



(51) International Patent Classification:

B25J 19/06 (2006.01) F16D 3/50 (2006.01)  
B25J 17/02 (2006.01)

(21) International Application Number:

PCT/IB2018/056470

(22) International Filing Date:

26 August 2018 (26.08.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/551,965 30 August 2017 (30.08.2017) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,

(54) Title: BINARY PASSIVE VARIABLE STIFFNESS JOINT

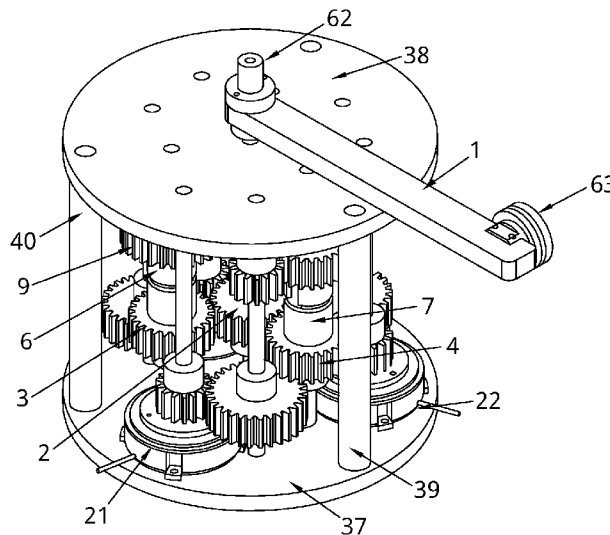


FIG. 1

(57) Abstract: A variable stiffness joint and method to alter the stiffness of the joint with multiple stiffness levels is described wherein a plurality of stiffness bits (m) are used for enabling 2<sup>m</sup> stiffness level variations for the joint. Each stiffness bit comprises an elastic element in mechanical connection with a clutch (21, 22, 23). The joint revolves with zero stiffness level when all the clutches (21, 22, 23) are disengaged whereas a clutch (21, 22, 23) involves one of the elastic elements which alter the stiffness of the joint. Engaging other clutches (21, 22, 23) involve more elastic elements for altering the joint stiffness and the resultant joint stiffness is determined by adding the stiffness values of all the involved springs (6, 7, 8).



SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,  
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

**(84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

**Published:**

- *with international search report (Art. 21(3))*
- *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

## BINARY PASSIVE VARIABLE STIFFNESS JOINT

### FIELD OF THE INVENTION

[0001] The present invention relates to stiffness joints and more specifically, the present invention relates to a variable stiffness joint and method for altering the stiffness of a robotic joint. A stiffness of the joint is varied according to a number of stiffness levels in order to enhance safety interactions.

### BACKGROUND OF THE INVENTION

[0002] There has been a rapid development in the fields of wearable robotics and compliant actuators during the past few decades. This has resulted in robots operating closely with humans, physically interacting or even being worn by humans which has further led to the rise of several safety aspects and design requirements. Safety should be an essential feature in robots especially in the case of unexpected interactions or sensor failures. Other than the safety aspect, applications such as rehabilitation robots, exoskeletons and haptics have proved that the interaction between the robot and the operator must show adaptability and force accuracy.

[0003] Safety and actuation performance initiated the development of variable impedance actuators (VIA), where the actuator mechanical properties like inertia, damping or stiffness affect the system's equilibrium position. This changes the interaction forces to adapt to different situations between robots and the environment or users aiming to provide safer operations and energy efficiency. Then, based on how the impedance (stiffness and damping) is achieved, active and passive variable impedance actuator (VIA) concepts were proposed. In the active-by-control impedance, the behavior of a highly-reduced stiff actuator is altered via software. This concept allowed to adapt both stiffness and damping in a wide range for several speeds. The disadvantages of this system include high energy consumption, the need of accurate and expensive force or torque sensors, complexity of the control system, incapability of storing energy and absorbing shocks. In order to overcome these drawbacks, passive compliant elements

were added to the actuator, resulting in the Serial Elastic Actuator (SEA). Drawbacks involved with the SEA included non-optimal performance energy efficiency. An optimal performance required careful tuning of the joint stiffness values. This motivated lots of study and new designs of variable stiffness mechanisms with passive compliance.

**[0004]** Another method used to vary the joint stiffness included changing the spring preload, where stiffness altering was achieved by changing the energy stored in the spring. An evolution of this concept is the antagonistic variable stiffness actuators, where the joint stiffness is varied through the combination of two antagonistic SEAs controlled by two separate motors. Other techniques were applied and several solutions were presented such as using a non-linear connector between the output link and the spring element to adjust the preload of the linear spring, applying a lever mechanism between the output link and the elastic element, or by altering the link length between the pivot and the elastic element or the output link.

**[0005]** Although different variable stiffness joints have been developed they have not been successfully applied to robotic arms due to complex stiffness tuning mechanisms, bulky size and non – ideal stiffness curves.

**[0006]** Variable stiffness actuators have been used in many applications, such as rehabilitation exoskeletons, surgical robotics and multiple haptics applications. Although applying compliant mechanisms to haptic devices has shown several advantages in reducing wear and weight, the disadvantages includes an increased control complexity. The resultant force obtained by altering a compliant element can be the key for force feedback in haptic devices.

**[0007]** Generally, all the previous designs involve a continuous stiffness tuning curve from low to high or zero to infinity with a motor based control. Accordingly, there exists a need to provide a mechanism to alter the stiffness of a revolute joint for a wide range of stiffness.

**SUMMARY OF THE INVENTION**

[0008] Therefore it is an object of the present invention to provide a system and method for altering the stiffness levels of a robotic joint, which overcomes atleast a part of the above disadvantages.

[0009] The present invention involves a variable stiffness joint comprising a plurality of stiffness bits (m) for enabling  $2^m$  stiffness level variations for the variable stiffness joint, wherein each stiffness bit comprises an elastic element in mechanical connection with a clutch.

[0010] In an embodiment, the elastic elements are torsional springs.

[0011] In another embodiment, the clutches are electromagnetic friction clutches.

[0012] In another embodiment, the torsional springs are connected to the clutches, which are grounded.

[0013] In another embodiment, the torsional springs are Hook's type torsional springs or Linear torsional springs.

[0014] In another embodiment, each of the torsional springs is encapsulated in a spring holder.

