and the kinematic chain provided between the motor **140**, the pivotable linkage **130**, the attachment anchor **135**, and the joints therebetween can actively suppress tremors in the EFE of the arm **110**. Additionally, the pivotable linkage **132** extends between a hub joint connection at the motor **142** and a joint connection at the attachment platform **123**A. The motor **142** and the kinematic chain provided between the motor **142**, the pivotable linkage **132**, the attachment platform **123**A, and the joints therebetween can actively suppress tremors in the RUD of the arm **110**.

[0049] FIG. **3** illustrates a side view of the forearm exoskeleton **100** shown in FIG. **1** according to various embodiments described herein. The pivotable linkage **131** extends between a joint connection at the motor **141** and a joint connection at the attachment platform **122**A. The motor **141** and the kinematic chain provided between the motor **141**, the pivotable linkage **131**, the attachment platform **122**A, and the joints therebetween can actively suppress tremors in the FPS of the arm **110**. Additionally, the pivotable linkage **132** extends between another hub joint connection at the motor **142** and a joint connection at the attachment platform **123**A. The motor **142** and the kinematic chain provided between the motor **142**, the pivotable linkage **132**, the attachment platform **123**A, and the joints therebetween can actively suppress tremors in the WFE of the arm **110**.

[0050] FIG. **4** illustrates the pivotable linkage **130** and pivot points or joints **180-182** of the pivotable linkage **130** in the exoskeleton **100** shown in FIG. **1** according to various embodiments described herein. Particularly, FIG. **4** illustrates the links **130**A and **130**B of the pivotable linkage **130**, separated from the joints **180-182**. The joint **180** is positioned at an end of a shaft of the motor **140**. The joint **180** provides two degrees of freedom between the motor **140** and the link **130**A. The joint **181** provides one degree of freedom between the link **130**A and the link **130**B. The joint **182** provides three degrees of freedom between the link **130**B and the attachment anchor **135**. The joint **182** is a Euler-type joint, as shown in FIG. **2**A. Movement (i.e., rotation) of the motor **140** imparts forces on the pivotable linkage **130** and between the attachment platform **120**A and the attachment anchor **135**. In turn, movement of the motor **140** imparts forces between the bicep **111** and forearm **112** of the arm **110** for EFE movement.

[0051] FIG. **5** illustrates the pivotable linkage **131** and pivot points or joints **183-185** of the pivotable linkage **131** in the exoskeleton **100** shown in FIG. **1** according to various embodiments described herein. Particularly, FIG. **5** illustrates the links **131**A and **131**B of the pivotable linkage **131**, separated from the joints **183-185**. The joint **183** is positioned at an end of a shaft of the motor **141**. The joint **183** provides two degrees of freedom between the motor **141** and the link **131**A. The joint **184** provides one degree of freedom between the link **131**A and the link **131**B. The joint **185** provides three degrees of freedom between the link **131**B and the attachment platform **122**A. The joint **185** is a Euler-type joint. Movement of the motor **141** imparts forces on the pivotable linkage **131** and between the attachment platform **121**A and the attachment platform **122**A. In turn, movement of the motor **141** imparts forces between the forearm **112** and the wrist **113** of the arm **110** for FPS movement.

[0052] FIG. **6** illustrates the pivotable linkage **132** and pivot points or joints **186-189** in the exoskeleton **100** shown in FIG. **1** according to various embodiments described herein. Particularly, FIG. **6** illustrates the links **132**A and **132**B of the pivotable linkage **132**. The joint **186** is formed at a hub between the motor **142** and the attachment platform **122**A and provides one degree of freedom. Particularly, the attachment platform **122**A includes an attachment U-frame **125**. The U-frame **125** extends up from the attachment platform **122**A. The motor **142** is positioned and secured within the U-frame **125** and can pivot at the joint **186** with respect to the attachment platform **122**A. More particularly, the motor **142** includes two separate motors, with one capable of pivoting the motor **142** (or the housing of the motor **142**) with respect to the U-frame **125** at the joint **186**. In turn, movement of the motor **142** at the joint **186** imparts forces on the wrist **113** of the arm **110** for RUD movement.

