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United States Patent Application Publication 20250255680
Kind Code A1
Publication Date August 14, 2025
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SURGICAL ROBOTIC SYSTEM AND METHOD FOR PREDICTING CABLE WEAR AND FAILURE

Abstract

A surgical robotic system includes an instrument, at least one sensor, a processor, and a memory. The instrument includes an end effector and a plurality of cables. The at least one sensor detects a vibration signature produced by the plurality of cables. The memory is coupled to the processor and has instructions stored thereon which, when executed by the processor, cause the surgical robotic system to: store an vibration signal threshold corresponding to an vibration signature of the plurality of cables when the plurality of cables are in a first state; detect, by the at least one sensor, an in-use a vibration signature produced by the plurality of cables during use of the instrument in surgery; determine, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument; determine, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, an in-use state of the plurality of cables; and output an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

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Family ID: **96661287**

Appl. No.: **19/040568**

Filed: **January 29, 2025**

Related U.S. Application Data

us-provisional-application US 63551209 20240208

Publication Classification

Int. Cl.: **A61B34/30** (20160101); **A61B34/00** (20160101)

U.S. Cl.:

CPC **A61B34/30** (20160201); **A61B34/71** (20160201);

Background/Summary

BACKGROUND

[0001] Surgical robotic systems are currently being used in a variety of surgical procedures, including minimally invasive medical procedures. Some surgical robotic systems include a surgeon console controlling a surgical robotic arm and a surgical instrument having an end effector (e.g., forceps or grasping instrument) coupled to and actuated by the robotic arm. In operation, the robotic arm is moved to a position over a patient and then guides the surgical instrument into a small incision via a surgical port or a natural orifice of a patient to position the end effector at a work site within the patient's body.

[0002] Surgical robotic instruments are actuated by one or more cables, which may snap during use due to high strain placed on them during actuation. Cable snapping may result in unintentional, uncontrolled movement of portions of the instruments, e.g., the end effector.

SUMMARY

[0003] According to one aspect of the present disclosure, a surgical robotic system is described. The surgical robotic system includes an instrument, at least one sensor, a processor, and a memory. The instrument includes an end effector and a plurality of cables. The at least one sensor is configured to detect a vibration signature produced by the plurality of cables. The memory stores a vibration signal threshold corresponding to a vibration signature of the plurality of cables prior to use of the plurality of cables in the instrument in surgery, and is coupled to the processor and has instructions stored thereon which, when executed by the processor, cause the surgical robotic system to: store a vibration signal corresponding to a vibration signature of the plurality of cables when the plurality of cables are in a first state; detect, by the at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery; determine, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument; and determine, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, an in-use state of the plurality of cables; and output an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

[0004] In another aspect of the present disclosure, the in-use state of the plurality of cables may correspond to a failure state of at least one cable of the plurality of cables.

[0005] In yet another aspect of the present disclosure, the surgical robotic system may be configured to receive a user command for controlling the instrument, and the instructions, when executed by the processor, may further cause the surgical robotic system to disable execution of the user command when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables.

[0006] In a further aspect of the present disclosure, the surgical robotic system may further include a surgeon console including a display screen for displaying a graphical user interface. The graphical user interface may be configured to receive a user input for setting a trigger event.

[0007] In yet a further aspect of the present disclosure, the instructions, when executed by the processor, may further cause the surgical robotic system to determine, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables.

[0008] In another aspect of the present disclosure, the third state may correspond to a failure state of a filar of at least one cable of the plurality of cables.

[0009] In yet another aspect of the present disclosure, the surgical robotic system may further include an instrument drive unit coupled to the instrument. The instrument drive unit may include a plurality of motors and a controller. The instructions, when executed by the processor, may further cause the surgical robotic system to control the plurality of motors to reduce tension in the plurality of cables.

[0010] In a further aspect of the present disclosure, the stored and in-use vibration signals may correspond to a frequency of the vibration signature of the plurality of cables prior to and during use of the instrument.

[0011] In another aspect of the present disclosure, the alert may include at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear.

[0012] According to one aspect of the present disclosure, a processor-implemented method of cable failure detection is disclosed. The method includes: storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; and determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, a second state of the plurality of cables; and outputting an alert indicating a condition of the plurality of cables corresponding to an in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

[0013] In another aspect of the present disclosure, the in-use state of the plurality of cables may correspond to a failure state of at least one cable of the plurality of cables.

[0014] In yet another aspect of the present disclosure, the method may further include disabling entry of a user input for controlling the instrument when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables.

[0015] In a further aspect of the present disclosure, the method may further include displaying a graphical user interface on a display screen of a surgeon console, the graphical user interface configured to receive a user input for setting a trigger event.

[0016] In yet a further aspect of the present disclosure, the method may further include determining, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables.

[0017] In another aspect of the present disclosure, the third state may correspond to a failure state of a filar of at least one cable of the plurality of cables.

[0018] In yet another aspect of the present disclosure, the method may further include controlling, by an instrument drive unit coupled to the instrument, the plurality of cables to reduce tension in the plurality of cables.

[0019] In a further aspect of the present disclosure, the stored and in-use vibration signals may correspond to a frequency of the vibration signature of the plurality of cables prior to and during use.

[0020] In yet a further aspect of the present disclosure, the alert may include at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear.

[0021] According to one aspect of the present disclosure, one or more non-transitory processor-readable media are disclosed. The media stores instructions which, when executed by one or more processors, cause performance of: storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; and determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, a second state of the plurality of cables; and outputting an alert indicating a condition of the plurality of cables corresponding to an in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Various embodiments of the present disclosure are described herein with reference to the drawings wherein:

[0023] FIG. **1** is a perspective view of a surgical robotic system including a control tower, a console, and one or more surgical robotic arms each disposed on a movable cart according to an aspect of the present disclosure;

[0024] FIG. **2** is a perspective view of a surgical robotic arm of the surgical robotic system of FIG. **1** according to an aspect of the present disclosure;

[0025] FIG. **3** is a perspective view of a movable cart having a setup arm with the surgical robotic arm of the surgical robotic system of FIG. **1** according to an aspect of the present disclosure;

[0026] FIG. **4** is a schematic diagram of a computer architecture of the surgical robotic system of FIG. **1** according to an aspect of the present disclosure;

[0027] FIG. **5** is a plan schematic view of movable carts of FIG. **1** positioned about a surgical table according to an aspect of the present disclosure;

[0028] FIG. **6** is a perspective view, with parts separated, of an instrument drive unit and a surgical instrument according to an aspect of the present disclosure;

[0029] FIG. **7** is a side, cross-sectional view of the instrument according to an aspect of the present disclosure, for use in the surgical robotic system of FIG. **1**;

[0030] FIG. **8** is a top, perspective view of the end effector of the instrument of FIG. **7**, according to an aspect of the present disclosure;

[0031] FIG. **9** shows the end effector in various configurations according to aspects of the present disclosure;

[0032] FIG. **10** is a perspective view of a system for predicting cable wear and breakage according to an aspect of the present disclosure; and

[0033] FIG. **11** is a flow chart of a method for predicting cable wear and breakage according to an aspect of the present disclosure.

DETAILED DESCRIPTION

[0034] Embodiments of the presently disclosed surgical robotic system are described in detail with reference to the drawings, in which like reference numerals designate identical or corresponding elements in each of the several views.

