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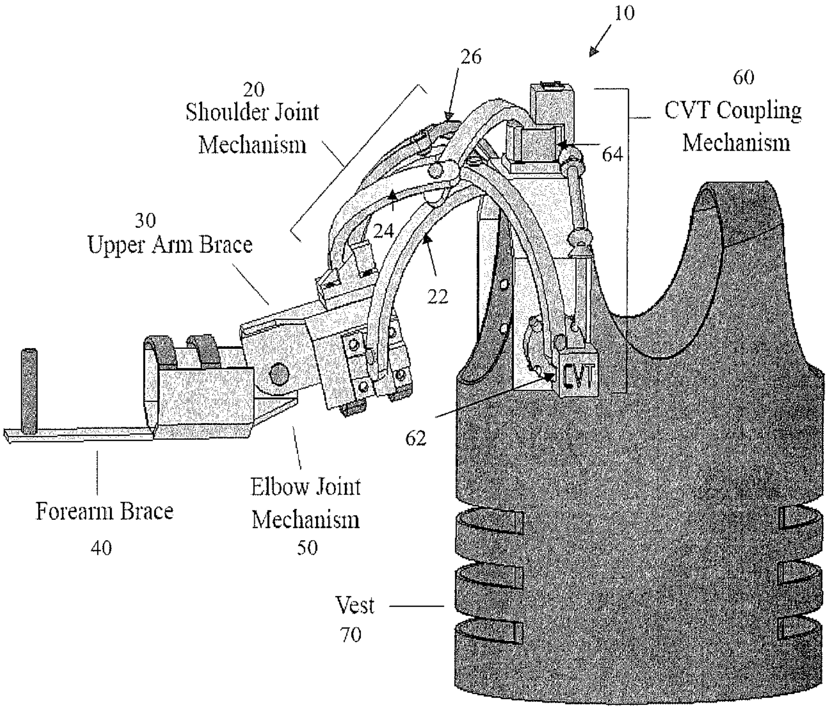
# (54) Title: HAPTIC EXOSKELETON



(57) **Abstract:** A dynamic coupling adapted for use in an exoskeleton includes a plurality of steerable transmissions connected to a first exoskeleton member and a plurality of linkages connected between a corresponding one of the steerable transmissions and a second member. The steerable transmissions thereby control movement of the joint through the linkages.

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## Abstract

A dynamic coupling adapted for use in an exoskeleton includes a plurality of steerable transmissions connected to a first exoskeleton member and a plurality of linkages connected between a corresponding one of the steerable transmissions and a second member. The steerable transmissions thereby control movement of the joint through the linkages.

# HAPTIC EXOSKELETON

## Cross Reference to Related Applications

This application claims the benefit of priority of U.S. Provisional Patent Application Serial No. 60/842,808 filed September 7, 2006, and incorporated herein by reference in its entirety for all purposes.

## Technical Field

The invention concerns generally the field of human-machine interaction and more particularly the use of haptic feedback in such interactions.

## Background

Within the last decade the area of haptic feedback has emerged as a component of human-machine interaction. Haptic feedback consists of providing tactile-feedback (often force-feedback) to a human user. By adding haptics to a human-machine interaction, the user is provided with additional tactile information. This is of relevance in virtual reality and teleoperation or telepresence applications, where haptic feedback allows the user to "feel" the virtual/remote objects they are interacting with. One of the most well-known haptic devices is the Phantom®, sold by SensAble Technologies, Inc. which allows a user to feel haptic forces at their fingertip via a thimble attached to an actuated linkage. Other devices such as the CyberGrasp™, sold by Mindflux, and HandMaster, sold by EXOS, Inc. are worn on the hand and provide haptic feedback to some or all of the user's fingers.

Advances in virtual reality and telepresence have highlighted the need for more effective human-computer interfaces. Of the many varieties of haptic devices, whole-arm haptic devices have the capability of providing immersive haptic feedback. By applying force feedback to a user's whole arm (rather than just the hand or fingertips) the user can experience feedback that is more "life-like." Thus whole-arm haptic devices usually take the form of exoskeletons that are worn on the user's arm.

Exoskeleton devices can be divided into two types: un-powered and powered. Un-powered exoskeletons function as sensor arrays, measuring the user's motion. These devices are sometimes used for master-slave applications.

Powered exoskeleton devices tend to fall into two main categories, based on whether they are designed to provide force-feedback to the user (haptic exoskeletons) or provide powered assistance to the user, increasing his or her effective strength. There are a number of existing exoskeletons that fall into the power-assist category. One of the better known exoskeletons in this category is the Berkeley Lower-Extremity Exoskeleton (BLEEX), which provides powered assistance to a wearer's legs via an exoskeleton, allowing the user to walk and run while carrying loads up to 45 kg strapped to a backpack-like frame. Another well-known exoskeleton is the University of Washington Full-Arm Exoskeleton which has been called a "human amplifier" and functions as an assistance device for people with neurological disabilities.

Haptic exoskeletons, in contrast, are not designed to amplify the forces exerted by the user, but rather to guide the user and provide tactile sensation of virtual objects. These exoskeletons are used in applications such as virtual reality, teleoperation/telepresence, and physical therapy/rehabilitation. Some desirable characteristics of an effective haptic exoskeleton (or any other haptic device) include low inertia, low friction, high bandwidth, high stiffness, high back-drivability and zero backlash. A realizable stiffness aids in creating hard realistic virtual objects/surfaces.

Arm exoskeletons are well suited for telepresence applications (including remote surgery, undersea salvage, and operation of space manipulators) because their intuitive operation requires little training to become proficient. Exoskeleton master-slave teleoperation systems also utilize the redundancy of human arm to allow obstacle avoidance in unstructured environments. Some of these exoskeletons include the motion of only the shoulder and elbow, while others include wrist motion as well as hand/finger motion.

## Summary

A dynamic coupling adapted for use in an exoskeleton includes a plurality of steerable transmissions connected to a first exoskeleton member and a plurality of linkages connected between a corresponding one of the steerable transmissions and a second member. The steerable transmissions thereby control movement of the joint through the linkages.

Brief Description of the Drawings

Figure 1 is a front view of an exoskeleton constructed in accordance with one embodiment of the present invention.

Figure 2 is a schematic illustration of relative positioning of spherical links of the exoskeleton of Figure 1.

Figure 3 is a partial view of the exoskeleton of Figure 1.

Figures 4a and 4b are views of a tetrahedral continuously variable transmission component of the exoskeleton of Figure 1.

Figure 5 is a functional flowchart of the tetrahedral continuously variable transmission of Figure 2.

Figure 6 is a rear isometric view of the exoskeleton of Figure 1.

Figure 7 is a schematic representation of a fluid coupling configuration employed in one embodiment of the exoskeleton of Figure 1.

Figure 8 is a schematic representation of an alternative coupling configuration employed in a further embodiment of the exoskeleton of Figure 1.

Figure 9 is an front perspective view of a continuously variable transmission to elbow coupling mechanism of the exoskeleton of Figure 1

Figure 10 is an isometric view of a continuously variable transmission to elbow coupling mechanism of the exoskeleton of Figure 1.

Figure 11 is a perspective view of a pulley assembly of the exoskeleton of Figure 1.

Figure 12 is a front view of the pulley assembly of Figure 11.

Figure 13 is a front perspective view of a continuously variable transmission to elbow coupling mechanism of the exoskeleton of Figure 1.

Figure 14 is an enlarged view of a flexible joint of the coupling mechanism of Figure 13.

Figure 15 is an enlarged view of a flexible joint of the coupling mechanism of Figure 13.

Figure 16 is an enlarged view of a flexible joint of the coupling mechanism of Figure 13.

Figure 17 is a functional block diagram of a dynamic coupling that can be used as part of the exoskeleton of Figure 1.

Figure 18 is a flowchart outlining one procedure for operating the coupling of Figure 17.