[0053] Additionally, the motor **142** is also capable of pivoting or rotating the link **132**A with respect to the housing of the motor **142** at the joint **187**. The joint **187** is formed at another hub between the motor **142** and the link **132**A and provides one degree of freedom. Movement of the motor **142** at the joint **187** imparts forces on the link **132**A and, in turn, on the hand **114** of the arm **110** for WFE movement. The joint **188** provides one degree of freedom between the link **132**A and the link **132**B. The joint **189** provides three degrees of freedom between the link **132**B and the attachment platform **123**A. The joint **189** is a Euler-type joint. The joint **189** permits additional degrees of freedom between the wrist **113** and the hand **114** while also permitting the exoskeleton to impart RUD and WFE control.

[0054] Referring among the illustrations, exoskeleton **100** includes a kinematic chain. The kinematic chain extends between the motors **140-142**, the joints **180-189**, the pivotable linkages **130-132**, and the attachment modules **120-123**. The joints **180-189** are positioned in the kinematic chain between the motors **140-142**, between the motors **140-142** and the pivotable linkages **130-132**, in the pivotable linkages **130-132**, and between the pivotable linkages **130-132** and the attachment modules **120-123** (and the attachment anchors **135** and **136**). The degrees of freedom at each of the joints **180-189**, the distances between the attachment modules **120-123**, the lengths of the pivotable linkages **130-132** (and the individual links in the pivotable linkages **130-132**), and related mechanical aspects of the exoskeleton **100** are stored as the model parameters **152**B in the embedded controller **150**. Thus, the embedded controller **150** can reference the model parameters **152**B to form one or more models for the kinematic chain of the exoskeleton **100**. The embedded controller **150** can evaluate the models for the kinematic chain of the exoskeleton **100** as part of the control algorithm used by the robot control system **156** to direct the motors **140-142** for tremor suppression and assistance with the voluntary movement of the arm **110**.

[0055] Referring to FIG. **1**, the robot control system **156** includes the model identifier **157**, the motion planner **158**, and the motion controller **159**. Among other processes, the robot control system **156** is configured to store and analyze the motion of the arm **110**, in real time, based on the feedback signals and data provided from the positional encoders in the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168**. The real-time motion of the arm **110** can be analyzed and monitored in view of the feedback data, as the feedback data is indicative of the actual movement of the arm **110** over time. The real-time motion of the arm **110** can be used by the model identifier **157** to develop models associated with the arm **110**, as described below, and to recursively update the models over time. The real-time motion of the arm **110** can also be analyzed and monitored in connection with the models and model parameters **152**B associated with the exoskeleton **100**. The real-time motion of the arm **110** can also be used by the motion planner **158** to plan the motion of and forecast trajectories of the arm **110**.

[0056] The robot control system **156** is configured to analyze the motion of the arm **110** through a frequency or related analysis of the feedback data. For an individual with Parkinson's disease, for example, the motion of the arm **110** can include both involuntary quivering movements (e.g., tremor motion) and voluntary movements. Based on the results of the frequency analysis of the feedback data and the control information **152**A, the robot control system **156** can identify and isolate the portion of the movement in the arm **110** that is attributed to the involuntary quivering movements. The robot control system **156** is also configured to identify and isolate the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the arm **110**. Data related to both the tremor motion and the voluntary movements of the arm **110** can be stored in the data store **152** for further processing.

[0057] The model identifier **157** is configured to perform a multibody analysis on the exoskeleton **100** using the model parameters **152**B and the real-time motion of the arm **110** with reference to the control information **152**A. In some cases, the model identifier **157** can perform a multibody analysis on the exoskeleton **100** using the model parameters **152**B and example data related to motions of the arm **110**, rather than data related to the real-time motion of the arm **110**. As part of the multibody analysis, the model identifier **157** is configured to identify the kinematic parameters of motion associated with the EFE, FPS, WFE, and RUD motions in the arm **110**.