[0015] In an embodiment of the present invention, the variable stiffness joint comprises a lower base and an upper base, wherein the lower base and the upper base are connected using frame rods; a main shaft between the lower and upper base; an output link at the upper base connected to the main shaft for receiving a torque from a user and a gear train comprising a main driving gear connected to the main shaft.

[0016] In another embodiment, for each stiffness bit, a planetary gear is in mechanical connection with the main driving gear for engaging the elastic elements using the torque for activating the clutch.

[0017] In another embodiment of the present invention, the elastic elements are torsional springs.

[0018] In another embodiment of the present invention, the clutches are electromagnetic friction clutches.

[0019] In another embodiment of the present invention, the torsional springs are Hook's type torsional springs or Linear torsional springs, connected to the clutches which are grounded.

[0020] In another embodiment of the present invention, each of the torsional springs is encapsulated in a spring holder.

**[0021]** In another embodiment of the present invention, each one of the spring holders comprise an upper container and a lower container and each one of the upper containers are mounted on shafts which hold first and second torque reduction stages.

**[0022]** In another embodiment of the present invention, the first torque reduction stage connects the upper container of the spring holder through a (1:5) torque reduction ratio, and the second torque reduction stage with a (1:5) torque reduction ratio, transmits torque to the clutches resulting in a (1:10) torque reduction.

**[0023]** Considering another aspect of the present invention, a method for altering a stiffness level of a robotic or revolute joint is proposed, wherein the method comprises providing an output link for enabling a user to create a torque; using the torque for rotating a main shaft with a main driving gear; and transmitting the torque from the main shaft into a plurality of elastic elements using planetary gears.

**[0024]** In an embodiment, the torque from the plurality of elastic elements is transmitted to activate grounded clutches for altering the stiffness level of the joint, wherein the stiffness is at zero level if the clutches are disengaged or inactive.

**[0025]** In another embodiment of the present invention, the torque is transmitted into the plurality of elastic elements through planetary gears associated with a sun gear, wherein lower ends of the plurality of elastic elements are connected to the planetary gears.

**[0026]** In another embodiment of the present invention, the torque is transmitted from the plurality of elastic elements to grounded clutches through torque reduction stages.

**[0027]** In another embodiment of the present invention, a first torque reduction stage connects to upper ends of the plurality of elastic elements and the torque is transmitted from the plurality of elastic elements to grounded clutches through a second torque reduction stage.

**[0028]** In another embodiment of the present invention, a number of series - parallel elastic elements ( $m$ ) are involved to achieve  $2^m$  levels of stiffness.

**[0029]** In another embodiment of the present invention, an elastic element in mechanical connection with a clutch forms a stiffness bit and each stiffness bit contributes torque on the output link if the clutch associated with the respective stiffness bit is active.

**[0030]** In a preferable embodiment of the present invention, a variable stiffness joint with variable stiffness levels is disclosed, comprising an output link for enabling a user to create a torque; stiffness bits, wherein each stiffness bit comprises an elastic element in mechanical connection with a clutch; and a mechanical mechanism to transfer the torque to the stiffness bits, wherein a selection on the levels of stiffness are made based on the torque.

**[0031]** In another embodiment of the present invention, m number of stiffness bits is used to achieve  $2^m$  levels of stiffness.

**[0032]** In another embodiment, the elastic element is a torsional spring.

**[0033]** In another embodiment, the clutch is an electromagnetic friction clutch.

**[0034]** In another embodiment, the torsional spring is connected to the clutch which is grounded.

**[0035]** In another embodiment, the torsional spring is a Hook's type torsional spring or a Linear torsional spring.

**[0036]** In another embodiment, the mechanical mechanism includes two torque reduction stages.

**[0037]** In another embodiment, a first torque reduction stage connects to an upper end of the elastic element and a second torque reduction stage transmits the torque to the clutch.

**[0038]** In another embodiment of the present invention, variable joint stiffness is achieved if the clutch to which the torque is transferred, is engaged or active.

**[0039]** In another embodiment of the present invention, zero joint stiffness is achieved if the clutch to which the torque is transferred is disengaged or inactive.

**[0040]** In another embodiment of the present invention, a transparent mode involves disengaging the clutches and enabling free rotation of the joint.

**[0041]** In another embodiment of the present invention, a variable stiffness mode is activated when the elastic elements are selectively grounded via the clutches.

**BRIEF DESCRIPTION OF THE DRAWINGS**

**[0042]** The subject matter that is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other aspects, features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

**[0043]** FIG. 1 shows an oblique view of the passive binary controlled variable stiffness joint (BpVSJ) in accordance with an embodiment of the present invention.

**[0044]** FIG. 2 illustrates gear trains and actuators (clutches) of the passive binary controlled variable stiffness joint (BpVSJ) in accordance with an embodiment of the present invention.

**[0045]** FIG. 3 shows an exploded assembly of the spring compartment and torsional spring used in the passive binary controlled variable stiffness joint (BpVSJ) in accordance with an embodiment of the present invention.

**[0046]** FIG. 4 shows an exploded assembly of the lower part of a clutch shaft used in the passive binary controlled variable stiffness joint (BpVSJ) in accordance with an embodiment of the present invention.

**[0047]** FIG. 5 describes torque transmission path through one of the bit stages involved in the passive binary controlled variable stiffness joint (BpVSJ) in accordance with an embodiment of the present invention.

**[0048]** FIG. 6 illustrates the stiffness model associated with an embodiment of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

[0049] The invention introduces a system and mechanism to alter the stiffness of a robotic revolute joint according to a number of stiffness levels, by proposing the design of a passive binary controlled variable stiffness joint (BpVJS).

[0050] In a preferred embodiment of the invention, as shown in FIG. 1 – 6, the structure of the variable stiffness joint comprises of two bases **37** and **38** connected using three frame rods **39**, **40**, and **41**. An output link **1** is mounted on a shaft **24** which is mounted on bases **37** and **38**. Shaft **24** holds also a main driving gear **2** which connects with three planetary gears **3**, **4**, and **5** in a (1:1) ratio. Each of these three gears is mounted on shafts **25**, **26** and **27** respectively. These shafts are held to the lower base **37**. Each of these shafts holds the lower container - **6A**, **7A** and **8A** respectively - of three elastic elements **6B**, **7B** and **8B** respectively. The elastic elements are torsional springs. Each of these torsional springs is encapsulated in upper containers **6C**, **7C** and **8C** respectively, which are mounted on shafts **28**, **29** and **30** respectively. These shafts are mounted on base **38**.