## Detailed Description

The exoskeleton described herein utilizes a new approach to provide haptic feedback to the user. By using cobot technology, haptic surfaces can be produced with high stiffness. Cobots, short for "collaborative robots," were first introduced by Colgate and Peshkin. The cobot concept is based on shared control between the human operator and the cobot, where the cobot provides constraints that "guide" the motion of the user. This is best illustrated by considering a very simple cobot, termed the "unicycle cobot," consisting of a vertical steered wheel, un-powered about its rolling axis, rolling without slipping on a flat horizontal surface. The wheel can be moved about the surface by the user (the user provides all motion), but the direction that the user is allowed to move in is controlled by the steering angle of the wheel (like a unicycle). The cobot can operate in "free mode," where a force sensor atop the unicycle cobot interprets the direction the user is pushing and steers the wheel in that direction to allow motion. In this mode the user feels no constraints from the cobot, as the wheel is always steered in the direction the user is pushing (much like the behavior of a caster). The computer controlling the cobot can also be programmed with virtual surfaces, lower-dimensional surfaces representing some desired virtual object. If the cobot is pushed into a virtual surface, the cobot switches into "virtual surface mode" and steers the wheel parallel to the virtual surface. If the user pushes the cobot towards the surface the no-slip condition of the wheel prevents the cobot from passing through the virtual surface and instead only allows the cobot to move along the surface. In this way haptic forces can be exerted on the user (by reaction forces enforcing the no-slip condition) without an actuator acting on the user. If the user then pushes the cobot away from the surface the cobot resumes free mode and allows the user to move away from the surface.

This concept can be generalized for more complicated cobots. The underlying technology is the use of non-holonomic constraints to guide the motion of the user. In the previous example the unicycle wheel acts as a continuously variable transmission (CVT), coupling the translation of the wheel in the two horizontal directions such that instantaneously the cobot has one degree of freedom, controlled by the steering angle of the wheel. In general a cobot uses CVTs to couple the degrees of freedom of the system such that there is only one instantaneous degree of freedom. Control of the cobot and the resulting virtual surfaces felt by the user is accomplished by controlling the gear ratios/steering angles of the CVTs.

Because no actuators act on the user, cobots are passive and relatively stable. With appropriate design of the CVTs, cobots can also produce virtual surfaces with high stiffness. For example, the 6-degrees of freedom (DoF) cobotic hand controller, a cobot based on a parallel platform creates surfaces with stiffnesses of 20-400 kN/m (depending on the configuration of the robot and the location of the end-effector). In comparison, existing haptic devices like the Phantom 1.5, the Virtuose 6D35-45, and the L-EXOS exoskeleton exhibit stiffness of 3.5 kN/m, 2 kN/m, and 2 kN/m respectively.

## Operational Modes

The exoskeleton ("REACH" exoskeleton) described herein is designed to control the user's motion in two distinct modes; virtual surface mode and virtual path or trajectory mode. Virtual surface mode utilizes the unique ability of the Cobot structure to provide very high stiffness virtual surfaces to the user without doing work on the user. The Cobot structure of the REACH exoskeleton will allow for surfaces to be pre-programmed or provided based on a real time physical environment. This ability allows the REACH exoskeleton a very adept haptic device for both virtual reality and tele-operation applications.

Where the REACH exoskeleton is of particular interest is in its ability to operate in virtual path or trajectory mode for uses in physical therapy. In physical therapy when a patient suffers from a neurological disorder or has lost the ability to control their extremities they must undergo long and sometimes painful rehabilitation. One of the key techniques in this rehabilitation is re-teaching neural pathways through assisted repetitive motions to re-introduce the user's own natural muscle memory. An example of muscle memory is learning how to swing a golf club or a baseball bat. By repeating a perfect form the user is able to control their body almost unconsciously. With neurological disorders, muscle memory rehabilitation is conducted by having a Physical Therapist hold and guide the patient through various motions. These motions are repeated excessively until the user has gained the necessary control and strength. One of the major challenges of this practice is repeatability.

The strength of any robotic system to its human counterpart is repeatability. In virtual path mode the REACH exoskeleton's Cobot structure will have the ability to reduce the four DoFs and into a single guided instantaneous DoF which the user must follow. All that is required by the physical therapist is to place the user in the exoskeleton and move the exoskeleton along the desired trajectory once. The control system will record the necessary joint angles and will not allow the user to move outside the programmed motion, thus producing the desired highly-repeatable motion. Also note that another application would be for healthy people to wear the exoskeleton and rapidly learn a desired motion such as the previous examples of a golf or baseball bat swing by utilizing pre-programmed trajectories built into the control structure.

A schematic of a haptic exoskeleton 10 is shown in Figure 1 (here the exoskeleton is worn on the user's right arm). The exoskeleton described herein consists of four subsystems: wearable braces 30, 40, 70; shoulder and elbow joint mechanisms 20, 50; CVT coupling mechanism 60 with CVTs 62, 64, 66, 68, and the control system (not shown in Figure 1).

## Wearable Brace

The wearable braces are the simplest of the subsystems. This includes a vest 70 worn on the torso, an upper arm brace 30 worn on the bicep, and a forearm brace 40. The user must strap each of these braces on in order to use the exoskeleton. All other mechanical elements of the exoskeleton are mounted to these braces. In addition, each brace will have adjustable pads and straps to allow the exoskeleton to fit most users (5th to 95th percentiles of the population), by allowing the user's shoulder joint and elbow joint to be aligned with the corresponding joint axes of the exoskeleton 10.

## Shoulder and Elbow Joint Mechanisms

The shoulder and elbow joint mechanisms 20, 50 define the motion and workspace of the exoskeleton. Each of the joint mechanisms is designed to replicate the range of motion of the user. The shoulder joint mechanism 50 is a 3RRR spherical parallel mechanism. That is, the upper arm brace is connected to the vest by three sets of spherical linkage chains 22, 24,26, each of which has three revolute joints. All nine of the revolute joints are aligned such that their axes of rotation intersect at a single point which coincides with the center of rotation of the user's shoulder.

To avoid collisions the front chain 22 and rear chain 26 are arranged on a different spherical shell than the middle chain 24 so that the three chains may pass each other without interference. This design is different from other exoskeleton designs, which use a serial structure to produce spherical motion about the user's shoulder. The use of a parallel mechanism rather than a serial mechanism to create spherical motion of the upper arm brace improves the stiffness of the shoulder mechanism and simplifies the CVT coupling mechanism.

The shoulder joint mechanism's geometry is selected such that the mechanism can replicate the range of motion of a user's shoulder while avoiding collisions between the links and avoiding singularities of the mechanism. Singularities are a common problem in parallel mechanisms, where in certain configurations some of the passive joints align such that the mechanism instantaneously gains or loses a degree of freedom. As this could cause the exoskeleton to behave in an unpredictable manner, singularity avoidance is important in the design of the shoulder mechanism. It bears noting that while the true range of motion of the human shoulder includes translation or "shrugging" of the shoulder joint, due to the complexities of incorporating this motion, the exoskeleton 10 does not include these degrees of freedom.

The kinematic parameters of the mechanism are selected such that the normal range of motion of the human shoulder is contained within the mechanism workspace. In addition, the workspace is free of singularities and collisions.

The spherical mechanisms are designed with linkages and all axes of the revolute joints to align to the center of rotation (CoR), in this case, the shoulder. Because of this property the linkages move about as if following a spherical path within a spherical surface or shell. When two or more linkages inhabit the same spherical shell there is the possibility of a collision. By increasing or decreasing the interior and exterior radius of the linkages (see Figure 2) the linkage chains can inhabit different spherical shells. An example of this is shown in Figure 3, where chains 22 and 26 both inhabit the same spherical shell. The intermediate chain 24 is raised above chains 22 and 26 to avoid collision. Also chain 24 is pointed forward to allow space for the CVT coupling along chain 26.

Referring back to Figure 1, The CVT coupling mechanism 60 is designed to correctly function as a cobot, therefore the four degrees of freedom (DOF) of the exoskeleton (one at the elbow, three at the shoulder) are coupled to each other through CVTs 62, 64, 66, 68 (also shown in Figure 6) such that the exoskeleton has only one DOF. Essentially, the exoskeleton will use a CVT at each degree of freedom.

The CVTs 62, 64, 66, 68 are as compact as possible in order to be mounted to the vest without interfering with the user's range of motion. The CVT is a spherical-CVT (S-CVT) that includes a sphere enclosed by four rollers arranged in a tetrahedral pattern as shown in Figure 4a. As can be seen best in Figure 4b, one set of rollers are the drive rollers 102, including an input roller, connected to one of the exoskeleton joints, and an output roller, which is coupled to the other CVTs. The other set of rollers are the steering rollers 101, which are steered by a steering motor to control the transmission ratio between the input and output rollers. Note that the transmission ratio ($\omega_{out}/\omega_{in}$) can take on any value from $-\infty$ to $+\infty$.