[0035] With reference to FIG. **1**, a surgical robotic system **10** includes a control tower **20**, which is communicatively coupled to all of the components of the surgical robotic system **10** including a surgeon console **30** and one or more movable carts **60**. Each of the movable carts **60** includes a robotic arm **40** having an instrument **50** coupled thereto. The robotic arms **40** also couple to the movable carts **60**. The surgical robotic system **10** may include any number of movable carts **60** and/or robotic arms **40**.

[0036] The surgical instrument **50** is configured for use during minimally invasive surgical procedures. In embodiments, the surgical instrument **50** may be configured for open surgical procedures. In further embodiments, the surgical instrument **50** may be an electrosurgical forceps configured to seal tissue by compressing tissue between jaw members and applying electrosurgical current thereto. In yet further embodiments, the surgical instrument **50** may be a surgical stapler including a pair of jaws configured to grasp and clamp tissue while deploying a plurality of tissue fasteners, e.g., staples, and cutting stapled tissue. In yet further embodiments, the surgical instrument **50** may be a surgical clip applier including a pair of jaws configured to apply a surgical clip onto tissue. However, it will be understood that various types of surgical instruments for use during minimally invasive surgical procedures are contemplated and within the scope of this disclosure.

[0037] One of the robotic arms **40** may include an endoscopic camera **51** configured to capture video of the surgical site. The endoscopic camera **51** may be a stereoscopic endoscope configured to capture two side-by-side (i.e., left and right) images of the surgical site to produce a video stream of the surgical scene. The endoscopic camera **51** is coupled to a video processing device **56**, which may be disposed within the control tower **20**. The video processing device **56** may be any computing device as described below configured to receive the video feed from the endoscopic camera **51** and output the processed video stream.

[0038] The surgeon console **30** includes a first screen **32**, which displays a video feed of the surgical site provided by camera **51** disposed on the robotic arm **40**, and a second screen **34**, which displays a user interface for controlling the surgical robotic system **10**. The first screen **32** and second screen **34** may be touchscreens allowing for displaying various graphical user inputs.

[0039] The surgeon console **30** also includes a plurality of user interface devices, such as foot pedals **36** and a pair of handle controllers **38***a* and **38***b* which are used by a user to remotely control robotic arms **40**. The surgeon console further includes an armrest **33** used to support clinician's arms while operating the handle controllers **38***a* and **38***b*.

[0040] The control tower **20** includes a screen **23**, which may be a touchscreen that may display the graphical user interfaces (GUIs). The control tower **20** also acts as an interface between the surgeon console **30** and one or more robotic arms **40**. In particular, the control tower **20** is configured to control the robotic arms **40**, such as to move the robotic arms **40** and the corresponding surgical instrument **50**, based on a set of programmable instructions and/or input commands from the surgeon console **30**, in such a way that robotic arms **40** and the surgical instrument **50** execute a desired movement sequence in response to input from the foot pedals **36** and the handle controllers **38***a* and **38***b*. The foot pedals **36** may be used to enable and lock the hand controllers **38***a* and **38***b*, repositioning camera movement and electrosurgical activation/deactivation. In particular, the foot pedals **36** may be used to perform a clutching action on the hand controllers **38***a* and **38***b*. Clutching is initiated by pressing one of the foot pedals **36**, which disconnects (i.e., prevents movement inputs) the hand controllers **38***a* and/or **38***b* from the robotic arm **40** and corresponding instrument **50** or camera **51** attached thereto. This allows the user to reposition the hand controllers **38***a* and **38***b* without moving the robotic arm(s) **40** and the instrument **50** and/or camera **51**. This is useful when reaching control boundaries of the surgical space.

[0041] Each of the control tower **20**, the surgeon console **30**, and the robotic arm **40** includes a respective computer **21**, **31**, **41**. The computers **21**, **31**, **41** are interconnected to each other using any suitable communication network based on wired or wireless communication protocols. The term “network,” whether plural or singular, as used herein, denotes a data network, including, but not limited to, the Internet, Intranet, a wide area network, or a local area network, and without limitation as to the full scope of the definition of communication networks as encompassed by the present disclosure. Suitable protocols include, but are not limited to, transmission control protocol/internet protocol (TCP/IP), datagram protocol/internet protocol (UDP/IP), and/or datagram congestion control protocol (DCCP). Wireless communication may be achieved via one or more wireless configurations, e.g., radio frequency, optical, Wi-Fi, Bluetooth (an open wireless protocol for exchanging data over short distances, using short length radio waves, from fixed and mobile devices, creating personal area networks (PANs), ZigBee® (a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 122.15.4-1203 standard for wireless personal area networks (WPANs)).

[0042] The computers **21**, **31**, **41** may include any suitable processor (not shown) operably connected to a memory (not shown), which may include one or more of volatile, non-volatile, magnetic, optical, or electrical media, such as read-only memory (ROM), random access memory (RAM), electrically erasable programmable ROM (EEPROM), non-volatile RAM (NVRAM), or flash memory. The processor may be any suitable processor (e.g., control circuit) adapted to perform the operations, calculations, and/or set of instructions described in the present disclosure including, but not limited to, a hardware processor, a field programmable gate array (FPGA), a digital signal processor (DSP), a central processing unit (CPU), a microprocessor, and combinations thereof. Those skilled in the art will appreciate that the processor may be substituted by using any logic processor (e.g., control circuit) adapted to execute algorithms, calculations, and/or set of instructions described herein.

[0043] With reference to FIG. **2**, each of the robotic arms **40** may include a plurality of links **42***a*, **42***b*, **42***c*, which are interconnected at joints **44***a*, **44***b*, **44***c*, respectively. Other configurations of links and joints may be utilized as known by those skilled in the art. The joint **44***a* is configured to secure the robotic arm **40** to the movable cart **60** and defines a first longitudinal axis. With reference to FIG. **3**, the movable cart **60** includes a lift **67** and a setup arm **61**, which provides a base for mounting of the robotic arm **40**. The lift **67** allows for vertical movement of the setup arm **61**. The movable cart **60** also includes a display **69** for displaying information pertaining to the robotic arm **40**. In embodiments, the robotic arm **40** may include any type and/or number of joints.

[0044] The setup arm **61** includes a first link **62***a*, a second link **62***b*, and a third link **62***c*, which provide for lateral maneuverability of the robotic arm **40**. The links **62***a*, **62***b*, **62***c* arc interconnected at joints **63***a* and **63***b*, each of which may include an actuator (not shown) for rotating the links **62***b* and **62***b* relative to each other and the link **62***c*. In particular, the links **62***a*, **62***b*, **62***c* are movable in their corresponding lateral planes that are parallel to each other, thereby allowing for extension of the robotic arm **40** relative to the patient (e.g., surgical table). In embodiments, the robotic arm **40** may be coupled to the surgical table (not shown). The setup arm **61** includes controls **65** for adjusting movement of the links **62***a*, **62***b*, **62***c* as well as the lift **67**. In embodiments, the setup arm **61** may include any type and/or number of joints.

[0045] The third link **62***c* may include a rotatable base **64** having two degrees of freedom. In particular, the rotatable base **64** includes a first actuator **64***a* and a second actuator **64***b*. The first actuator **64***a* is rotatable about a first stationary arm axis which is perpendicular to a plane defined by the third link **62***c* and the second actuator **64***b* is rotatable about a second stationary arm axis which is transverse to the first stationary arm axis. The first and second actuators **64***a* and **64***b* allow for full three-dimensional orientation of the robotic arm **40**.