[0058] The model identifier **157** is informed of the kinematic structure of the exoskeleton **100** based on the model parameters **152**B stored in the data store **152**. The model identifier **157** is also informed of the motions of the exoskeleton **100** and the arm based on the control information **152**A stored in the data store **152**. However, the kinematic structure of the exoskeleton **100** and the arm **110** may be undefined and vary from arm to arm. Thus, the model identifier **157** is also configured to identify a range of kinematic parameters of motion that are particular to the exoskeleton **100**, to the arm **110**, or both for the EFE, FPS, WFE, and RUD motions in the arm **110**. The model identifier **157** is also configured to develop one or more models that are particular to the EFE, FPS, WFE, and RUD motions in the exoskeleton **100**, in the arm **110**, or both.

[0059] For example, the model identifier **157** is configured to identify the kinematic parameters of motion in the wrist **113** and the hand **114** by performing a wrist kinematic identification (WKI) algorithm. The WKI algorithm can be performed through an ellipsoidal joint approximation model and real-time sparsity-promoting regression, for example, by the model identifier **157**. The results of the WKI algorithm define additional parameters related to the kinematic structure of the wrist **113** and the hand **114** and are stored as the model parameters **152**B in the data store **152**. As another example, the model identifier **157** is configured to identify the kinematic parameters of motion in the wrist **113** and the forearm **112** by performing a forearm kinematic identification (FKI) algorithm. The FKI algorithm can be performed through another joint approximation model by the model identifier **157**. The results of the FKI algorithm define additional parameters related to the kinematic structure of the wrist **113**, the forearm **112**, and the joints between them, and those parameters are also stored as the model parameters **152**B in the data store **152**. The model identifier **157** is also configured to identify the kinematic parameters of motion in the forearm **112** and the bicep **111** by performing an upper arm kinematic identification (UKI) algorithm. The UKI algorithm can be performed through another joint approximation model by the model identifier **157**. The results of the UKI algorithm define additional parameters related to the kinematic structure of the forearm **112**, the bicep **111**, and the joints between them, and those parameters are stored also as the model parameters **152**B in the data store **152**. The WKI, FKI, UKI, and possibly other models can be developed by the model identifier **157** through the real-time analysis of the motion of the arm **110**. The models can also be developed based on example or training data in some cases. The WKI, FKI, and UKI models can also be recursively updated in real time by the model identifier **157**.

[0060] The motion planner **158** of the robot control system **156** is configured to perform a motion planning algorithm for the exoskeleton **100**. The motion planner **158** can process the data related to both the tremor motion and the voluntary movements of the arm **110**, in real time, as that data is analyzed and stored in the data store **152** by the robot control system **156**. The motion planner **158** can also extrapolate or project a forecasted trajectory for the arm **110**. That is, based on the isolation of voluntary movement of the arm **110** over a partial trajectory, the motion planner **158** can forecast the remainder of the trajectory (e.g., an extended or forecasted trajectory) of the arm

110 for rehabilitation or assistive purposes.

[0061] The motion planner **158** is configured to perform trajectory tracking and forecasting under inertia/load uncertainties and external disturbances for both the arm **110** and the exoskeleton **100**. In one example, the motion planner **158** incorporates an adaptive controller and can perform an inverse optimality technique for motion tracking and trajectory forecasting based on a general model for upper limb rehabilitation. The motion planner **158** can also perform motion tracking and trajectory forecasting based on the previously-developed WKI, FKI, and UKI models to tailor the forecasted trajectories in view of the particular kinematic structure of the arm **110**, as previously modeled by the model identifier **157**. The motion planner **158** is also configured to perform trajectory forecasting in view of uncertainties in the previously-developed WKI, FKI, and UKI models.

[0062] Additionally, the motion planner **158** can also perform trajectory forecasting based on the known model parameters **152**B of the exoskeleton **100** to tailor the control of the exoskeleton **100**. Thus, the motion planner **158** can develop a forecasted trajectory of the arm **110** based on both models of the arm **110**, as determined by the model identifier **157**, and the known model parameters **152**B of the exoskeleton **100**. Forecasted trajectories of the arm **110**, as developed by the motion planner **158**, can be stored as the motion trajectories **152**C in the data store **152**.