A flow-chart describing the functional connection of the CVT coupling mechanism is shown in Figure 5. Rotation rates $\omega_1$, $\omega_2$, and $\omega_3$ are the angular rates of the three revolute joints within the shoulder joint mechanism that are attached to the vest, while $\omega_4$ is the angular rate of the elbow joint. This configuration is termed a parallel configuration, as all four of these rotations are coupled through CVTs to an internal motion $\omega_0$. The steering angles $\theta_1$ through $\theta_4$ determine the transmission ratios of the CVTs and are controlled by four steering motors. $\mathbf{J}_1$ and $\mathbf{J}_2$ are Jacobian matrices. $\mathbf{J}_1$ transforms the four joint velocities into $\omega_x$, $\omega_y$, $\omega_z$, and $\omega_e$, the rotational velocities of the exoskeleton, where $\omega_x$, $\omega_y$, and $\omega_z$ are the rotation rates of the upper arm brace in the global $x$-$y$-$z$ coordinate frame (attached to the vest) and $\omega_e$ is the rotation rate of the elbow (identical to $\omega_4$). $\mathbf{J}_2$ transforms the rotational velocities of the exoskeleton to the "functional" velocities of the exoskeleton, $v_x$, $v_y$, $v_z$, and $\dot{\phi}_e$, where $v_x$, $v_y$, and $v_z$ are the linear velocities of the user's hand in the global $x$-$y$-$z$ coordinate frame and $\dot{\phi}_e$ is the angular rate of elbow elevation (rotation about the axis passing through the hand and the shoulder).

The use of a parallel mechanism for the shoulder joint mechanism has advantages over a serial mechanism in which the CVTs would have to be coupled to all three revolute joints in the serial chain. Even S-CVTs, which are compact compared to most CVTs, would be too heavy and bulky to place on the serial mechanism, and locating them on the vest would necessitate complicated routings of transmission elements (such as gears, pulleys, cables, etc.) to perform the necessary coupling. The use of a spherical parallel mechanism allows front CVT 62, top CVT 64, and rear CVT 66 (Figure 6) to be mounted on the vest and directly coupled to the three revolute joints attached to the vest.

The elbow joint mechanism is relatively simple, consisting of a revolute joint 70 aligned with the elbow's axis of rotation. The revolute joint 70 (shown in Figure 6), located at the back of the user's arm, is connected to the CVT coupling mechanism 60 (located on the vest), in particular to CVT 68 through an elbow CVT coupling linkage 72. In addition, the four CVTs on the vest are coupled to one another to ensure that at any one time the entire system has only one degree of freedom. In Figure 6, the coupling of the CVTs to one another is shown schematically as 60 while the coupling of the elbow CVT to the revolute joint 70 is shown as 72. The coupling can be accomplished in several ways, such as, for example, fluid or cables.

Passively coupling the CVTs along the vest is a trivial problem and can be solved with any of a number existing solutions ranging from fluids, cable or tendon drives, direct gearing, and gearing with chains or belts. However the coupling of the elbow mechanism and corresponding CVT on the vest is a very difficult problem, simply because the coupling must be routed along a one or more of the shoulder mechanism's linkage chains.

For coupling the elbow mechanism to the CVTs on the vest, fluid couplings offer two very different solutions; a twin piston and a twin pump/turbine. With both systems high pressure fluid is pushed through fluid lines which can either be placed along the user's arm or a linkage chain. High pressure lines are required to keep thermal expansion and compression to a minimum. High pressure lines will most likely be placed on the linkage chain to improve the user's safety.

Referring to Figure 7, the twin piston method would have an input piston 135 placed on the upper arm and an output pump to be placed on the vest. In operation input rotation from a shaft 134 is converted to linear motion by a rotational to linear motion mechanism like a slider-crank mechanism (shown in Figure 7) or a rack and pinion connection. The linear force will push or pull the fluid in the input piston 135 causing a pressure difference and a displacement in an output piston 136 because both will be connected using a fluid line. When the output piston 136 is displaced the linear motion will be converted back to rotational motion on an output shaft 137 using again either a slider-crank mechanism or a rack and pinion connection. Advantages to this system are that there is only one high pressure line and the hydraulic pistons are readily available from many manufacturers. One disadvantage to this system is the need for a mechanism to convert linear motion to rotational motion.

The alternative coupling method is the twin pump/turbine method shown in Figure 8. Like the previous example an input pump 139 will be placed on the platform of the upper arm and an output pump 140 will be placed on the vest and coupled to the CVT. Where this system differs is that the input rotational motion from an input shaft 138 is used to drive an input pump or turbine to push the fluid along one line and pull the fluid along another line. The motion of the fluid the drives the output pump in the same motion. The major advantage of this system is that no external mechanisms are introduced. However some of the disadvantages to the twin pump/turbine system are that pumps have larger inherent inefficiencies, require multiple pressure lines, and it isn't very likely there are any commercially available small precision pump/turbines which would meet specification requiring future researchers to fabricate the pumps.

Fluid systems offer flexibility of connecting the vest to the elbow mechanism. Both coupling methods allow for the high pressure lines to be easily attached to the linkage chains by many conventional methods such as tape or speed ties. However using a fluid system entails designing a system that can operate on high pressure while limiting thermal expansion and preventing pressure losses due to leaks.

Cables or "tendons" are one of the most common methods of routing motion along mechanical structures in robotic applications. Cable systems offer low weight, low inertia, high flexibility and high strength while keeping heavier actuators and transmissions off the structure. For these reasons a cable driven coupling was selected for the REACH exoskeleton. The concept of the coupling mechanism, shown in Figures 9 and 10, is to route two opposing cables 171, 172 along the linkage chain 72 of the shoulder mechanism. One drawback to using cable driven systems is that cables can only transmit motion when held in tension. For this reason the elbow coupling mechanism will require two opposing cables to transmit positive and negative rotational motion.

The opposing cables will be affixed to a pair of 5/6th half moon pulleys 175. The pulleys 175, guide holes 183, and pulley enclosure will make the coupling assembly 180, shown in Figure 11 and Figure 12. Each pulley has a set of two tracks 193 shown in Figure 12 to keep the cables aligned and separated. The cable is fed to the pulleys via a set of guide holes 183 that is drilled into the pulley enclosure From the pulley enclosure the cables are guided along semi-flexible tubing 195 to the next pulley as shown in Figure 13.

The tubing selected is a hard rubber tube that is reinforced by steel braided wire, similar to the tubing used to route cables in bicycles. The tubing will have a set length longer than the minimum connection distance between contact points to ensure that the cable inside tubing cannot increase or decrease length as the pose of the mechanism changes. As the mechanism moves the tubing will alter is own geometry to follow along the mechanism but not the length of the cable.

The path selected for the tubing 195 is to attach the tubing along the outside edges of the linkage shown in Figure 13. The outside edge of the linkage chain offers the smallest deviation in the tubing lengths. The tubing will be connected to the linkage chain by four contact points and have two rigid sections 198 shown in Figure 13 and three flexible sections 196a, 196b, 196c as shown in Figures 14, 15, 16.

Between the connection points on the linkages the tubing will not change geometry; however tubing is required to prevent contact between the cables and the user. Selecting the proper lengths of the tubing of the flexible sections will vary based on the final shoulder mechanism geometry selected.

## Control System

The final subsystem of the exoskeleton is the control system. Using encoder and torque sensor feedback from the four coupled joints, the control system determines the state of the exoskeleton as well as the direction the user is trying to move. Using a computer model of virtual surfaces within the virtual environment, the controller determines whether to act in free mode or virtual surface mode and steers the steering motors accordingly.

In an exemplary embodiment, the control of the is performed by a microcontroller, enabling the control hardware to be mounted on the vest or worn in a backpack. In addition, because the steering motors do not have to be very powerful (they only need to overcome steering friction) the system is battery powered. Thus the batteries and control system can both be worn by the user (either on the vest or in a backpack) enabling the entire system to be portable.

Referring now to Figures 17 and 18, a dynamic coupling 200 that can be used as the shoulder joint mechanism is outlined in functional terms. The coupling 200 includes three steerable transmissions 240, 250, 260 that are connected to a first member, such as, for example a shoulder brace 210. The transmissions are connected to a second member, such as, for example, an upper arm brace 220 by three linkages 270, 280, 290 and to each other by an internal linkage 340. A controller 230 controls a transmission ratio of each of the transmissions according to a virtual workspace such that motion of the second member is limited as constrained by the workspace. For example the controller 230 provides instructions to transmission 240 to control how much rotation of the linkage 270 should be allowed for a given amount of rotation of the internal linkage 340. Figure 8 outlines a procedure 300 that can be implemented by the controller to control the transmissions. At 310 the workspace constraints are input. At 320 the workspace constraints are separated into subsets of constraints appropriate for each of the transmissions. At 330, each of the transmissions is controlled according to the constraints.