[0046] The actuator **48***b* of the joint **44***b* is coupled to the joint **44***c* via the belt **45***a*, and the joint **44***c* is in turn coupled to the joint **46***b* via the belt **45***b*. Joint **44***c* may include a transfer case coupling the belts **45***a* and **45***b*, such that the actuator **48***b* is configured to rotate each of the links **42***b*, **42***c* and a holder **46** relative to each other. More specifically, links **42***b*, **42***c*, and the holder **46** are passively coupled to the actuator **48***b* which enforces rotation about a pivot point “P” which lies at an intersection of the first axis defined by the link **42***a* and the second axis defined by the holder **46**. In other words, the pivot point “P” is a remote center of motion (RCM) for the robotic arm **40**. Thus, the actuator **48***b* controls the angle θ between the first and second axes allowing for orientation of the surgical instrument **50**. Due to the interlinking of the links **42***a*, **42***b*, **42***c*, and the holder **46** via the belts **45***a* and **45***b*, the angles between the links **42***a*, **42***b*, **42***c*, and the holder **46** are also adjusted in order to achieve the desired angle **0**. In embodiments, some or all of the joints **44***a*, **44***b*, **44***c* may include an actuator to obviate the need for mechanical linkages.

[0047] The joints **44***a* and **44***b* include an actuator **48***a* and **48***b* configured to drive the joints **44***a*, **44***b*, **44***c* relative to each other through a series of belts **45***a* and **45***b* or other mechanical linkages such as a drive rod, a cable, or a lever and the like. In particular, the actuator **48***a* is configured to rotate the robotic arm **40** about a longitudinal axis defined by the link **42***a*.

[0048] With reference to FIG. **2**, the holder **46** defines a second longitudinal axis and configured to receive an instrument drive unit (IDU) **52** (FIG. **1**). The IDU **52** is configured to couple to an actuation mechanism of the surgical instrument **50** and the camera **51** and is configured to move (e.g., rotate) and actuate the instrument **50** and/or the camera **51**. IDU **52** transfers actuation forces from its actuators to the surgical instrument **50** to actuate components of an end effector **49** of the surgical instrument **50**. The holder **46** includes a sliding mechanism **46***a*, which is configured to move the IDU **52** along the second longitudinal axis defined by the holder **46**. The holder **46** also includes a joint **46***b*, which rotates the holder **46** relative to the link **42***c*. During endoscopic procedures, the instrument **50** may be inserted through an endoscopic access port **55** (FIG. **3**) held by the holder **46**. The holder **46** also includes a port latch **46***c* for securing the access port **55** to the holder **46** (FIG. **2**).

[0049] The IDU **52** is attached to the holder **46**, followed by a sterile interface module (SIM) **43** being attached to a distal portion of the IDU **52**. The SIM **43** is configured to secure a sterile drape (not shown) to the IDU **52**. The instrument **50** is then attached to the SIM **43**. The instrument **50** is then inserted through the access port **55** by moving the IDU **52** along the holder **46**. The SIM **43** includes a plurality of drive shafts configured to transmit rotation of individual motors of the IDU **52** to the instrument **50** thereby actuating the instrument **50**. In addition, the SIM **43** provides a sterile barrier between the instrument **50** and the other components of robotic arm **40**, including the IDU **52**.

[0050] The robotic arm **40** also includes a plurality of manual override buttons **53** (FIG. **1**) disposed on the IDU **52** and the setup arm **61**, which may be used in a manual mode. The user may press one or more of the buttons **53** to move the component associated with the one or more buttons **53**.

[0051] With reference to FIG. **4**, each of the computers **21**, **31**, **41** of the surgical robotic system **10** may include a plurality of controllers, which may be embodied in hardware and/or software. The computer **21** of the control tower **20** includes a controller **21***a* and safety observer **21***b*. The controller **21***a* receives data from the computer **31** of the surgeon console **30** about the current position and/or orientation of the handle controllers **38***a* and **38***b* and the state of the foot pedals **36** and other buttons. The controller **21***a* processes these input positions to determine desired drive commands for each joint of the robotic arm **40** and/or the IDU **52** and communicates these to the computer **41** of the robotic arm **40**. The controller **21***a* also receives the actual joint angles measured by encoders of the actuators **48***a* and **48***b* and uses this information to determine force feedback commands that are transmitted back to the computer **31** of the surgeon console **30** to provide haptic feedback through the handle controllers **38***a* and **38***b*. The safety observer **21***b* performs validity checks on the data going into and out of the controller **21***a* and notifies a system fault handler if errors in the data transmission are detected to place the computer **21** and/or the surgical robotic system **10** into a safe state.

[0052] The computer **41** includes a plurality of controllers, namely, a main cart controller **41***a*, a setup arm controller **41***b*, a robotic arm controller **41***c*, and an instrument drive unit (IDU) controller **41***d*. The main cart controller **41***a* receives and processes joint commands from the controller **21***a* of the computer **21** and communicates them to the setup arm controller **41***b*, the robotic arm controller **41***c*, and the IDU controller **41***d*. The main cart controller **41***a* also manages instrument exchanges and the overall state of the movable cart **60**, the robotic arm **40**, and the IDU **52**. The main cart controller **41***a* also communicates actual joint angles back to the controller **21***a*.

[0053] Each of joints **63***a* and **63***b* and the rotatable base **64** of the setup arm **61** are passive joints (i.e., no actuators are present therein) allowing for manual adjustment thereof by a user. The joints **63***a* and **63***b* and the rotatable base **64** include brakes that are disengaged by the user to configure the setup arm **61**. The setup arm controller **41***b* monitors slippage of each of joints **63***a* and **63***b* and the rotatable base **64** of the setup arm **61**, when brakes are engaged or can be freely moved by the operator when brakes are disengaged, but do not impact controls of other joints. The robotic arm controller **41***c* controls each joint **44***a* and **44***b* of the robotic arm **40** and calculates desired motor torques required for gravity compensation, friction compensation, and closed loop position control of the robotic arm **40**. The robotic arm controller **41***c* calculates a movement command based on the calculated torque. The calculated motor commands are then communicated to one or more of the actuators **48***a* and **48***b* in the robotic arm **40**. The actual joint positions are then transmitted by the actuators **48***a* and **48***b* back to the robotic arm controller **41***c*.
[0054] The IDU controller **41***d* receives desired joint angles for the surgical instrument **50**, such as wrist and jaw angles, and computes desired currents for the motors in the IDU **52**. The IDU controller **41***d* calculates actual angles based on the motor positions and transmits the actual angles back to the main cart controller **41***a*.
[0055] The robotic arm **40** is controlled in response to a pose of the handle controller controlling the robotic arm **40**, e.g., the handle controller **38***a*, which is transformed into a desired pose of the robotic arm **40** through a hand eye transform function executed by the controller **21***a*. The hand eye function, as well as other functions described herein, is/are embodied in software executable by the controller **21***a* or any other suitable controller described herein. The pose of one of the handle controllers **38***a* may be embodied as a coordinate position and roll-pitch-yaw (RPY) orientation relative to a coordinate reference frame, which is fixed to the surgeon console **30**. The desired pose of the instrument **50** is relative to a fixed frame on the robotic arm **40**. The pose of the handle controller **38***a* is then scaled by a scaling function executed by the controller **21***a*. In embodiments, the coordinate position may be scaled down and the orientation may be scaled up by the scaling function. In addition, the controller **21***a* may also execute a clutching function, which disengages the handle controller **38***a* from the robotic arm **40**. In particular, the controller **21***a* stops transmitting movement commands from the handle controller **38***a* to the robotic arm **40** if certain movement limits or other thresholds are exceeded and in essence acts like a virtual clutch mechanism, e.g., limits mechanical input from effecting mechanical output.
[0056] The desired pose of the robotic arm **40** is based on the pose of the handle controller **38***a* and is then passed by an inverse kinematics function executed by the controller **21***a*. The inverse kinematics function calculates angles for the joints **44***a*, **44***b*, **44***c* of the robotic arm **40** that achieve the scaled and adjusted pose input by the handle controller **38***a*. The calculated angles are then passed to the robotic arm controller **41***c*, which includes a joint axis controller having a proportional-derivative (PD) controller, the friction estimator module, the gravity compensator module, and a two-sided saturation block, which is configured to limit the commanded torque of the motors of the joints **44***a*, **44***b*, **44***c*. In aspects, handle controller **38***a* may be substituted for and/or employed in conjunction with handle controller **38***b*.
[0057] With reference to FIG. **5**, the surgical robotic system **10** is set up around a surgical table **90**. The system **10** includes movable carts **60***a-d*, which may be numbered "**1**" through "**4**." During setup, each of the carts **60***a-d* are positioned around the surgical table **90**. Position and orientation of the carts **60***a-d* depends on a plurality of factors, such as placement of a plurality of access ports **55***a-d*, which in turn, depends on the surgery being performed. Once the port placements are determined, the access ports **55***a-d* are inserted into the patient, and carts **60***a-d* are positioned to insert instruments **50** and the endoscopic camera **51** into corresponding ports **55***a-d*.
[0058] During use, each of the robotic arms **40***a-d* is attached to one of the access ports **55***a-d* that is inserted into the patient by attaching the latch **46***c* (FIG. **2**) to the access port **55** (FIG. **3**). The IDU **52** is attached to the holder **46**, followed by the SIM **43** being attached to a distal portion of