[0063] The motion planner **158** can incorporate learning models or algorithms in some cases, to help estimate the trajectory of the intended motion of the arm **110**. For example, data related to a history of the voluntary movements of the arm **110** can be stored in the motion trajectories **152**C. As the intended motion of the arm **110** is currently isolated, in real time, by the robot control system **156**, the current voluntary motion can be compared against the history of the voluntary movements of the arm **110** stored in the motion trajectories **152**C. The motion planner **158** can seek to identify correlations (e.g., trajectory matches) between the current voluntary motion of the arm **110** and the history of the previous voluntary movements of the arm **110** stored in the motion trajectories **152**C to develop the forecasted trajectory of the intended motion of the arm **110**.

[0064] The motion controller **159** of the robot control system **156** is configured to develop motor control signals for control of the motors **140-142**. In one example, the motion controller **159** is configured to control the motors **140-142** in the exoskeleton **100** for two primary objectives, including tremor suppression and voluntary movement assistance. For example, based on the results of the frequency analysis performed by the robot control system **156**, the robot control system **156** can isolate the portion of the movement in the arm **110** that is attributed to the involuntary quivering movements of the arm **110**. The robot control system **156** can also isolate the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the arm **110**. Additionally, the motion planner **158** can evaluate the trajectory, or partial trajectory, of the intended motion of the arm **110**. The motion planner **158** can also forecast, in some cases, a remaining or extended trajectory of the arm **110**. The motion controller **159** can also control the motors **140-142** for other objectives, such as for teaching or rehabilitative motions.

[0065] In view of the isolated voluntary and involuntary components of movement in the arm **110**, the motion controller **159** is configured to develop motor control signals that suppress (e.g., counterbalance against) the involuntary quivering movements of the arm **110** and enhance (e.g., support or further direct) the intended or voluntary movements of the arm **110**. The motion controller **159** can develop the motor control signals for enhancing the intended movements of the arm **110** based on the forecasted trajectory of the intended motion of the arm **110**, as provided by the motion planner **158**. The motion controller **159** can also control the motors **140-142** for other objectives, however, such as to teach an individual new motions or new motion trajectories for rehabilitative purposes.

[0066] In some aspects, the motion controller **159** is configured to develop motor control signals through the minimization of interaction resistance between an individual and the exoskeleton **100**. Based on model assumptions, the motion controller **159** can optimize the tracking reference of the exoskeleton **100** by minimizing the human-exoskeleton interaction loads estimated, e.g., based on a support vector regression (SVR) model. The model can also be updated recursively by the robot control system **156** in real time.

[0067] The motion control signals are provided to the motor drivers **153** to control the motors **140-142**. Based on the motor control signals, the motors **140-142** can impart forces on the exoskeleton **100** to both suppress tremors and to assist with voluntary movements in the arm **110**. Through the signal processing performed by the robot control system **156**, the motors **140-142** produce safe actuations based on adaptive control and motion planning algorithms to simultaneously suppress tremors and assist with voluntary motions. The exoskeleton **100** provides a non-invasive, compliant, and stable tremor suppression and rehabilitation system for the arm **110**. The exoskeleton **100** also provides movement assistance in the arm **110**. Beyond healthcare, the exoskeleton **100** can also be applied to other fields and uses, such as to reduce fatigue in manual laborers tasked with repetitive and dexterous task through continual assistance.

[0068] Turning to other examples, FIG. **7** illustrates an example method **200** of tremor alleviation and voluntary movement assistance using an exoskeleton according to various embodiments described herein. Although the method or process shown in FIG. **7** is described in connection with the exoskeleton **100** shown in FIG. **1**, the method or process can be performed by other exoskeletons or assistive systems. Additionally, although the process is described to occur in a certain sequence, the process steps can be varied as compared to that shown. One or more of the process steps can be performed in alternative sequences or orders, concurrently, with partial concurrence, or in other ways. One or more of the process steps can be omitted, and additional steps can be added in some cases.