While the method and apparatus have been described herein above in connection with one or more embodiments, it is understood that such description is presented by way of example with no intent of limiting the method and apparatus in any way.

Claims

1. A dynamic coupling adapted for use as a joint mechanism between first and second members in an exoskeleton comprising:

a plurality of steerable transmissions disposed on the first member;

a plurality of linkages, each connected between the second member and a corresponding one of the steering transmissions on the first member.

2. The dynamic coupling of claim 1 wherein the steerable transmissions comprise a spherical continuously variable transmission.

3. The dynamic coupling of claim 2 wherein the spherical continuously variable transmission comprises a spherical bearing surrounded by four rollers arranged in a tetrahedral pattern, wherein a first of the four rollers is an input roller in operative communication with the first member, a second of the four rollers is an output roller in operative communication with the second member, and third and fourth of the four rollers are steering rollers that control a transmission ratio between the first and second rollers.

4. The dynamic coupling of claim 1 wherein the first member is a vest worn by a human wearer of the exoskeleton.

5. The dynamic coupling of claim 1 wherein the second member is an upper arm brace worn by a human wearer of the exoskeleton.

6. The dynamic coupling of claim 1 wherein the number of steerable transmissions and linkages is three.

7. The dynamic coupling of claim 1 wherein each linkage includes first and second legs pivotally connected to each other and wherein the first leg is pivotally connected at one distal end to the corresponding steerable transmission and wherein the second leg is pivotally connected the second member.

8. The dynamic coupling of claim 1 comprising a revolute joint at a distal end of the second member that is connected to a steerable transmission on the first member.

9. The dynamic coupling of claim 1 comprising a controller in communication with at least one of the steerable transmissions that controls a range of movement allowed by the steerable transmission.

10. The dynamic coupling of claim 1 wherein each linkage is arranged such that the linkage constrains motion of the second member within a spherical path of motion centered about a center of motion associated with the first member.

11. The dynamic coupling of claim 10 wherein each linkage has a generally sector shape, the circle of which the sector is part being centered about the center of motion.

12. The dynamic coupling of claim 11, wherein motion of each linkage is constrained to a spherical shell centered about the center of motion and wherein at least two of the linkages operate on spherical shells having different diameters.

13. The dynamic coupling of claim 8 wherein the revolute joint is connected to the steerable transmission with a cable.

14. A method that controls relative motion between first and second members according to workspace constraints comprising:

disposing a plurality of steerable transmissions of the first member;

pivotally connecting one of plurality of linkages from the second member to one of the steerable transmissions;

separating the workspace constraints into subsets of constraints corresponding to each steerable transmission; and

controlling relative motion between the first and second members by changing operating parameters on each of the steerable transmissions based on a corresponding subset of the workspace constraints.

15. The method of claim 14 wherein the step of controlling relative motion between the first and second members is performed by controlling a transmission ratio of the steerable transmission.