the IDU **52**. Thereafter, the instrument **50** is attached to the SIM **43**. The instrument **50** is then inserted through the access port **55** by moving the IDU **52** along the holder **46**.

[0059] With reference to FIG. **6**, the IDU **52** is shown in more detail and is configured to transfer power and actuation forces from its motors **152***a-d* to the instrument **50** to drive movement of components of the instrument **50**, such as articulation, rotation, pitch, yaw, clamping, cutting, etc. The IDU **52** may also be configured for the activation or firing of an electrosurgical energy-based instrument or the like (e.g., cable drives, pulleys, friction wheels, rack and pinion arrangements, etc.).

[0060] The IDU **52** includes a motor pack **150** and a sterile barrier housing **130**. Motor pack **150** includes motors **152***a-d* for controlling various operations of the instrument **50**. The instrument **50** is removably couplable to IDU **52**. As the motors **152***a-d* of the motor pack **150** are actuated, rotation of the drive transfer shafts **154***a*, **154***b*, **154***c*, **154***d* of the motors **152***a-d*, respectively, is transferred to the drive assemblies of the instrument **50**. The instrument **50** is configured to transfer rotational forces/movement supplied by the IDU **52** (e.g., via the motors **152***a-d* of the motor pack **150**) into longitudinal movement or translation of the cables or drive shafts to effect various functions of an end effector **200** (FIG. **7**).

[0061] Each of the motors **152***a-d* includes a current sensor **153**, a torque sensor **155**, and a position sensor **157**. For conciseness only operation of the motor **152***a* is described below, however, it will be understood that motors **152***b-d* may operate in a similar manner. The sensors **153**, **155**, **157** monitor the performance of the motor **152***a*. The current sensor **153** is configured to measure the current draw of the motor **152***a* and the torque sensor **155** is configured to measure motor torque. The torque sensor **155** may be any force or strain sensor including one or more strain gauges configured to convert mechanical forces and/or strain into a sensor signal indicative of the torque output by motor **152***a*. Position sensor **157** may be any device that provides a sensor signal indicative of the number of rotations of the motor **152***a*, such as a mechanical encoder or an optical encoder. Parameters which are measured and/or determined by position sensor **157** may include speed, distance, revolutions per minute, position, and the like. The sensor signals from sensors **153**, **155**, **157** are transmitted to the IDU controller **41***d*, which then controls the motors **152***a-d* based on the sensor signals. In particular, the motors **152***a-d* are controlled by an actuator controller **159**, which controls torque outputted and angular velocity of the motors **152***a-d*. In embodiments, additional position sensors may also be used, which include, but are not limited to, potentiometers coupled to movable components and configured to detect travel distances, Hall Effect sensors, accelerometers, and gyroscopes. In embodiments, a single controller can perform the functionality of the IDU controller **41***d* and the actuator controller **159**.

[0062] With reference to FIGS. **6** and **7**, instrument **50** includes an adapter **160** having a housing **162** at a proximal end portion thereof and an elongated shaft **164** that extends distally from housing **162**. Housing **162** of instrument **50** is configured to selectively couple to IDU **52** to enable motors **152***a-d* of IDU **52** to operate the end effector **200** of the instrument **50**. Housing **162** of instrument **50** supports a drive assembly **170** that mechanically and/or electrically cooperates with motors **152***a-d* of IDU **52**. Drive assembly **170** of instrument **50** includes a plurality of rotatable input couplers **172**, each of which is actuated by the corresponding motors **152***a-d*. The couplers **172** are threaded and include one corresponding drive nut **174** threadably coupled to a corresponding drive screw **173**. The drive nuts **174** are prevented from rotational movement by the housing of the drive assembly **170**. The drive nuts **174** move longitudinally along the couplers **172** as the couplers **172** are rotated by the motors **152***a-d* and are maintained in the longitudinal position via tension springs **175**. Each of the drive nuts **174** is coupled to a corresponding cable **201***a-d* via a drive rod **176** and a crimp **178**. Thus, as drive nuts **174***a-d* are moved longitudinally, the cables **201***a-d* are also moved longitudinally, thereby tensioning the cables **201***a-d*.

[0063] The surgical instrument also includes an end effector **200** coupled to the elongated shaft **164**. The end effector **200** may include any number of degrees of freedom allowing the end effector

200 to articulate, pivot, etc., relative to the elongated shaft **164**. The end effector **200** may be any suitable surgical end effector configured to treat tissue, such as a dissector, grasper, sealer, stapler, etc.

[0064] As shown in FIGS. **7**, **8**, and **9**, the end effector **200** may include a pair of opposing jaws **120** and **122** that are movable relative to each other. The jaws **120** and **122** may be grippers as shown or any other suitable type of jaws, e.g., shears, sealers, etc. In embodiments, the end effector **200** may include a proximal portion **112** having a first pin **113** and a distal portion **114**. The end effector **200** may be actuated using a plurality of cables **201***a-d* routed through proximal and distal portions **112** and **114** around their respective pulleys **112***a*, **112***b*, **114***a*, **114***b*, which are integrally formed as arms of the proximal and distal portions **112** and **114**. Each of the cables **201***a-d* is actuated by a respective motor **152***a-d* via corresponding couplers disposed in adapter **160**. In embodiments, the end effector **200**, namely, the distal portion **114** and the jaws **120** and **122**, may be articulated about the axis "A-A" to control a yaw angle of the end effector with respect to a longitudinal axis "X-X". The distal portion **114** includes a second pin **115** with a pair of jaws including a first jaw **120** and a second jaw **122** pivotably coupled to the second pin **115**. The jaws **120** and **122** are configured to pivot about an axis "B-B" defined by the second pin **115** allowing for controlling a pitch angle of the jaws **120** and **122** as well as opening and closing the jaws **120** and **122**. The yaw, pitch, and jaw angles between the jaws **120** and **122** as they are moved between open and closed positions are controlled by adjusting the tension and/or length and direction (e.g., proximal or distal) of the cables **201***a-d* as shown in FIG. **8**. The end effector **200** also includes a cable displacement sensor **116** configured to measure position of the cables **201**. Thus, the end effector **200** may have three degrees of freedom, yaw, pitch, and jaw angle between jaws **120** and **122**. Examples of control algorithms for a cable actuated instrument **50** are described in International Patent Application No. PCT/US2022/019703, "Surgical Robotic System for Realignment of Wristed Instruments," filed on Mar. 10, 2022.