[0069] At step **202**, the process includes analyzing movement data of an exoskeleton based on position feedback from the exoskeleton. For example, step **202** can include the robot control system **156** receiving feedback signals and data from the positional encoders in the motors **140-142**, the positional encoders **160-164**, and the IMUs **166-168** of the exoskeleton **100**. The robot control system **156** can store data related to the feedback signals as the control information **152**A in the data store **152** of the embedded controller **150**. Step **202** also includes analyzing the movement data of the arm **110** through frequency analysis techniques. For example, step **202** includes the robot control system **156** analyzing the motion of the arm **110** through a frequency analysis and identifying both involuntary and voluntary movements. Step **202** also includes the robot control system **156** identifying and isolating the portion of the movement in the arm **110** that is attributed to the involuntary quivering movements. It also includes identifying and isolating the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the arm **110**. Data related to both the involuntary and voluntary movements of the arm **110** can be stored in the data store **152** for further processing at step **202** and in later process steps.

[0070] At step **204**, the process includes identifying or generating one or more models based on the analysis at step **202**. For example, step **204** can include the model identifier **157** performing a multibody analysis on the exoskeleton **100**, on the arm **110**, or on both using the model parameters **152**B and the analysis of the motion of the arm **110** from step **202**. As part of the multibody analysis, step **204** includes the model identifier **157** identifying the kinematic parameters of motion associated with the EFE, FPS, WFE, and RUD motions in the arm **110**, as described above, and performing one or more of the WKI, FKI, and UKI algorithms to develop the models of the arm **110**, develop models of the exoskeleton **100**, or both. The models can be developed by the model identifier **157** through the real-time analysis of the motion of the arm **110**. The models can also be developed based on example or training data in some cases. The models can also be updated recursively in real time by the model identifier **157** at step **204**.

[0071] At step **206**, the process includes planning motion for the arm **110** and the exoskeleton **100**. For example, step **206** can include the motion planner **158** processing the involuntary and voluntary movements of the arm **110**, as isolated and analyzed at step **202**, using the models identified at step

204. Step **206** can also include the motion planner **158** extrapolating or projecting a forecasted trajectory for the arm **110**. That is, based on the isolation of voluntary movement of the arm **110** over a partial trajectory, the motion planner **158** can forecast the remainder of the trajectory of the arm **110** for rehabilitation or assistive purposes.

[0072] The motion planner **158** can project or forecast a trajectory for the arm **110** using learning models or algorithms in some cases. For example, at step **206**, the process can include the motion planner **158** identifying correlations (e.g., trajectory matches) between the current voluntary motion of the arm **110** and a history of previous voluntary movements of the arm **110** stored in the motion trajectories **152**C, to develop a forecasted trajectory for the arm **110**.

[0073] At step **208**, the process includes generating motor control signals. For example, step **208** can include the motion controller **159** generating motor control signals for the motors **140-142**. The motion controller **159** can control the motors **140-142** for two primary objectives, including tremor suppression and voluntary movement assistance. For example, based on the results of the frequency analysis performed by the robot control system **156**, the robot control system **156** can isolate the portion of the movement in the arm **110** that is attributed to the involuntary quivering movements of the arm **110**. The robot control system **156** can also isolate the portion of the movement in the arm **110** that is attributed to the intended or voluntary movements of the arm **110**. Additionally, the motion planner **158** can evaluate the trajectory, or partial trajectory, of the intended motion of the arm **110**. The motion planner **158** can also forecast, in some cases, the remaining trajectory of the arm **110**.