[0051] In an embodiment, the three torsional springs used as elastic elements for the variable stiffness joint structure, are Hook's type torsional springs.

[0052] In an embodiment, the three torsional springs used as elastic elements for the variable stiffness joint structure, are linear torsional springs.

[0053] Each of the three torsional springs **6B**, **7B** and **8B** are connected to three grounded clutches **21**, **22** and **23** respectively. Each set of spring – clutch connection represents a Stiffness Bit in a binary representation of stiffness levels.

[0054] In an embodiment of the invention, the three grounded clutches **21**, **22** and **23** used in combination with the three torsional springs **6B**, **7B** and **8B** are electromagnetic friction clutches.

[0055] The structure of the variable stiffness joint further includes two stages of torque reduction gear trains. The shafts **28**, **29** and **30** hold a first torque reduction stage **100**. The first torque reduction stage **100** involves two sets of gears. Shafts **28**, **29** and **30** hold a first set of gears **9**, **10** and **11** for the first torque reduction gear train. Gears **9**, **10** and **11** are connected to a second set of gears **12**, **13** and **14**

respectively to complete the first torque reduction stage **100** of the two stage torque reduction gear train. Gears **12**, **13** and **14** are mounted on shafts **31**, **32** and **33** respectively and each of these shafts is mounted on bases **37** and **38**.

**[0056]** Each of the shafts **31**, **32** and **33** hold a first set of gears **15**, **16** and **17** of the second torque reduction stage **200** of the two stage torque reduction gear train. Gears **15**, **16** and **17** are connected to a second set of gears **18**, **19** and **20** respectively to complete the second torque reduction stage **200** of the two stage torque reduction gear train. Gears **18**, **19** and **20** are mounted on shafts **34**, **35** and **36** respectively and each of these shafts is mounted on bases **37** and **38**.

**[0057]** Additionally, the shafts **31**, **32** and **33** hold dynamic parts **21A**, **22A**, and **23A** respectively, of the three grounded clutches **21**, **22**, and **23**, as shown in FIG. 4. Stationary parts of the grounded clutches **21B**, **22B** and **23B** are mounted on base **37**.

**[0058]** The first torque reduction gear train **100** connects the upper containers **6C**, **7C** and **8C** of the torsional spring encapsulations through a (1:5) torque reduction ratio. The second stage of torque reduction **200** further includes a (1:5) torque reduction ratio. This second stage of torque reduction **200** transmits torque to the grounded clutches **21**, **22** and **23**, resulting in a total ratio of (1:10) torque reduction.

**[0059]** In an embodiment of the present invention, the mechanical system designed to implement a passive binary – controlled variable stiffness joint (BpVSI) includes a fixed lower base **37**. The lower base **37** consists of ten bearings that hold ten shafts. Three of these shafts are connected to the three electromagnetic friction clutches **21**, **22** and **23**, which are grounded. Four shafts are used for a sun-planetary gear train, wherein the planetary gears **3**, **4** and **5**, hold the three torsional springs **6**, **7** and **8**. The last three shafts are used for the two torque reduction stages since the selected grounded clutches may not be able to hold the designated torque.

**[0060]** In a further embodiment of the invention, a sensory system may be enabled using a mount **62** for an encoder, and a mount **63** for a force/torque sensor.

**[0061]** In a preferred embodiment of the present invention, a method or mechanism for altering the stiffness levels of a revolute joint involves an output link or arm **1**, which is connected on shaft **24**. The

main driving gear (sun gear) **2** is held by shaft **24** and connects with three planetary gears **3**, **4** and **5** in a (1:1) ratio. A torque is transmitted from a user's hand through the output link **1**. The output link **1** is connected to the sun gear **2** which transmits the torque to the torsional springs **6**, **7** and **8** holders through the planetary gears **3**, **4** and **5**. The other ends **6A**, **7A** and **8A** of each spring is connected to the planetary gears **3**, **4** and **5** which contribute part of the resultant torque on the sun gear **2**. The first torque reduction stage **100** involving gears **9**, **10**, **11**, **12**, **13** and **14**, connects the upper containers of the torsional spring encapsulations **6C**, **7C** and **8C** through a (1:5) torque reduction ratio. The second stage of torque reduction **200** including a (1:5) torque reduction ratio involving gears **15**, **16**, **17**, **18**, **19** and **20**, transmits this torque to the three grounded clutches **21**, **22** and **23**, resulting in a total (1:10) torque reduction.

**[0062]** In a further embodiment, the proposed variable stiffness mechanism functions in two modes. The first mode involves a scenario where the stiffness is to be minimized which allows a user to deflect the output arm **1**, with an unlimited range of deflection. This mode is the transparent mode. The output link possesses zero stiffness with infinite angle deflection unless a change in the joint stiffness is required. The three springs **6**, **7** and **8** may rotate freely with the output link using lower shafts **25**, **26**, and **27** and upper shafts **28**, **29** and **30**. As shown in FIG. 5, the torque or motion during the transparent mode travels through a path from output link **1** through the main gear **2**, to the planetary gears **3**, **4**, and **5**. The torque then passes through the torsional spring compartments **6**, **7** and **8**, to the first torque reduction gear train, the second torque reduction gear train and then to the grounded bearings.

**[0063]** The other mode is required when a significant change in stiffness is needed. This second mode, the variable stiffness mode, is activated when a significant value of stiffness is required. This desired value may be either one or the sum of the stiffness values of the two or three elastic elements or springs. The values of the torsional spring's constants follow a binary sequence as shown below:

$$k_n = 2^{n-1} (k_0), n \in \{1, 2, 3\} \quad (1)$$

where  $k_0$  is the base stiffness value (which may be selected by a designer). The value of  $n$  represents the number of spring stages. The values of  $(k_0, n)$  provide design flexibility with respect to compactness, desired levels of stiffness, and range of stiffness.