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

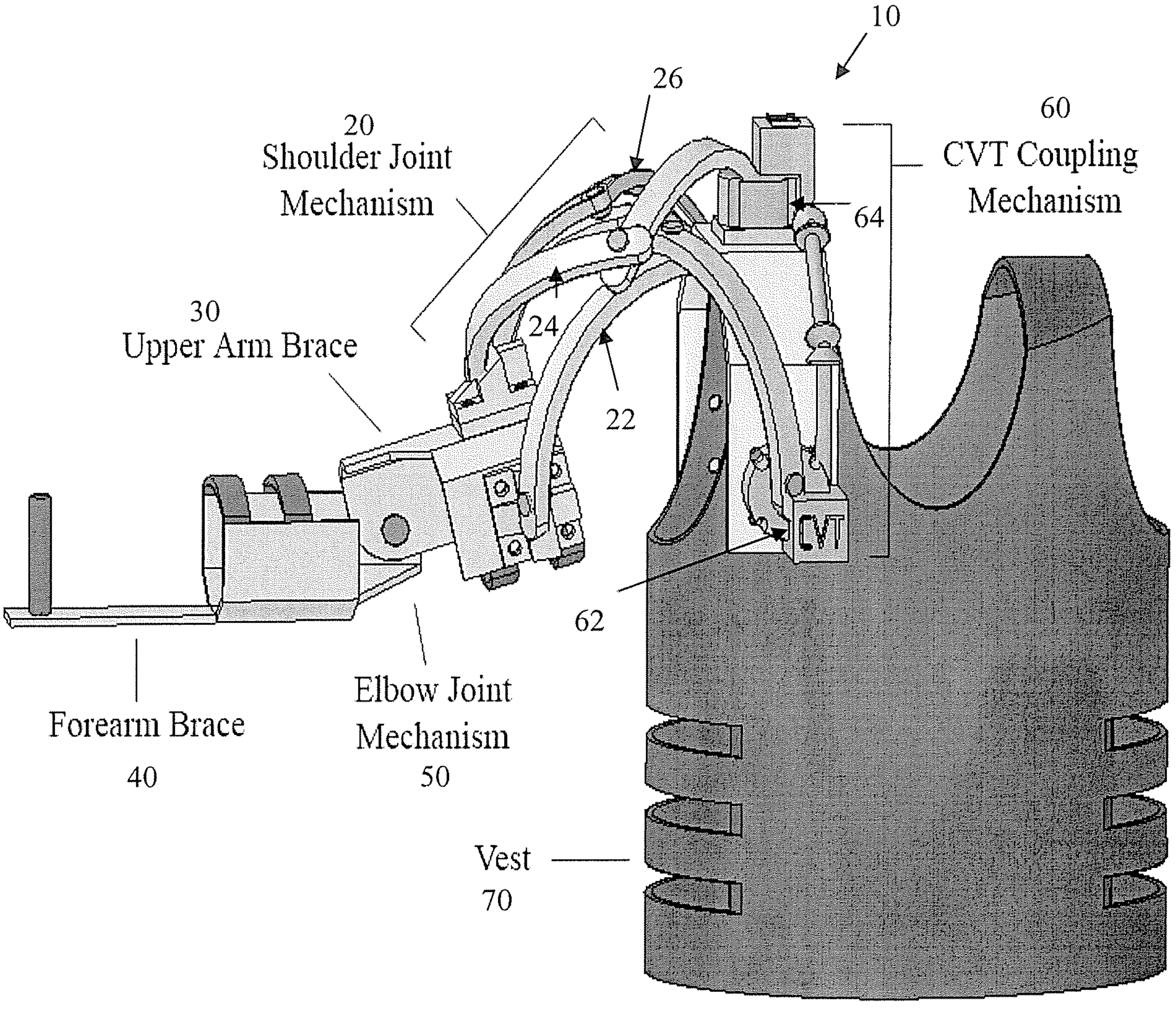

Figure 1

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

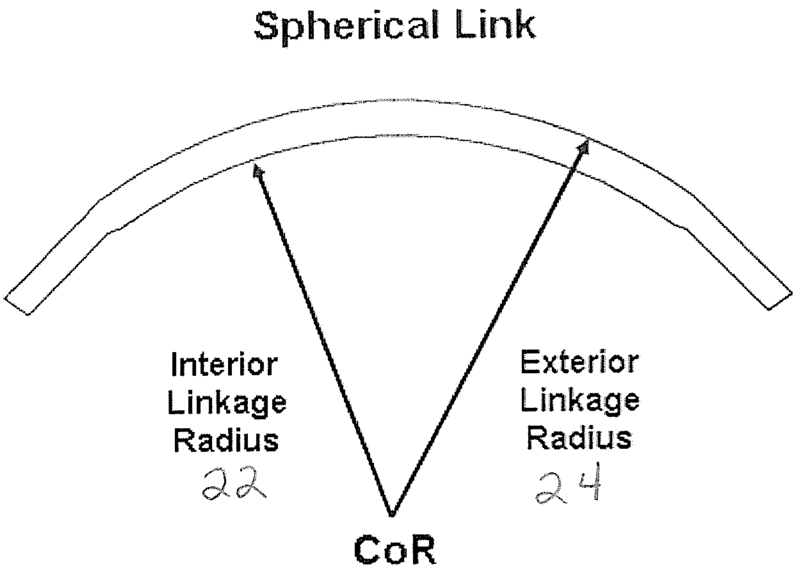

Figure 2

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

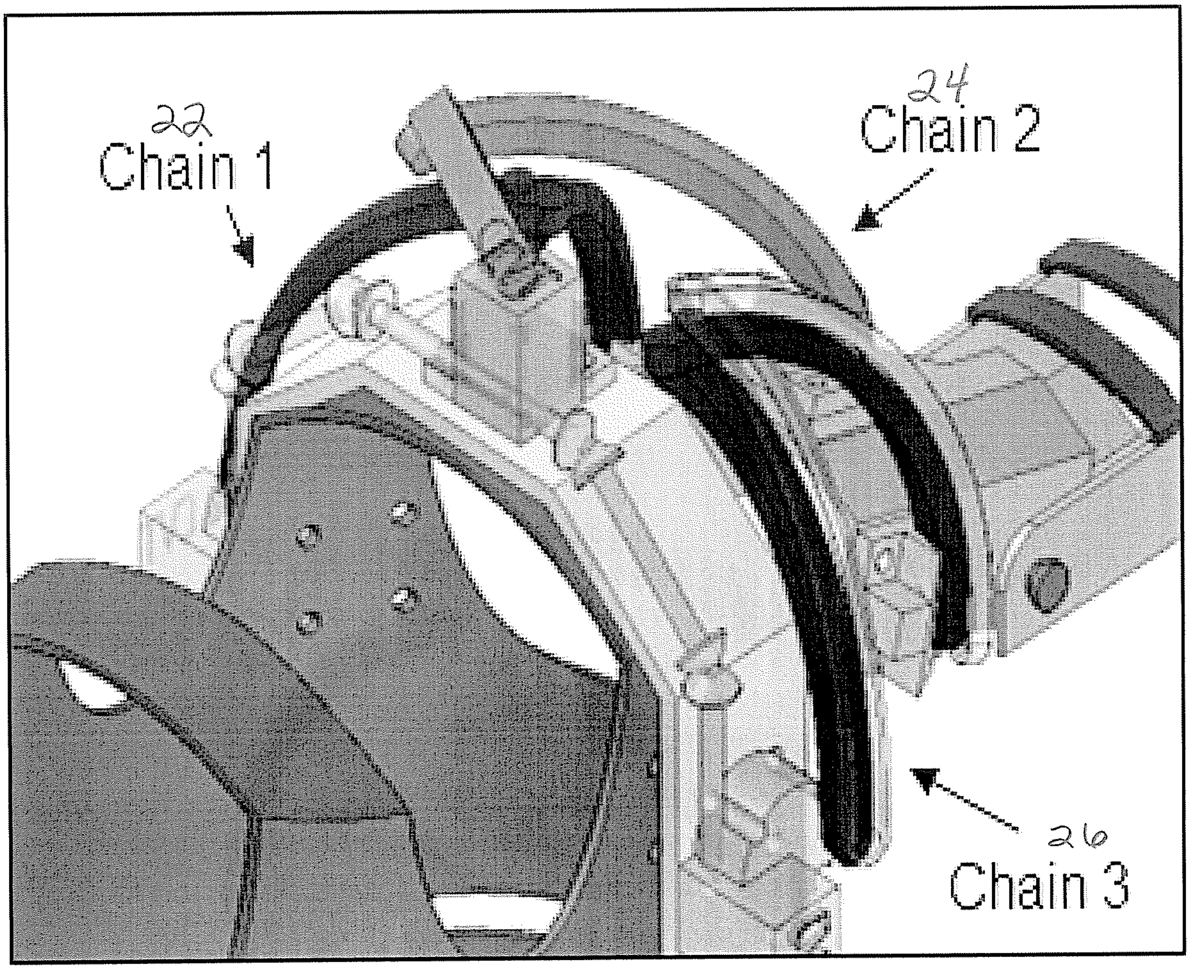

Figure 3

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

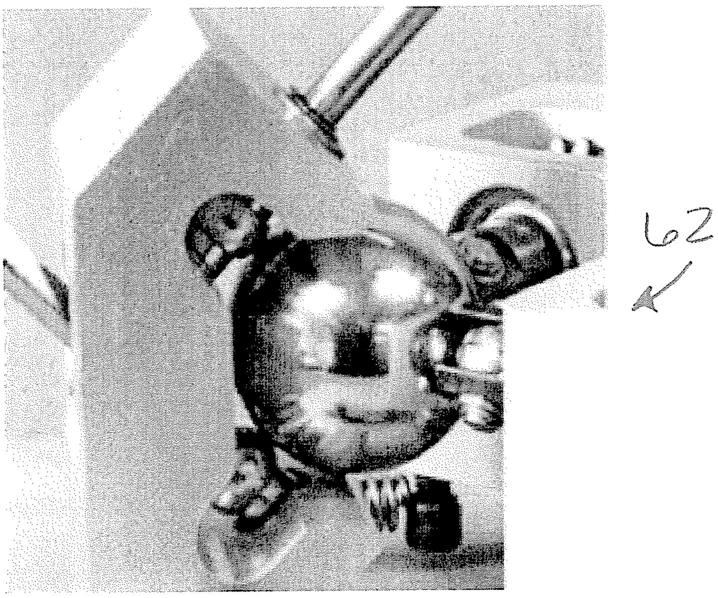

Figure 4a