[0074] In view of those isolated components of movement in the arm **110**, step **208** can include the motion controller **159** generating motor control signals that suppress (e.g., counterbalance against) the involuntary quivering movements of the arm **110** and enhance (e.g., support or further direct) the intended or voluntary movements of the arm **110**. The motion controller **159** can develop the motor control signals for enhancing the intended movements of the arm **110** based on the forecasted trajectory of the intended motion of the arm **110**, as provided by the motion planner **158**. The motion controller **159** can also control the motors **140-142** for other objectives, however, such as to teach an individual new motions or new motion trajectories for rehabilitative purposes.

[0075] At step **210**, the process includes directing the motion of the exoskeleton **100** and the arm **110** based on the control signals generated at step **208**. For example, step **210** can include the motion controller **159** providing the motion control signals to the motor drivers **153**, to control the motors **140-142**. Based on the motor control signals, the motors **140-142** can impart forces on the exoskeleton **100** to both suppress tremors and to assist with voluntary movements in the arm **110**. Through the signal processing performed by the robot control system **156**, the motors **140-142** produce safe actuations based on adaptive control and motion planning algorithms to simultaneously suppress tremors and assist with voluntary motions.

[0076] The components of the exoskeleton **100** can be embodied in hardware, software, or a combination of hardware and software. Particularly, the embedded controller **150** can be embodied in hardware, software, or a combination of hardware and software. If embodied in software, each element of the robot control system **156** can represent a module of code or a portion of code that includes program instructions to implement the specified logical function(s). The program instructions can be embodied in the form of, for example, source code that includes human-readable statements written in a programming language or machine code that includes machine instructions recognizable by a suitable execution system, such as a processor in a computer system or other system. If embodied in hardware, each element can represent a circuit or a number of interconnected circuits that implement the specified logical function(s).

[0077] The embedded controller **150** can include at least one processing circuit. Such a processing circuit can include, for example, one or more processors and one or more storage or memory devices that are coupled to a local interface. The local interface can include, for example, a data bus with an accompanying address/control bus or any other suitable bus structure. The storage devices

can store data, such as the control information **152**A, the model parameters **152**B, and the motion trajectories **152**C, as well as components that are executable by the processors of the embedded controller **150**. For example, the robot control system **156** can be embodied as software stored in the storage devices and be executable by the processors of the embedded controller **150**.
[0078] Overall, the robot control system **156** can be embodied in the form of hardware, as software components that are executable by hardware, or as a combination of software and hardware. If embodied as hardware, the robot control system **156** and other components described herein can be implemented as a circuit or state machine that employs any suitable hardware technology. The hardware technology can include, for example, one or more microprocessors, discrete logic circuits having logic gates for implementing various logic functions upon an application of one or more data signals, application specific integrated circuits (ASICs) having appropriate logic gates, programmable logic devices (e.g., field-programmable gate array (FPGAs), and complex programmable logic devices (CPLDs)).
[0079] Also, one or more or more of the components described herein that include software or program instructions can be embodied in a non-transitory computer-readable medium, such as a memory device or memory devices, for use by an instruction execution system, such as a processor. The computer-readable medium can contain, store, and/or maintain the software or program instructions for use by or in connection with the instruction execution system. The computer-readable medium can be embodied as a physical media, such as magnetic, optical, semiconductor, and/or other suitable media. Examples of a suitable computer-readable media include, but are not limited to, solid-state drives, magnetic drives, or flash memory. Further, any logic or component described herein can be implemented and structured in a variety of ways. For example, one or more components described can be implemented as modules or components of a single application. Further, one or more components described herein can be executed in one computing device or by using multiple computing devices.
[0080] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

Claims

1. A forearm exoskeleton for an arm, comprising: a plurality of attachment modules; a plurality of pivotable linkages between the plurality of attachment modules, a plurality of motors mechanically coupled between the plurality of attachment modules and the plurality of pivotable linkages; feedback sensors that provide position feedback for the exoskeleton; and a controller configured to direct the plurality of motors to suppress tremors in and assist with voluntary motions of the arm based on the position feedback.
2. The forearm exoskeleton according to claim 1, wherein each of the plurality of pivotable linkages comprises a first link, a second link, a pivot point between the first link and the second link, and a position encoder at the pivot point.
3. The forearm exoskeleton according to claim 1, wherein the controller is further configured to direct the plurality of motors based on a motion planning algorithm using the position feedback.
4. The forearm exoskeleton according to claim 1, wherein the controller is further configured to develop a model for the arm using the position feedback.
5. The forearm exoskeleton according to claim 1, wherein the controller is further configured to: develop a model for the arm using the position feedback; and direct the plurality of motors based on a motion planning algorithm using the position feedback and the model for the arm.