[0064] The springs **6**, **7** and **8** can be selectively grounded through clutches **21**, **22** and **23** respectively. When a clutch is active or engaged, torque flows from output link **1** through the main gear **2**, to the planetary gears **3**, **4**, and **5**. The torque then passes through the torsional spring compartments **6**, **7** and **8**, to the first torque reduction gear train, the second torque reduction gear train and then to the grounded bearings.

The equation for determining the joint stiffness is as follows:

$$K_{\theta} = \sum_{i=1}^m b_i 2^{i-1} (k_0)$$

$$b_i = \{0, \text{ if clutch (i) is inactive; } 1, \text{ if clutch (i) is active} \quad (1)$$

where  $m$  is the number of spring - clutch stages. The levels of stiffness may be represented in binary form and are shown in the form of a table. The table displays seven levels of stiffness obtained from 3 Stiffness Bits for  $k_0 = 0.5 \text{ Nm/degree}$ .

$b_3$	$b_2$	$b_1$	Stiffness level	Stiffness (N.m/degree)	Torque (N.m) @ 10 degrees
0	0	0	0	0	0
0	0	1	$K_0$	0.5	5
0	1	0	$2 K_0$	1.0	10
0	1	1	$3 K_0$	1.5	15
1	0	0	$4 K_0$	2.0	20
1	0	1	$5 K_0$	2.5	25
1	1	0	$6 K_0$	3.0	30
1	1	1	$7 K_0$	3.5	35

[0065] Each of the three torsional springs **6**, **7** and **8** are connected to three grounded clutches **21**, **22** and **23** respectively. Each set of spring – clutch connection represents a Stiffness Bit in a binary representation of stiffness levels. In accordance with the proposed variable stiffness mechanism, if one of the grounded clutches is active or engaged, the output arm **1** deflects the corresponding spring which leads to the user feeling an altered stiffness. This mode is called a variable stiffness mode. A Stiffness Bit contributes torque on the output arm **1**, if the bit’s clutch is active.

[0066] However, if the grounded clutches are inactive or disengaged, the gears will rotate freely and the user will feel no stiffness. This will facilitate the capability of unlimited motion of the output arm **1**, at zero stiffness level where all clutches are inactive, resulting in a transparent mode.

**[0067]** In an embodiment, the levels of stiffness may be represented in binary form. An active Stiffness Bit is represented by ‘1’ and an inactive Stiffness Bit is represented by ‘0’. This feature of the present invention provides a capability of altering the stiffness levels instantaneously at any joint deflection position, with low level switching time of 4ms.

**[0068]** In another embodiment of the invention, the three torsional springs **6**, **7** and **8**, have three different stiffness values ( $K_0$ ,  $2K_0$ ,  $4K_0$ ) respectively, and are connected to the three grounded-clutches **21**, **22** and **23**. Hence, scalability of the variable stiffness mechanism may be achieved either by changing the value of the seed stiffness value  $K_0$ , or by adding extra stiffness bits.

**[0069]** Considering another embodiment, the passive binary controlled variable stiffness joint (BpVJSJ) may be designed as a passive haptic interface capable to simulate different level stiffness in virtual reality and remote environment applications. Assuming that the desired maximum output torque is 35 N.m @ 10 degrees and there are three Stiffness Bits to simulate seven levels of stiffness, the springs should have stiffness levels of 0.5 N.m/degree, 1 N.m/degree, and 2 N.m/degree for the first, second and third Stiffness Bits, respectively.

**[0070]** Altering the stiffness of the variable stiffness joint, BpVJSJ is achieved by changing the number of parallel elastic elements involved in the system. The involvement of an elastic element is achieved through grounding one end of the torsional spring (elastic element) via an electromagnetic clutch. The stiffness model may be derived from a kinematics model of the joint as shown in FIG. 6.

**[0071]** The stiffness model may be derived starting with the resultant torque represented as  $\tau^{\Sigma}$ . The equation is as follows:

$$\tau^{\Sigma} = F \times L = -(\tau^0 + \tau^1 + \tau^2) \quad (2)$$

wherein  $\tau_0$ ,  $\tau_1$  and  $\tau_2$  are the torque values corresponding to the stiffness bits 0, 1 and 2 respectively.

**[0072]** F is a pushing force exerted by a user’s hand which creates a torque through the arm length, L. The resultant torque  $\tau^{\Sigma}$  will rotate the main shaft **24** with the sun gear **2**. In the case where all the Stiffness Bits are inactive, the torque is transmitted freely through the planetary gears **3**, **4** and **5**, into the torsional springs **6**, **7** and **8** which will rotate freely. However in the case of any active Stiffness Bits, motion of a shaft connecting the end of the involved torsional spring to the clutch will be blocked.

Hence when torque is exerted on the main shaft, the torsional springs that are involved will produce a counter torque that is felt as resistance force on a user's hand.

**[0073]** Each of these torques can be represented using the following equation:

$$\tau^n = \beta_n (2^n (K_0) (\theta - \phi_n - \varphi)), n \in \{0, 1, 2\} \quad (3)$$

$$\phi_n = \theta (t_{ON, n}), n \in \{0, 1, 2\} \quad (4)$$

$$\beta_n = \{0, \text{if clutch (n) is inactive}; 1, \text{if clutch (n) is active}\} \quad (5)$$

where  $(\beta, \theta, \phi, \varphi)$  is the binary function, the joint angular position, the joint angular position at the activation time  $(t_{ON})$ , and the backlash angle, respectively. The joint stiffness is the rate of change of torque with respect to the angular deflection. Considering FIG. 6, C0, C1 and C2 denote the clutches associated with the first, second and third springs denoted by 20K0, 21K0 and 22K0 respectively.

**[0074]** Considering the previous equations, the stiffness equation be driven as follows:

$$\tau^\Sigma = \sum_0^n \beta_n (2^n (K_0) (\theta - \phi_n - \varphi)), n \in \{0, 1, 2\} \quad (6)$$

$$K_\Sigma = \delta \tau^\Sigma / \delta \theta = \sum_0^n \beta_n (2^n (K_0)), n \in \{0, 1, 2\} \quad (7)$$

With consideration to equation number (7), the joint stiffness is dependent on the number of Stiffness Bits (n) and the seed stiffness value  $(K_0)$ . This feature allows for scalability of the model with respect to both the stiffness range and the realized number of stiffness values.

**[0075]** In another embodiment, the actuators of industrial or domestic robots may be replaced with the variable stiffness joint mechanism proposed by the present invention, in order to enhance safer robotic interactions.