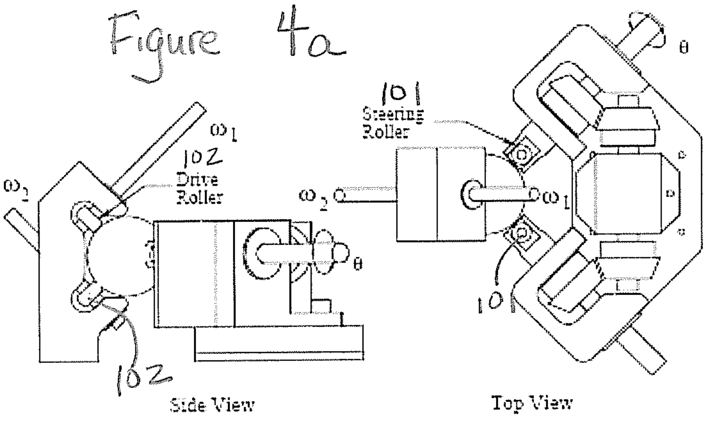

Figure 4b

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

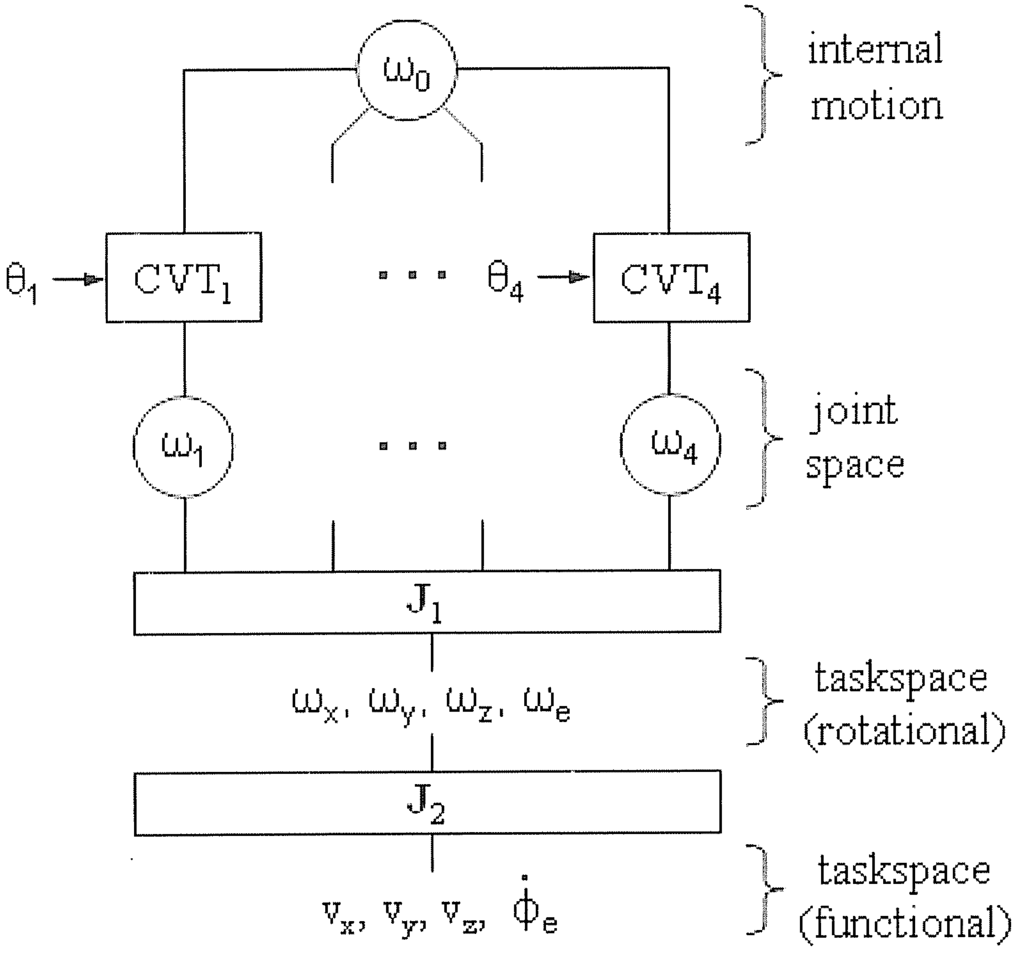

Figure 5

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

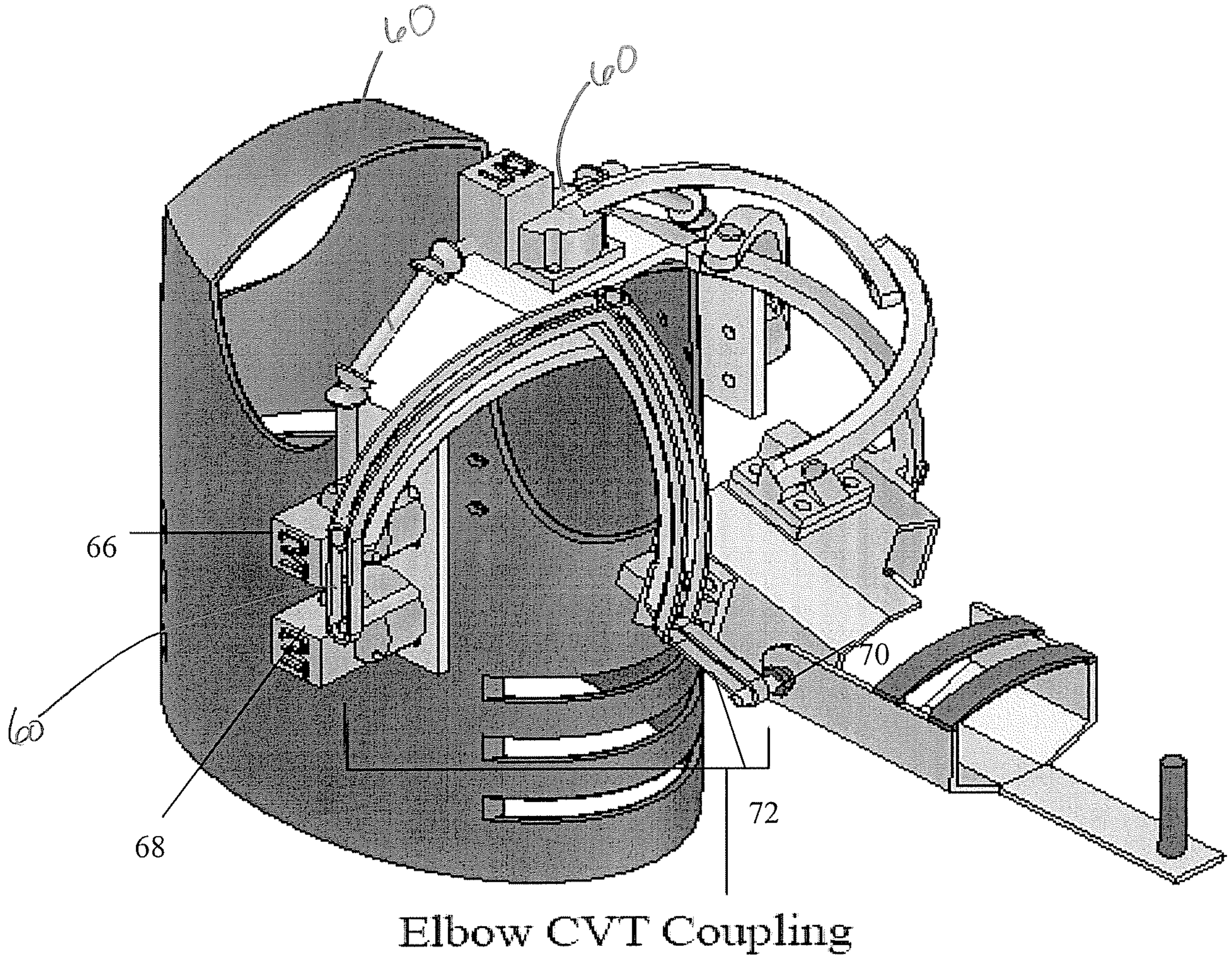

Figure 6

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

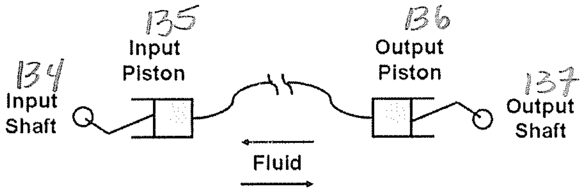

Figure 7

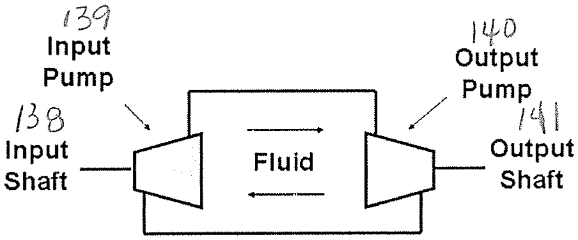

Figure 8

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