6. The forearm exoskeleton according to claim 1, wherein the controller is further configured to isolate involuntary movement from voluntary movement in the arm using the position feedback.
7. The forearm exoskeleton according to claim 6, wherein the controller is further configured to direct the plurality of motors based on a motion planning algorithm to suppress the involuntary movement and assist the voluntary movement in the arm.
8. The forearm exoskeleton according to claim 1, wherein the feedback sensors comprise at least one inertial measurement unit, at least one positional encoder in at least one of the plurality of motors, and at least one positional encoder in at least one of the plurality of pivotable linkages.
9. The forearm exoskeleton according to claim 1, wherein at least one pivotable linkage among the plurality of pivotable linkages comprises an Euler-type joint.
10. The forearm exoskeleton according to claim 1, wherein the plurality of attachment modules comprise an attachment module for a bicep of the arm, an attachment module for a proximal end of a forearm of the arm, an attachment module for a distal end of the forearm, and an attachment module for a dorsum of a hand of the arm.
11. The forearm exoskeleton according to claim 1, wherein the exoskeleton provides passive and active suppression of tremors in the arm.
12. The forearm exoskeleton according to claim 1, wherein the controller is further configured to: perform a first kinematic identification algorithm for elbow flexion-extension (EFE) motion of the arm using the position feedback; perform a second kinematic identification algorithm for forearm pronation-supination (FPS) motion of the arm using the position feedback; perform a third kinematic identification algorithm for wrist flexion-extension (WFE) motion of the arm using the position feedback; and perform a fourth kinematic identification algorithm for wrist radial-ulnar deviations (RUD) motions of the arm using the position feedback.
13. The forearm exoskeleton according to claim 12, wherein the controller is further configured to: develop a model for the arm based on a combination of the first, the second, the third, and the fourth kinematic identification algorithms; and direct the plurality of motors based on the model for the arm using the position feedback.
14. The forearm exoskeleton according to claim 13, wherein the controller is further configured to recursively update the model for the arm.
15. The forearm exoskeleton according to claim 1, wherein the controller is further configured to: perform trajectory tracking of an intended motion of the arm based on the position feedback; forecast a trajectory of the intended motion of the arm based on the position feedback; and direct the plurality of motors based on a motion planning algorithm to suppress involuntary movement in the arm and to assist with voluntary movement in the arm based on the forecast of the trajectory of the intended motion.
16. The forearm exoskeleton according to claim 1, wherein the controller is further configured to minimize human-exoskeleton interaction loads estimated based on a real-time updated regression model.
17. A method for control of a forearm exoskeleton for an arm, comprising: analyzing movement data of the forearm exoskeleton based on position feedback from feedback sensors of the forearm exoskeleton; generating a model for the forearm exoskeleton based on the analyzing; planning motion for the arm and the exoskeleton based on the model; and directing at least one motor of the forearm exoskeleton based on the planning.
18. The method according to claim 17, wherein the forearm exoskeleton comprises: a plurality of attachment modules; a plurality of pivotable linkages between the plurality of attachment modules, a plurality of motors mechanically coupled between the plurality of attachment modules and the plurality of pivotable linkages; feedback sensors that provide the position feedback for the exoskeleton; and a controller.
19. The method according to claim 18, wherein the feedback sensors comprise at least one inertial measurement unit and at least one positional encoder.

20. The method according to claim 18, wherein the plurality of attachment modules comprise an attachment module for a bicep of the arm, an attachment module for a proximal end of a forearm of the arm, an attachment module for a distal end of the forearm, and an attachment module for a dorsum of a hand of the arm.