**[0076]** Many changes, modifications, variations and other uses and applications of the subject invention will become apparent to those skilled in the art after considering this specification and the accompanying drawings which disclose the preferred embodiments thereof. All such changes, modifications, variations and other uses and applications which do not depart from the spirit and scope of the invention are deemed to be covered by the invention, which is to be limited only by the claims which follow.

**CLAIMS**

1. A variable stiffness joint comprising a plurality of stiffness bits (m) for enabling  $2^m$  stiffness level variations for the variable stiffness joint, wherein each stiffness bit comprises an elastic element in mechanical connection with a clutch.
2. A variable stiffness joint according to claim 1, wherein the elastic elements are torsional springs.
3. A variable stiffness joint according to claim 1, wherein the clutches are electromagnetic friction clutches.
4. A variable stiffness joint according to claim 2, wherein the torsional springs are connected to the clutches, which are grounded.
5. A variable stiffness joint according to claim 2, wherein the torsional springs are Hook's type torsional springs or Linear torsional springs.
6. A variable stiffness joint according to claim 2, wherein each of the torsional springs is encapsulated in a spring holder.
7. A variable stiffness joint according to claim 1 comprising:
  - a lower base and an upper base, wherein the lower base and the upper base are connected using frame rods;
  - a main shaft between the lower and upper base;
  - an output link at the upper base connected to the main shaft for receiving a torque from a user;
  - a gear train comprising a main driving gear connected to the main shaft; and
  - for each stiffness bit,

a planetary gear in mechanical connection with the main driving gear for engaging the elastic elements using the torque for activating the clutch.

8. A variable stiffness joint according to claim 7, wherein the elastic elements are torsional springs.
9. A variable stiffness joint according to claim 7, wherein the clutches are electromagnetic friction clutches.
10. A variable stiffness joint according to claim 8, wherein the torsional springs are Hook's type torsional springs or Linear torsional springs, connected to the clutches which are grounded.
11. A variable stiffness joint according to claim 8, wherein each of the torsional springs is encapsulated in a spring holder.
12. A variable stiffness joint according to claim 11, wherein each one of the spring holders comprise an upper container and a lower container and each one of the upper containers are mounted on shafts which hold first and second torque reduction stages.
13. A variable stiffness joint according to claim 12 wherein,
  - the first torque reduction stage connects the upper container of the spring holder through a (1:5) torque reduction ratio, and
  - the second torque reduction stage with a (1:5) torque reduction ratio, transmits torque to the clutches resulting in a (1:10) torque reduction.
14. A method for altering a stiffness level of a robotic or revolutive joint, the method comprising:
  - providing an output link for enabling a user to create a torque;
  - using the torque for rotating a main shaft with a main driving gear;

transmitting the torque from the main shaft into a plurality of elastic elements using planetary gears;

transmitting the torque from the plurality of elastic elements to activate grounded clutches for altering the stiffness level of the joint,

wherein the stiffness is at zero level if the clutches are disengaged or inactive.

**15.** The method according to claim 14, wherein the torque is transmitted into the plurality of elastic elements through planetary gears associated with a sun gear, wherein lower ends of the plurality of elastic elements are connected to the planetary gears.

**16.** The method according to claim 14, wherein the torque is transmitted from the plurality of elastic elements to grounded clutches through torque reduction stages.

**17.** The method according to claim 16, wherein a first torque reduction stage connects to upper ends of the plurality of elastic elements and the torque is transmitted from the plurality of elastic elements to grounded clutches through a second torque reduction stage.

**18.** The method according to claim 14, wherein the elastic elements are torsional springs.

**19.** The method according to claim 14, wherein the clutches are electromagnetic friction clutches.

**20.** The method according to claim 18, wherein the torsional springs are Hook's type torsional springs or Linear torsional springs, and are connected to the clutches.

**21.** The method according to claim 14, wherein a number of series - parallel elastic elements ( $m$ ) are involved to achieve  $2^m$  levels of stiffness.

- 22.** The method according to claim 14, wherein an elastic element in mechanical connection with a clutch forms a stiffness bit and each stiffness bit contributes torque on the output link if the clutch associated with the respective stiffness bit is active.
- 23.** A variable stiffness joint with variable stiffness levels, comprising:
- an output link for enabling a user to create a torque;
  - stiffness bits, wherein each stiffness bit comprises an elastic element in mechanical connection with a clutch;
  - a mechanical mechanism to transfer the torque to the stiffness bits, wherein a selection on the levels of stiffness are made based on the torque.
- 24.** The variable stiffness joint according to claim 23, wherein m number of stiffness bits is used to achieve  $2^m$  levels of stiffness.
- 25.** The variable stiffness joint according to claim 23, wherein the elastic element is a torsional spring.
- 26.** The variable stiffness joint according to claim 23, wherein the clutch is an electromagnetic friction clutch.
- 27.** The variable stiffness joint according to claim 25, wherein the torsional spring is connected to the clutch which is grounded.
- 28.** The variable stiffness joint according to claim 25, wherein the torsional spring is a Hook's type torsional spring or a Linear torsional spring.
- 29.** The variable stiffness joint according to claim 23, wherein the mechanical mechanism includes two torque reduction stages.

- 30.** The variable stiffness joint according to claim 29, wherein a first torque reduction stage connects to an upper end of the elastic element and a second torque reduction stage transmits the torque to the clutch.
- 31.** The variable stiffness joint according to claim 23, wherein variable joint stiffness is achieved if the clutch to which the torque is transferred, is engaged or active.
- 32.** The variable stiffness joint according to claim 23, wherein zero joint stiffness is achieved if the clutch to which the torque is transferred is disengaged or inactive.
- 33.** The variable stiffness joint according to claim 23, wherein a transparent mode involves disengaging the clutches and enabling free rotation of the joint.
- 34.** The variable stiffness joint according to claim 23, wherein a variable stiffness mode is activated when the elastic elements are selectively grounded via the clutches.