[0065] After long periods of usage of the instrument **50**, the plurality of cables **201***a-d* may become worn. In particular, after extended usage of end effectors such as shears (e.g., monopolar curved shears), repetitive shear and wrist actuation may cause twisted filars (or fibers) within the plurality of cables **201***a-d* to fray and ultimately snap. After the plurality of cables **201***a-d* have become significantly worn, or after continued usage of the instrument **50** having cables **201***a-d* which are significantly worn, cable failure (e.g., snap or breakage) may occur, which requires replacement of instrument **50** and a ceasing of operations within the surgical robotic system **10**. Moreover, once cable breakage occurs, the end effector **200** is driven to an approximate right-angle position relative to the elongated shaft **164** due to tension applied by other (i.e., unsnapped) cables, which are still loaded under a tension force. Thus, it may be difficult or impossible to remove the instrument **50**, having an articulated end effector **200**, through the access port **55**. As a result, the clinician may enact an instrument slack procedure to reduce tension on the other (unsnapped cables). Examples of instrument slack procedures for the plurality of cables **201***a-d* are described further below.

[0066] Therefore, it is important for a clinician, or a surgical robotic system, to predict breakage of the plurality of cables **201***a-d* prior to a total cable failure. The present disclosure provides a system and a method configured to predict and/or detect wearing of the plurality of cables, **201***a-d*, such as high side cables **201***b* and **201***c* (i.e., cables which are under relatively greater tension loads), using sounds or vibration signatures emitted from cables **201***a-d* that are detected by vibration signature sensors.

[0067] With reference to FIG. **10**, a system **300** for predicting cable wear and failure is shown, which forms a part of the surgical robotic system **10**. System **300** includes a plurality of vibration signature sensors **310**, **312** configured to measure a frequency of a vibration signature produced by cables **201***a-d* and/or individual filars **202** of the cables **201***a-d*. The vibration signature sensors **310**, **312** may include a recording device **314** for capturing the vibration signature, such as a microphone. In embodiments, the vibration signature sensors **310**, **312** may be placed proximal to cables **201***a-d*, although alternative placements throughout the surgical robotic system **10** are contemplated and within the scope of this disclosure. It will be understood that while two sensors **310**, **312** are shown next to cables **102***a-d* and further described herein, any number and/or arrangement of sensors **310**, **312** may be included in system **300**. For example, the system **300** may function with only one vibration signature sensor **310** or **312**.

[0068] The vibration signature sensors **310**, **312** may be configured to detect a characteristic sound or signature, e.g., a vibration signature emitted from cables **201***a-d* and/or individual filars **202** due to vibration and/or breakage thereof. The vibration signature may be the result of vibration through the air, vibration of the cables and filars, and/or another part of the surgical robotic instrument **10**. For example, vibration signature sensors **310**, **312** may detect soundwaves emitted within a predetermined distance from the components of the system **300**. In another example, vibration signature sensors **310**, **312** may be configured to detect vibration of the components of the system **300**, such as vibrations detected from being physically positioned on said components. As used herein, a vibration signature may include a signal within the normal range of hearing, an ultrasonic frequency (e.g., over 20 kHz), a specific cable and/or filar vibration pattern, sound waves, electrical continuity, electrical resistance, an audio signal, and/or another signal and/or signature known by one skilled in the art, as discussed further below.

[0069] The vibration signature may be converted to a vibration signal for processing by the surgical robotic system **10**. The system may use the resulting signal for comparison with another signal. In aspects, the system may compare the signal to a vibration signal threshold, as further discussed below. This vibration signal threshold may be preprogrammed into surgical robotic system **10**, and/or set as a system default upon installation.

[0070] For example, the vibration signature sensors **310**, **312** may be configured to record a vibration signature “SF” produced by the individual filars **202**. The vibration signature “SF” may indicate snapping and/or vibration of individual filars **202** as cables **201***a-d* wear under tension (e.g., from shear and wrist actuation of the end effector **200** of the instrument **50**). In particular, the vibration signature sensors **310**, **312** may be programmed to detect a specific frequency of the vibration signature “SF” of the filars **202** when snapping, which corresponds to breakage. If the frequency of the vibration signature “SF” matches a preprogrammed frequency or threshold (e.g., a vibration signal threshold) corresponding to filar breakage, the vibration signature sensors **310**, **312** may transmit an alert to the surgical robotic system **10**. For example, the vibration signature sensors **310**, **312** may emit an audible or visual alert signal or cause the surgical robotic system **10** to emit an audible or visual alert signal. The alert signal may be used to alert the clinician that a filar breakage has occurred. Therefore, the clinician and/or the surgical robotic system **100** may be able to act appropriately.

[0071] In another example, the vibration signature sensors **310**, **312** may be configured to record a vibration signature “SC” produced by the cables **201***a-d*. A frequency of the vibration signature “SC” may change over time as the individual filars **202** of the cables **201***a-d* snap, which may indicate a health state of the plurality of cables **201***a-d*. In particular, the vibration signature sensors **310**, **312** may be configured to detect specific changes in the frequency of the vibration signature “SC”, which correspond to a likelihood of cable failure for the cables **201***a-d*. In doing so, the vibration signature sensors **310**, **312** continuously monitor the vibration signature “SC”, which is analyzed in comparison to a baseline vibration signature “SC” obtained from a vibration signal threshold prior to usage. If the vibration signature “SC” of the cables **201***a-d* exceeds a frequency threshold in relation to a baseline value, the vibration signature sensors **310**, **312** may transmit an alert to the surgical robotic system **10**. For example, the vibration signature sensors **310**, **312** may emit an audible or visual alert signal or cause the surgical robotic system **10** to emit an audible or visual alert signal. The alert signal may be used to alert the clinician that the cables **201***a-d* are likely to fail. Therefore, the clinician and/or the surgical robotic system **10** may be able cease operation and/or inspect and/or replace the instrument **50** and/or cables **201***a-d*. In aspects, the vibration signature sensors **310**, **312** may be configured to record a vibration signature "SC" of an individual cable **201***a-d*. This solves the problem of determining which cable **201***a-d* broke and may be useful for analyzing whether a particular cable or group of cables is experiencing more failure than others.