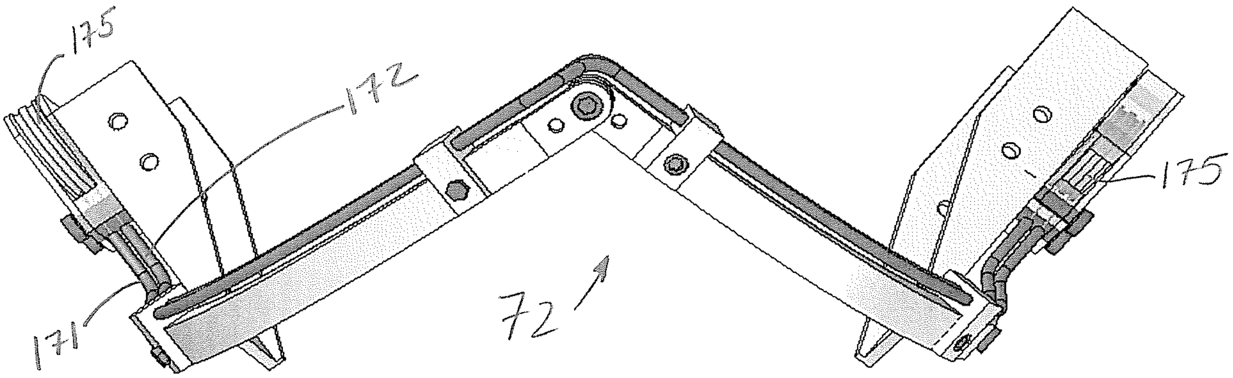

Figure 9

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

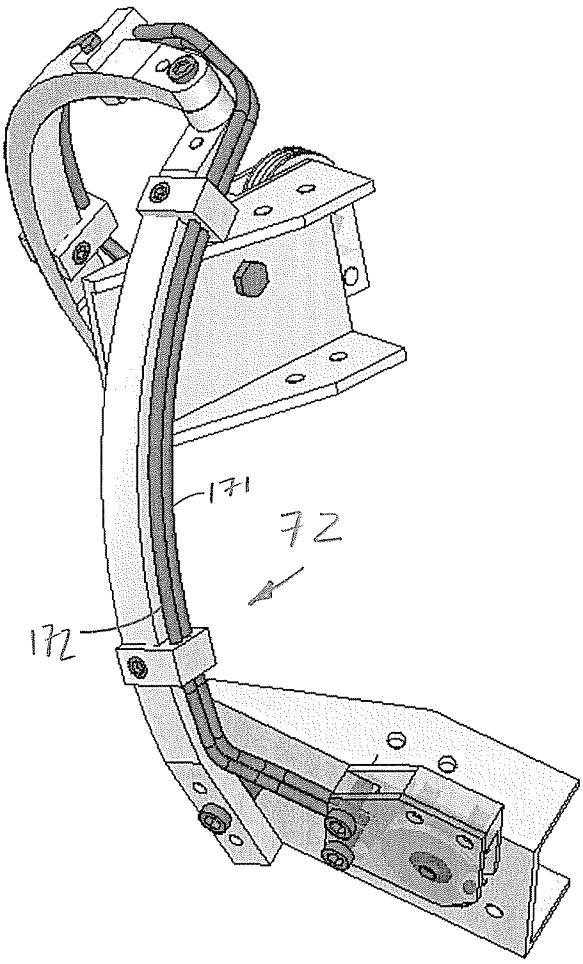

Figure 10

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

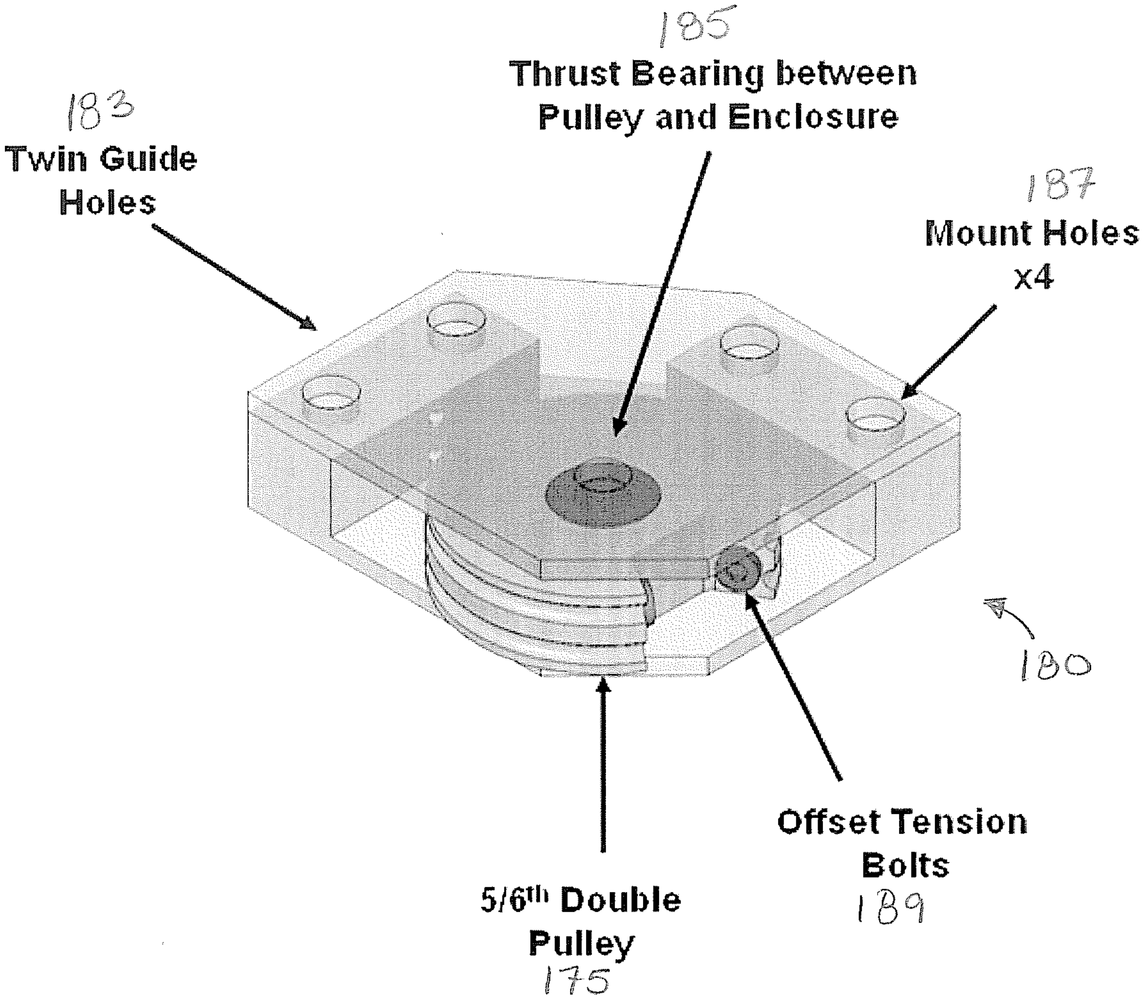

Figure 11

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

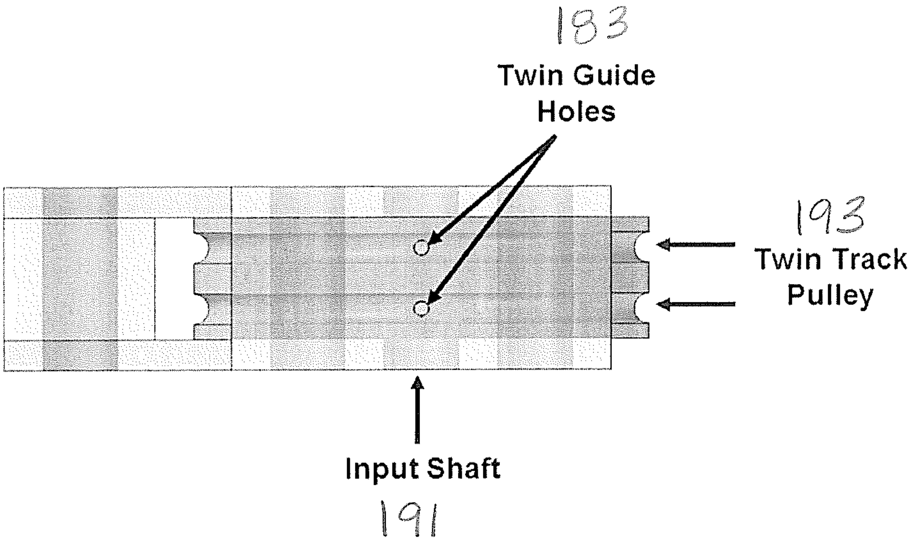

Figure 12

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