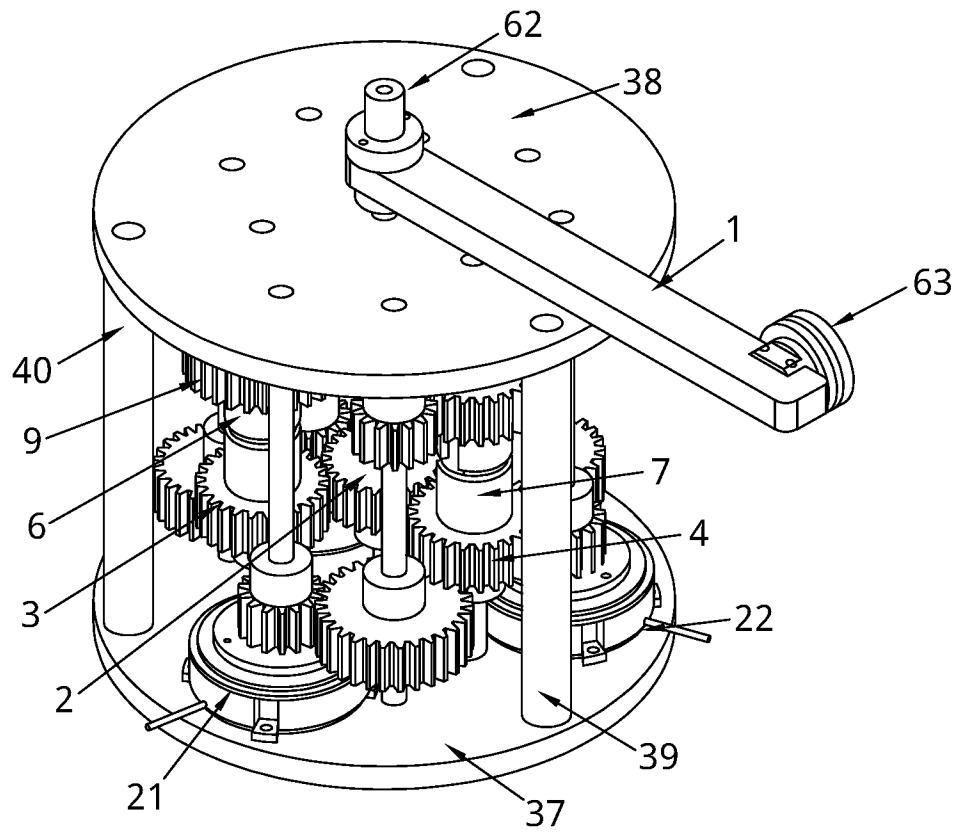


FIG. 1

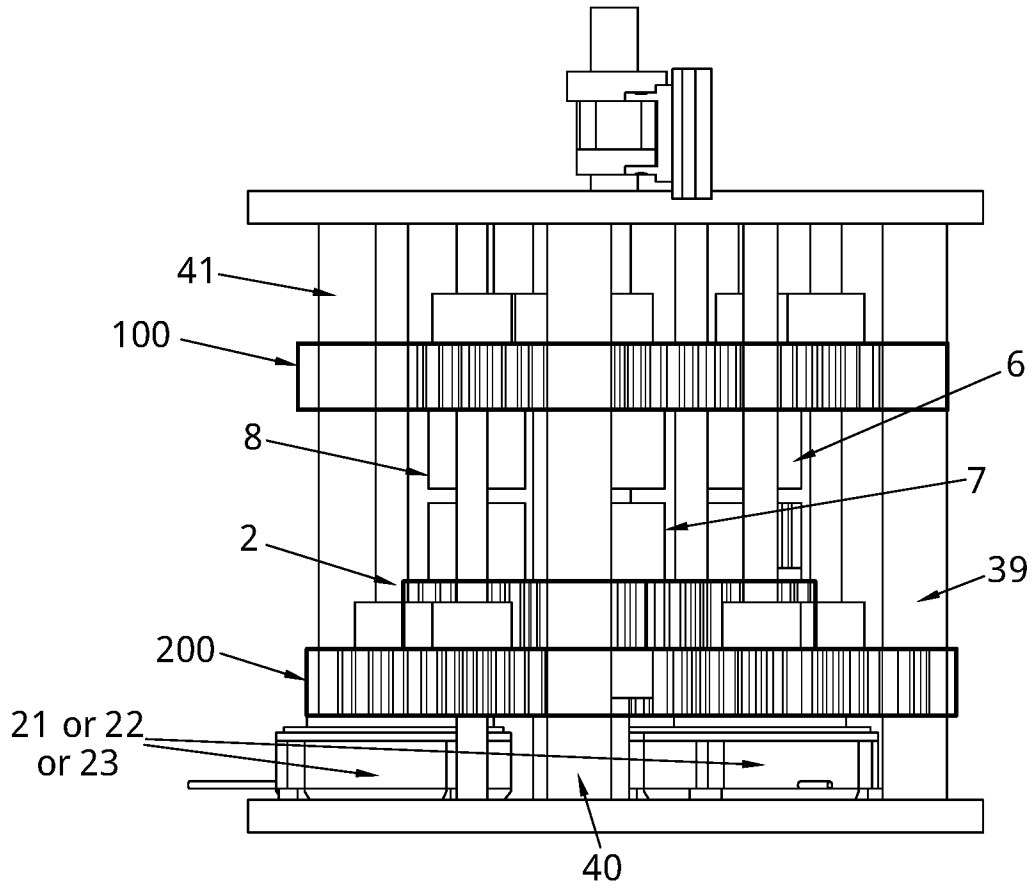


FIG. 2

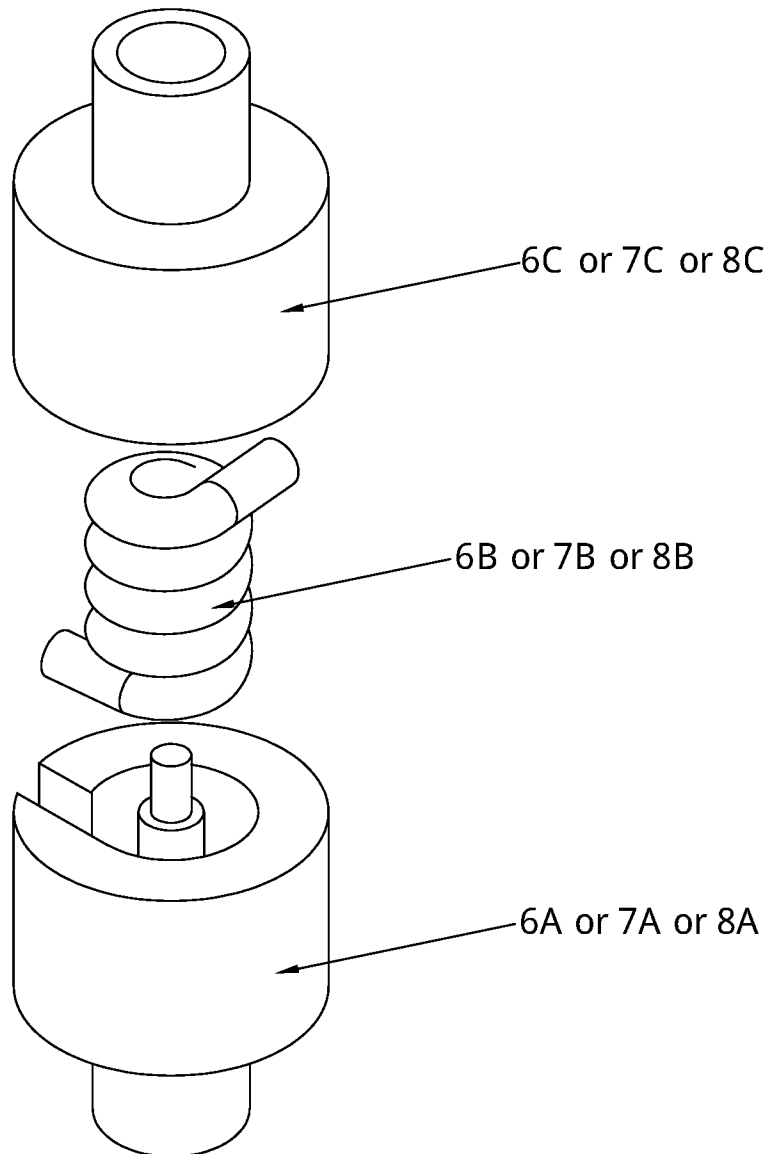


FIG. 3

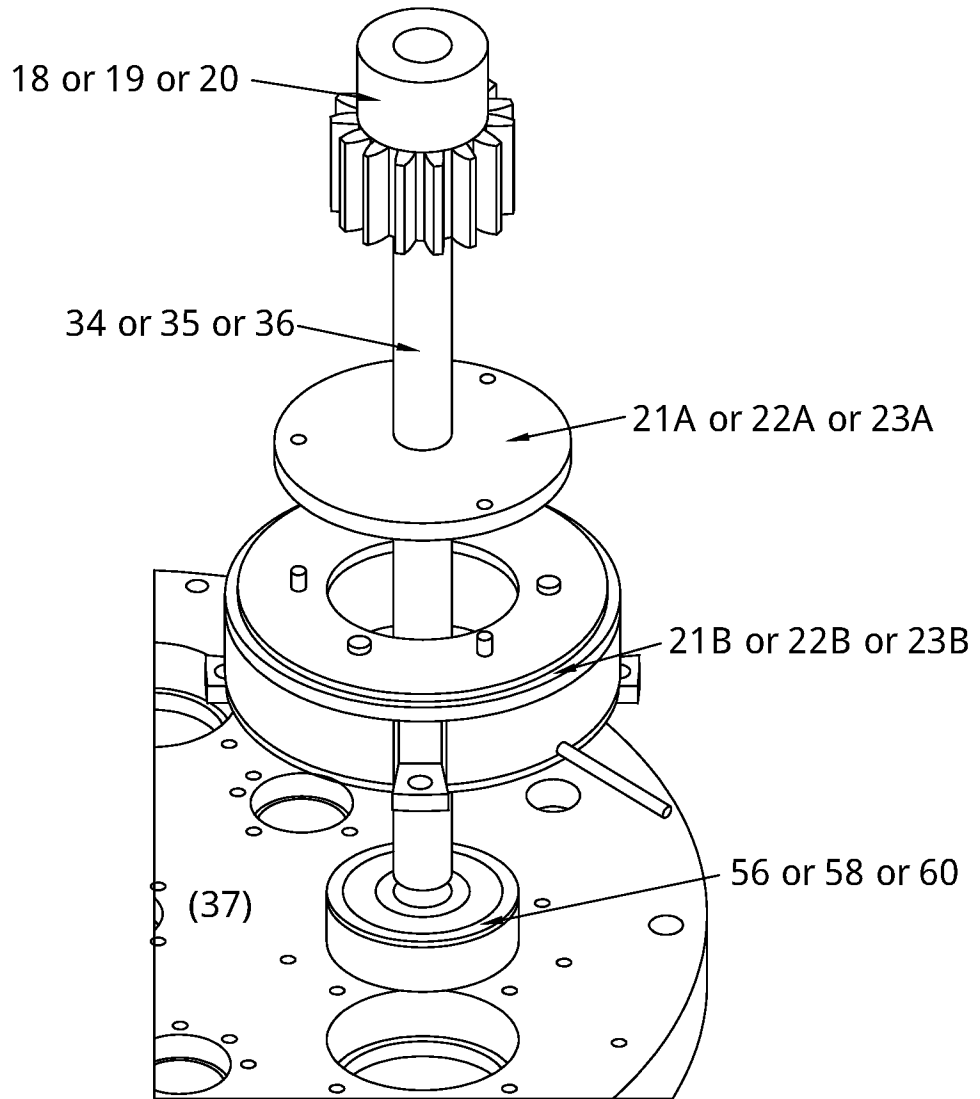


FIG. 4

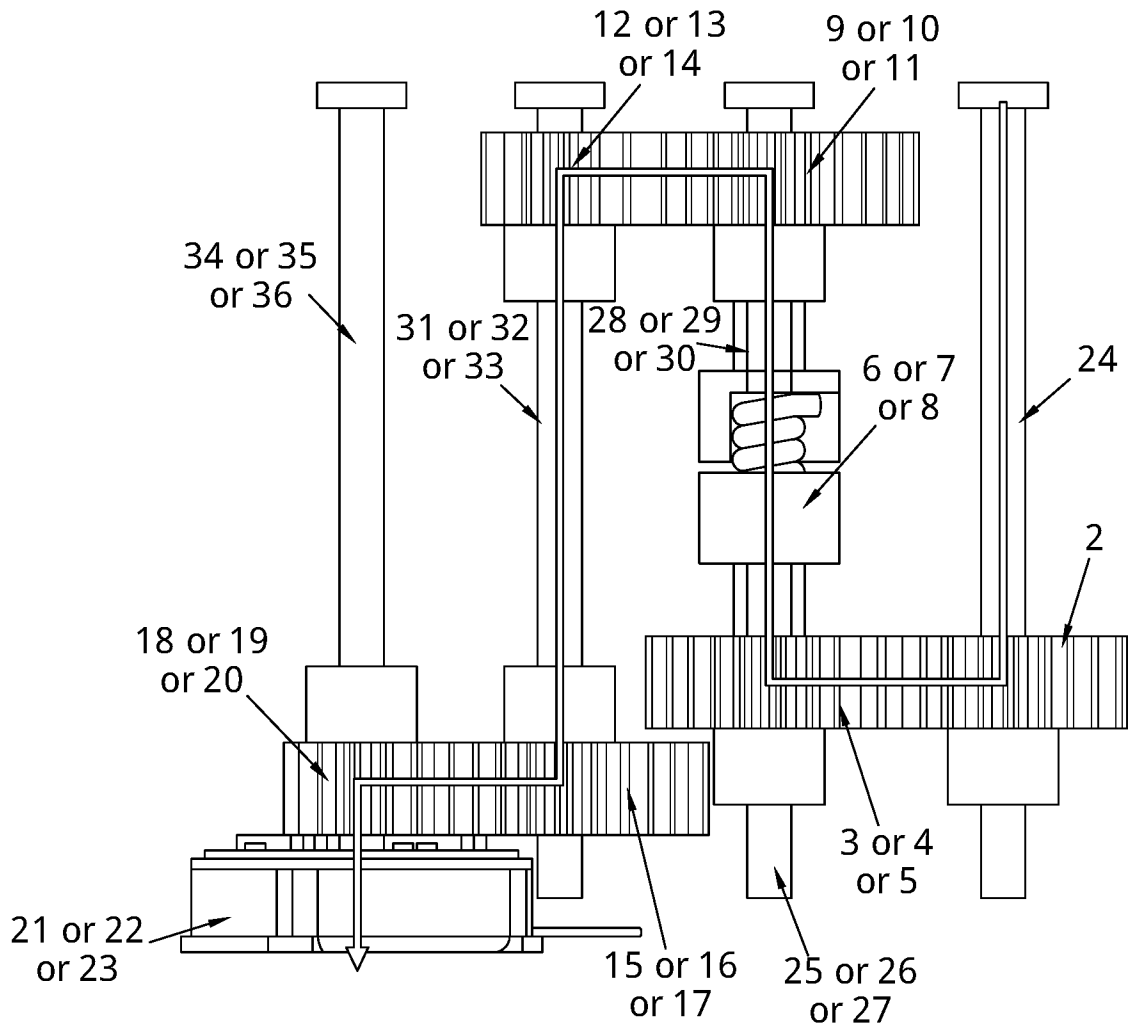


FIG. 5

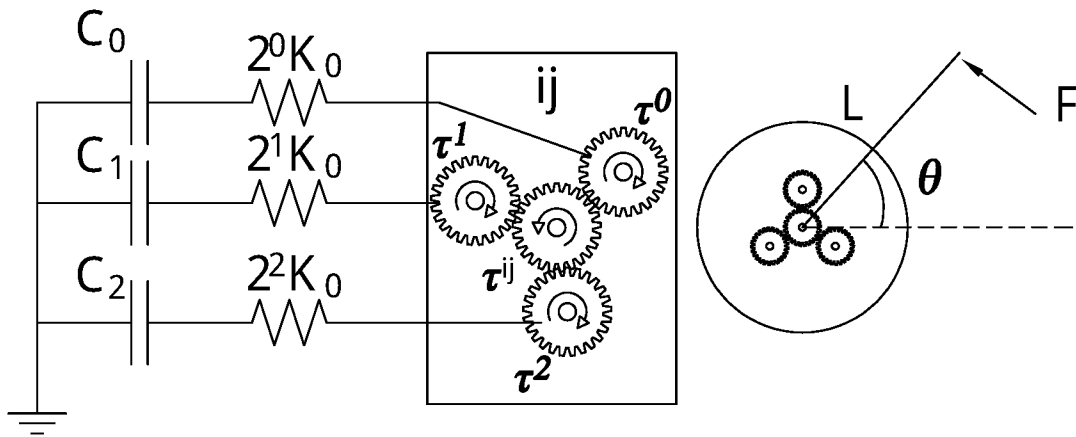


FIG. 6

## INTERNATIONAL SEARCH REPORT

International application No.

PCT / IB 2018/056470

A. CLASSIFICATION OF SUBJECT MATTER IPC: <b>B25J 19/06</b> (2006.01); <b>B25J 17/02</b> (2006.01); <b>F16D 3/50</b> (2006.01) According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) <b>B25J, F16D</b>		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) <b>EPODOC, XFULL, WPI</b>		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 106863348 A (UNIV SOUTH CHINA TECH) 20 June 2017 (20.06.2017) figs. 1 - 3	1, 2, 4, 5, 23 - 25, 27, 28
A	CN 204487594 U (HEBEI UNIVERSITY OF TECHNOLOGY) 22 July 2015 (22.07.2015) figs. 1 - 5	1 - 34
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
* Special categories of cited documents:		
"A" document defining the general state of the art which is not considered to be of particular relevance		"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent but published on or after the international filing date		"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means		"&" document member of the same patent family
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Date of the actual completion of the international search 09 November 2018 (09.11.2018)	Date of mailing of the international search report 16 November 2018 (16.11.2018)	
Name and mailing address of the ISA/AT Austrian Patent Office Dresdner Straße 87, A-1200 Vienna Facsimile No. +43 / 1 / 534 24-535	Authorized officer THALHAMMER C. Telephone No. +43 / 1 / 534 24-358	

**INTERNATIONAL SEARCH REPORT**  
Information on patent family members

International application No.  
PCT / IB 2018/056470

Patent document cited in search report			Patent family member(s)			Publication date
CN	A	106863348	CN	A	106863348	2017-06-20
CN	U	204487594	CN	U	204487594	2015-07-22