[0072] Alternatively, in embodiments, the surgical robotic system **10** may be able to adjust a tension of the cables **201***a-d* and/or a torque of the motors **152***a-d*, in order to extend a use life of the instrument **50** and prevent immediate failure. For example, a tension force on the cables **201***a-d* may be released or reduced by a certain factor for certain cables **201***a-d*, which have been observed by vibration signature sensors **310**, **312** to have filars **202** within those the cables **201***a-d* that exhibit signs of fraying, which may thus prevent a snapping of the filars **202** altogether and which may extend the use life of the instrument **50**. In another example, a torque produced by motors **152***a-d* may be reduced, thereby allowing the clinician to move an instrument **50** with reduced force. The adjustments may be made intraoperatively, thereby allowing the clinician to continue using the instrument **50** without interruption for a period of time.

[0073] In embodiments, the vibration signature sensors **310**, **312** may include an accelerometer to measure specific vibration or acoustical signals and/or vibration or acoustical lengths of the cables **201***a-d* and/or the filars **202**. For example, if a vibration speed of one or more of the cables **201***a-d* exceeds a preprogrammed threshold, the vibration signature sensors **310**, **312** may transmit an audible or visual alert signal and/or cause the surgical robotic system **10** to emit an audible or visual alert signal, which will similarly alert a clinician that snapping of filars **202** has occurred and/or potential failure of cables **201***a-d* may soon occur. In doing so, the vibration signature sensors **310**, **312** may provide an alternative means of detecting a frequency of a vibration signal, such as vibration signals "SF", "SC", for the filars **202** and cables **201***a-d*, respectively. For example, the accelerometer(s) may be able to detect an inaudible and/or an ultrasonic frequency band emitted by the cables **201***a-d* and/or the filars **202**, which is incapable of detection by a microphone. In another example, the vibration signature sensors **310**, **312**, may be configured to measure changes in tension per unit length of cables **210***a-d*. For example, as more filars **202** break, a tension of the cables **201***a-d* may increase. In doing so, the vibration signature sensors **310**, **312** may be able to measure a breakage percentage of filars **202** to determine the remaining use life of the cables **201***a-d*.

[0074] In embodiments, the signature sensors **310**, **312** may be replaced by, or additionally configured to detect electrical continuity and/or resistance through the cables **201***a-d*. For example, such electrical continuity sensors may detect a change in resistance through cables **201***a-d* indicating a partial cable failure, or an open circuit indicating a total cable failure.

[0075] Alternatively, in embodiments, the surgical robotic system **10** may induce a vibration in one of more cables **102***a-d* and/or individual filars **202** in order to detect a level of tension on the cables indicative of a health state. The vibration may be induced through tapping, plucking, or an alternative means of initiating vibration. Generally, the vibration may be induced without movement and/or prior to movement caused by use of the surgical robotic system **10**.

[0076] With reference to FIG. **11**, a method **400** for predicting and/or detecting cable wear and failure is implemented by the vibration signature sensors **310**, **312**, as software instructions executable by any suitable processor of the surgical robotic system **10**, such as the IDU controller **41***d*, the main controller **21***a*, etc., among others contemplated and within the scope of this disclosure.

[0077] Initially, at step **402**, the processor receives a vibration signal corresponding to a vibration signature of the plurality of cables **201***a-d* and/or filars **202** which has been recorded when the plurality of cables **201***a-d* are in a first state, typically when the instrument **50** is first constructed. This signal may be a digitized version of a vibration signature obtained from the surgical robotic system **10**. In addition, a vibration signal threshold is stored in the surgical robotic system **10**, which may be used as a threshold for comparison with a vibration signal, as discussed below. For example, during manufacturing and/or installation of the instrument **50**, vibration sensors may be used to record baseline vibration signature measurements related to cables **201***a-d* and/or filars **202**, which will correspond to the vibration signal threshold. The vibration sensors may record a baseline vibration signature "SF" of filars **202**. This baseline vibration signature "SF" may correspond to the initial frequency of a vibration produced by filars **202** before use of instrument **50** in surgery. In another example, audio sensors may record a baseline vibration signature "SC" of the cables **201***a-d*. This baseline vibration signature "SC" of the cables **201***a-d* may correspond to an initial frequency of a vibration produced by cables **201***a-d* before use of instrument **50**.

[0078] At step **404**, the processor causes the vibration signature sensors **310**, **312** to record vibration signature measurements related to cables **201***a-d* and/or filars **202** during use of instrument **50** in surgery. For example, the vibration signature sensors **310**, **312** may record a vibration signature "SF" of filars **202**. This vibration signature "SF" corresponds to the frequency of a vibration produced by filars **202** during use of instrument **50**. In addition and/or alternatively, the processor may determine a specific frequency of the vibration signature "SF" of the filars **202** that will correspond to filar breakage. This specific frequency of vibration signal "SF" of the filars **202** will be set as a trigger event.

[0079] In embodiments, the baseline vibration signature "SF", "SC", for the filars **202** and cables **201***a-d*, respectively, may be automatically transmitted to or provided to the processor of the surgical robotic system **10** based on detection of a specific instrument **50**, such as monopolar curved shears (e.g., a vibration signal threshold). In addition and/or alternatively, the processor may determine a specific frequency of vibration signal "SC" of the cables **201***a-d* that will correspond to cable wear and/or breakage. This specific frequency of vibration signal "SC" of the cables **201***a-d* will be set as a trigger event. Once obtained, all baseline vibration signal measurements and/or specific frequencies will be converted to vibration signals for cable wear and failure prediction analysis.

[0080] In embodiments, the controller **21***a* also outputs a prompt on one of the GUIs of the screens **23**, **32**, **34**. The prompt requests input from the clinician related to the procedure, including the types of instrument(s) **50** used. For example, the clinician may select a procedure that requires the use of monopolar curved shears. In response to the selection, baseline vibration signature measurements related to cables **201***a-d* and/or filars **202** may be preprogrammed (e.g., a vibration signal threshold). For example, a baseline vibration signature "SF" of the filars **202** and/or a baseline vibration signature "SC" of the cables **201***a-d* may be set. In addition and/or alternatively, a specific frequency corresponding to breakage of filars **202** of cables **201***a-d* in monopolar curved shears may be set. Further, the preprogrammed baseline vibration signature measurements may also be manually input by the clinician.

[0081] Next, at step **406**, the recorded vibration signature measurements are used to predict, determine and/or detect cable wear and failure. For example, the vibration signature sensors **310**, **312** will continuously measure the live frequency of vibration signals "SC" produced by cables **201***a-d* and the vibration signatures "SF" produced by individual filars **202** during use of the instrument **50** (e.g., the monopolar curved shears). These frequencies of live vibration signatures "SC", "SF", for the filars **202** and cables **201***a-d*, respectively, will be compared, in step **408**, to the stored vibration signature threshold(s), i.e., the baseline vibration signature measurements received by the processor in step **402**. In doing so, cable wear and/or failure may be detected by comparing, in step **408**, the measured frequencies of live vibration signals "SC", "SF"', for the filars **202** and cables **201***a-d*, respectively, to the corresponding thresholds that are indicative of the filar breakage and/or cable failure. For example, the vibration signature sensors **310**, **312** may detect that a frequency of vibration signature "SF", for the filars **202** has surpassed a specific threshold in relation to the baseline frequency of vibration signature "SF" for the filars **202**, indicating that a filar breakage is likely to occur. In addition and/or alternatively, the vibration signature sensors **310**, **312** may detect a frequency of vibration signature "SF" for the filars **202** corresponding to the programmed trigger event, such as a high-pitched snapping noise indicating breakage of a filar **202**.

[0082] In another example, the vibration signature sensors **310**, **312** may detect that a frequency of vibration signature "SC" for the cables **201***a-d* has surpassed a specific vibration signal threshold in relation to the frequency of vibration signature "SC" for the cables **201***a-d*, indicating that a cable failure is likely to occur. In addition and/or alternatively, the vibration signature sensors **310**, **312** may detect a frequency of vibration signature "SC" for the cables **201***a-d* corresponding to the programmed trigger event or a wear sound. In aspects, the vibration signature sensors **310**, **312** may detect sounds of the cables **102***a-d*, pulleys **112***a*, **112***b*, **114***a*, **114***b*, and/or an axle system changing beyond their normal vibrational signature range. Sounds may include a galling sound, hum, etc. indicating future failure of cables **201***a-d*.

[0083] At step **410**, once cable wear and/or failure is detected, the controller **21***a* may transmit a signal to the surgical robotic system **10** to perform one or more actions. For example, the controller **21***a* may cause the surgical robotic system **10** to emit an audible alert indicating cable failure. In addition and/or alternatively, the controller **21***a* may disable further user input commands for controlling the instrument **50** and output a prompt on one of the GUIs of the screens **23**, **32**, **34**. The prompt may be an alert indicating that (1) a cable failure is predicted; or (2) a cable failure has occurred. In doing so, the user will stop attempting to control the instrument **50**, preventing further damage. The prompt may include an indication of the location of the cable **102***a-d* that is worn and/or has failed, thereby instructing an operator which cable **102***a-d* requires repair, may soon require repair, or a remaining useful life for the cables **102***a-d* if operated under normal load conditions. In aspects, a tension of cables **201***a-d* and/or a torque of the motors **152***a-d* may be reduced. This may occur automatically or through user intervention.

[0084] In another case, such as where a cable failure is predicted, the clinician may be presented with multiple options. First, the clinician may select a "continue" option to ignore the cable failure alert, which will cause controller **21***a* to reenable further user input commands for controlling the instrument **50** to continue the procedure. Second, the clinician may select a "reduce tension" or "reduce torque" option to adjust a tension of cables **201***a-d* or a torque produced by motors **152***a-d*. For example, the user may lower a tension of cables **201***a-d* or a torque of the motors **152***a-d* by 50%, releasing a specific amount of tension on filars **202** to extend the lifespan of the instrument **50**. Third, the clinician may select a "replace instrument" option to replace the instrument **50**.

[0085] In another case, such as where a cable failure is detected, the clinician may be required to cease all operations and replace instrument **50** in order to re-enable further user input commands for controlling the instrument **50**. Therefore, the clinician cannot continue operating until a new instrument **50** including new cables **201***a-d* is installed.

[0086] Following selection of the "replace instrument" option or the detection of cable failure, at step **408**, the system enters an instrument exchange process during which the instrument **50** is withdrawn from the access port **55**. During the instrument exchange process and prior to withdrawal of the instrument **50**, all of the motors **152***a-d* are driven so that all of the input couplers **172** are driven to remove tension in the cables **201***a-d*, or at least the input couplers **172** of the cables **201***a-d* that are not broken are driven in this manner. Thus, the IDU controller **41***d* determines which cable **201***a-d* is broken and corresponding motor **152***a-d* to only control the motor(s) coupled to unbroken cables.

[0087] The IDU **52** may verify that sufficient slack has been achieved based on torque or position. The couplers **172***a-d* may be driven until the measured torque is minimal or approximately "0" with the drive nuts **174***a-d* being driven distally to remove tension. Conversely, the couplers **172***a-d* may be driven to a desired position with the drive nuts **174***a-d* being driven distally to remove tension. Once the remaining cables **201***a-d* are slackened, the end effector **200** may be passively manipulated.

[0088] Once the instrument **50** has been replaced, the controller **21***a* will reenable further user input commands for controlling the instrument **50** and will output a prompt on one of the GUIs of the screens **23**, **32**, **34**. The output will include a health state of the new instrument **50** and options for additional user input, such as specific triggering events and baseline vibration signature settings. For example, at any time, a clinician may select a "health state" option on one of the GUIs of the screens **23**, **32**, **34** to induce a vibration in one or more cables **102***a-d* and/or individual filars **202**. The surgical robotic system **10** may analyze the vibration and output a detected level of tension on the cables **102***a-d* and/or filars **202**. Thus, the steps **402-410** may repeat iteratively throughout a procedure until the clinician selects a "complete" button on one of the GUIs of the screens **23**, **32**, **34** indicating that the procedure is complete.

[0089] It should be understood that various aspects disclosed herein may be combined in different combinations than the combinations specifically presented in the description and accompanying drawings.

[0090] While the present disclosure specifically shows and describes systems and methods for monitoring conditions of the use-life of cables of instruments, and predicting and/or monitoring for failure of such cables, it is understood and within the scope of the present disclosure that the systems and methods described herein may be applied towards collisions of instruments (i.e., unintentional collisions with other instruments or hard objects), towards the monitoring of the useful life and/or the predicting of failure of various other components of the instruments (e.g., drive screws, coupling nuts, and the like), and/or towards the monitoring of disconnection or separation of the cables from crimps or coupling features which connect the cables to respective drive rods or the like (e.g., J-hook crimps, etc.).

[0091] Further aspects and embodiments of the present disclosure are set out in the below numbered clauses: [0092] 1. A surgical robotic system comprising: [0093] an instrument including an end effector and a plurality of cables; [0094] at least one sensor configured to detect a vibration signature produced by the plurality of cables; [0095] a processor; and [0096] a memory coupled to the processor, the memory storing a vibration signal threshold corresponding to a vibration signature of the plurality of cables prior to use of the plurality of cables in the instrument in surgery and having instructions stored thereon which, when executed by the processor, cause the surgical robotic system to: [0097] receive a vibration signal corresponding to a vibration signature of the plurality of cables when the plurality of cables are in a first state; [0098] detect, by the at least one sensor, a vibration signature produced by the plurality of cables during use of the instrument in surgery; [0099] determine, based on the detected vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; [0100] determine, based on a comparison of the in-use vibration signal with the stored vibration signal threshold, an in-use state of the plurality of cables; and [0101] output an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold. [0102] 2. The surgical robotic system of clause 1, wherein the in-use state of the plurality of cables corresponds to a failure state of at least one cable of the plurality of cables. [0103] 3. The surgical robotic system of clause 2, wherein the instrument is configured to receive a user command for controlling the instrument, and wherein the instructions, when executed by the processor, further cause the surgical robotic system to: [0104] disable execution of the user command when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables. [0105] 4. The surgical robotic system of clause 1, further comprising a surgeon console including a display screen for displaying a graphical user interface, the graphical user interface configured to receive a user input for setting a trigger event. [0106] 5. The surgical robotic system of clause 4, wherein the instructions, when executed by the processor, further cause the surgical robotic system to: [0107] determine, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables. [0108] 6. The surgical robotic system of clause 5, wherein the third state corresponds to a failure state of a filar of at least one cable of the plurality of cables. [0109] 7. The surgical robotic system of clause 1, further comprising an instrument drive unit coupled to the instrument, the instrument drive unit including a plurality of motors and a controller, and wherein the instructions, when executed by the processor, further cause the surgical robotic system to: [0110] control the plurality of motors to reduce tension in the plurality of cables. [0111] 8. The surgical robotic system of clause 1, wherein the in-use vibration signature produced by the plurality of cables includes sounds of cable galling. [0112] 9. The surgical robotic system of clause 8, wherein the in-use and stored vibration signals correspond to a frequency of the vibration signatures of the plurality of cables prior to and during use of the surgical instrument. [0113] 10. The surgical robotic system of clause 1, wherein the alert includes at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear. [0114] 11. A processor-implemented method of cable failure detection, the method comprising: [0115] storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; [0116] detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; [0117] determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; [0118] determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, a second state of the plurality of cables; and [0119] outputting an alert indicating a condition of the plurality of cables corresponding to an in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold. [0120] 12. The processor-implemented method of clause 11, wherein the in-use state of the plurality of cables corresponds to a failure state of at least one cable of the plurality of cables. [0121] 13. The processor-implemented method of clause 12, further comprising: [0122] disabling entry of a user command for controlling the instrument when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables. [0123] 14. The processor-implemented method of clause 11, further comprising: [0124] displaying a graphical user interface on a display screen of a surgeon console, the graphical user interface configured to receive a user input for setting a trigger event. [0125] 15. The processor-implemented method of clause 14, further comprising: [0126] determining, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables. [0127] 16. The processor-implemented method of clause 15, wherein the third state corresponds to a failure state of a filar of at least one cable of the plurality of cables. [0128] 17. The processor-implemented method of clause 11, further comprising: [0129] controlling, by an instrument drive unit coupled to the instrument, the plurality of cables to reduce tension in the plurality of cables. [0130] 18. The processor-implemented method of clause 11, wherein the stored and in-use vibration signals correspond to a frequency of the vibration signatures of the plurality of cables prior to and during use of the surgical instrument. [0131] 19. The processor-implemented method of clause 11, wherein the alert includes at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear. [0132] 20. One or more non-transitory processor-readable media storing instructions which, when executed by one or more processors, cause performance of: [0133] storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; [0134] detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; [0135] determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; [0136] determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, an in-use state of the plurality of cables; and [0137] outputting an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

[0138] It should also be understood that, depending on the example, certain acts or events of any of the processes or methods described herein may be performed in a different sequence, may be added, merged, or left out altogether (e.g., all described acts or events may not be necessary to carry out the techniques). In addition, while certain aspects of this disclosure are described as being performed by a single module or unit for purposes of clarity, it should be understood that the techniques of this disclosure may be performed by a combination of units or modules associated with, for example, the above-described servers and computing devices.
[0139] While the description above refers to particular aspects of the present disclosure, it will be understood that many modifications may be made without departing from the spirit thereof. Additional steps and changes to the order of the algorithms can be made while still performing the key teachings of the present disclosure. Thus, the accompanying claims are intended to cover such modifications as would fall within the true scope and spirit of the present disclosure. The presently disclosed aspects are, therefore, to be considered in all respects as illustrative and not restrictive, the scope of the disclosure being indicated by the appended claims rather than the foregoing description. Unless the context indicates otherwise, any aspect disclosed herein may be combined with any other aspect or aspects disclosed herein. All changes that come within the meaning of, and range of, equivalency of the claims are intended to be embraced therein.

Claims

1. A surgical robotic system comprising: an instrument including an end effector and a plurality of cables; at least one sensor configured to detect a vibration signature produced by the plurality of cables; a processor; and a memory coupled to the processor, the memory storing a vibration signal threshold corresponding to a vibration signature of the plurality of cables prior to use of the plurality of cables in the instrument in surgery and having instructions stored thereon which, when executed by the processor, cause the surgical robotic system to: receive a vibration signal corresponding to a vibration signature of the plurality of cables when the plurality of cables are in a first state; detect, by the at least one sensor, a vibration signature produced by the plurality of cables during use of the instrument in surgery; determine, based on the detected vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; determine, based on a comparison of the in-use vibration signal with the stored vibration signal threshold, an in-use state of the plurality of cables; and output an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.
2. The surgical robotic system of claim 1, wherein the in-use state of the plurality of cables corresponds to a failure state of at least one cable of the plurality of cables.
3. The surgical robotic system of claim 2, wherein the instrument is configured to receive a user command for controlling the instrument, and wherein the instructions, when executed by the processor, further cause the surgical robotic system to: disable execution of the user command when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables.
4. The surgical robotic system of claim 1, further comprising a surgeon console including a display screen for displaying a graphical user interface, the graphical user interface configured to receive a user input for setting a trigger event.
5. The surgical robotic system of claim 4, wherein the instructions, when executed by the processor, further cause the surgical robotic system to: determine, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables.
6. The surgical robotic system of claim 5, wherein the third state corresponds to a failure state of a filar of at least one cable of the plurality of cables.
7. The surgical robotic system of claim 1, further comprising an instrument drive unit coupled to

the instrument, the instrument drive unit including a plurality of motors and a controller, and wherein the instructions, when executed by the processor, further cause the surgical robotic system to: control the plurality of motors to reduce tension in the plurality of cables.

8. The surgical robotic system of claim 1, wherein the in-use vibration signature produced by the plurality of cables includes sounds of cable galling.

9. The surgical robotic system of claim 8, wherein the in-use and stored vibration signals correspond to a frequency of the vibration signatures of the plurality of cables prior to and during use of the surgical instrument.

10. The surgical robotic system of claim 1, wherein the alert includes at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear.

11. A processor-implemented method of cable failure detection, the method comprising: storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, a second state of the plurality of cables; and outputting an alert indicating a condition of the plurality of cables corresponding to an in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.

12. The processor-implemented method of claim 11, wherein the in-use state of the plurality of cables corresponds to a failure state of at least one cable of the plurality of cables.

13. The processor-implemented method of claim 12, further comprising: disabling entry of a user command for controlling the instrument when the in-use state of the plurality of cables corresponds to the failure state of at least one cable of the plurality of cables.

14. The processor-implemented method of claim 11, further comprising: displaying a graphical user interface on a display screen of a surgeon console, the graphical user interface configured to receive a user input for setting a trigger event.

15. The processor-implemented method of claim 14, further comprising: determining, based on the trigger event and the in-use vibration signal, a third state of the plurality of cables.

16. The processor-implemented method of claim 15, wherein the third state corresponds to a failure state of a filar of at least one cable of the plurality of cables.

17. The processor-implemented method of claim 11, further comprising: controlling, by an instrument drive unit coupled to the instrument, the plurality of cables to reduce tension in the plurality of cables.

18. The processor-implemented method of claim 11, wherein the stored and in-use vibration signals correspond to a frequency of the vibration signatures of the plurality of cables prior to and during use of the surgical instrument.

19. The processor-implemented method of claim 11, wherein the alert includes at least one of a visual or an audio indication that at least one cable of the plurality of cables has reached a predetermined level of wear.

20. One or more non-transitory processor-readable media storing instructions which, when executed by one or more processors, cause performance of: storing a vibration signal threshold corresponding to a vibration signature of a plurality of cables of a robotic surgical instrument when the plurality of cables are in a first state; detecting, by at least one sensor, an in-use vibration signature produced by the plurality of cables during use of the instrument in surgery, wherein the at least one sensor is configured to detect a vibration signature produced by the plurality of cables; determining, based on the in-use vibration signature, an in-use vibration signal corresponding to the plurality of cables during use of the instrument in surgery; determining, based on a comparison of the stored vibration signal threshold and the in-use vibration signal, an in-use state of the plurality of cables; and outputting an alert indicating a condition of the plurality of cables corresponding to the in-use state of the plurality of cables when the in-use vibration signal exceeds the vibration signal threshold.