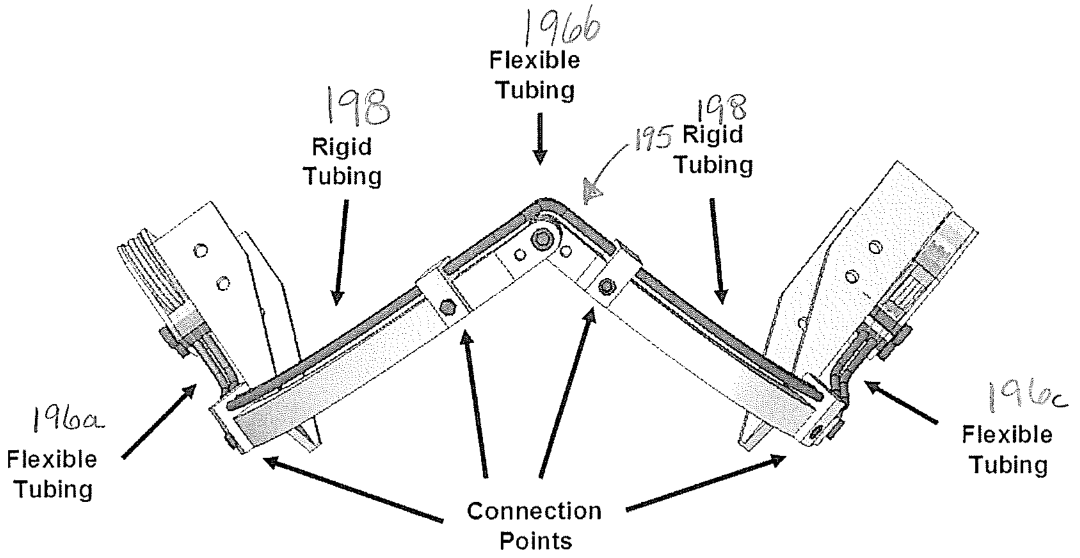

Figure 13

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

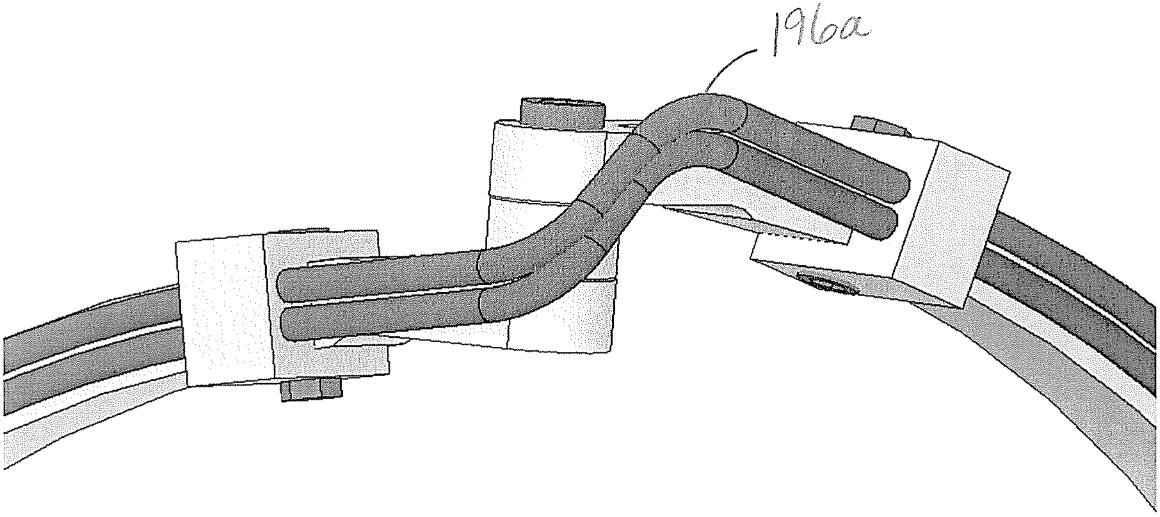

Figure 14

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

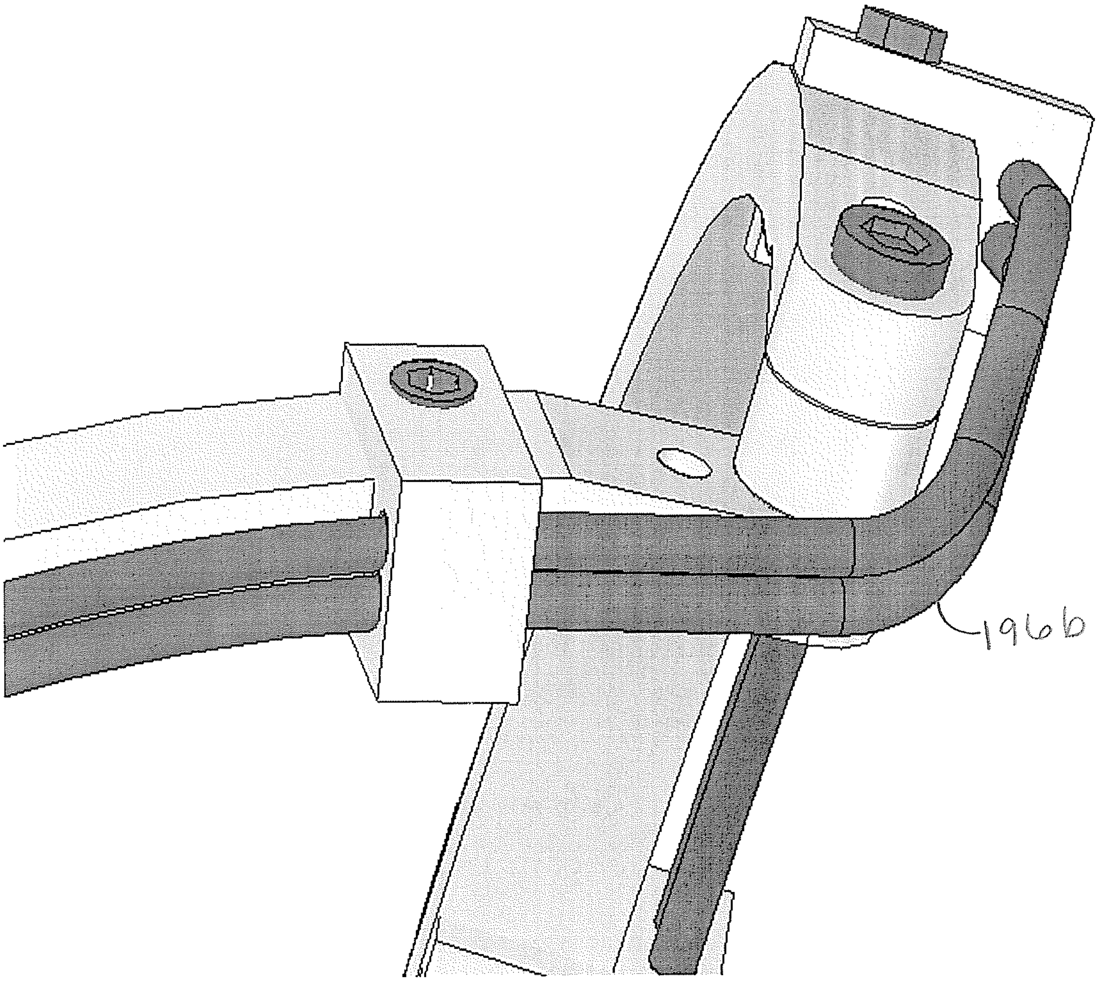

Figure 15

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

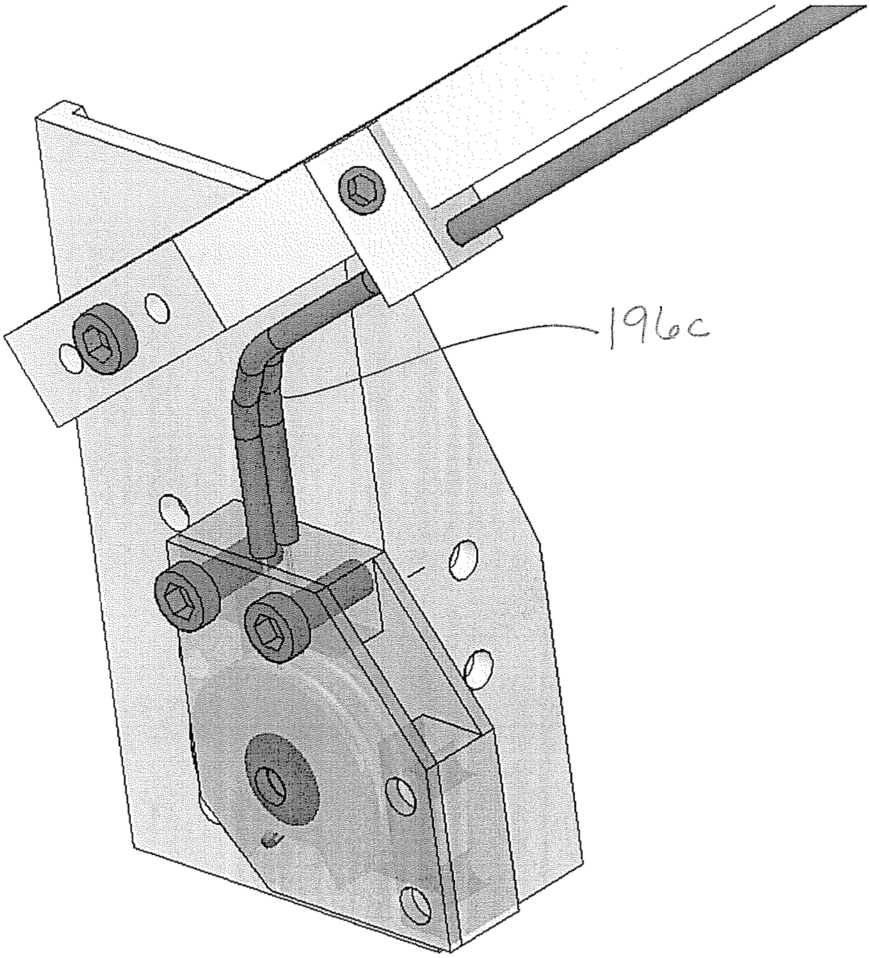

Figure 16

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

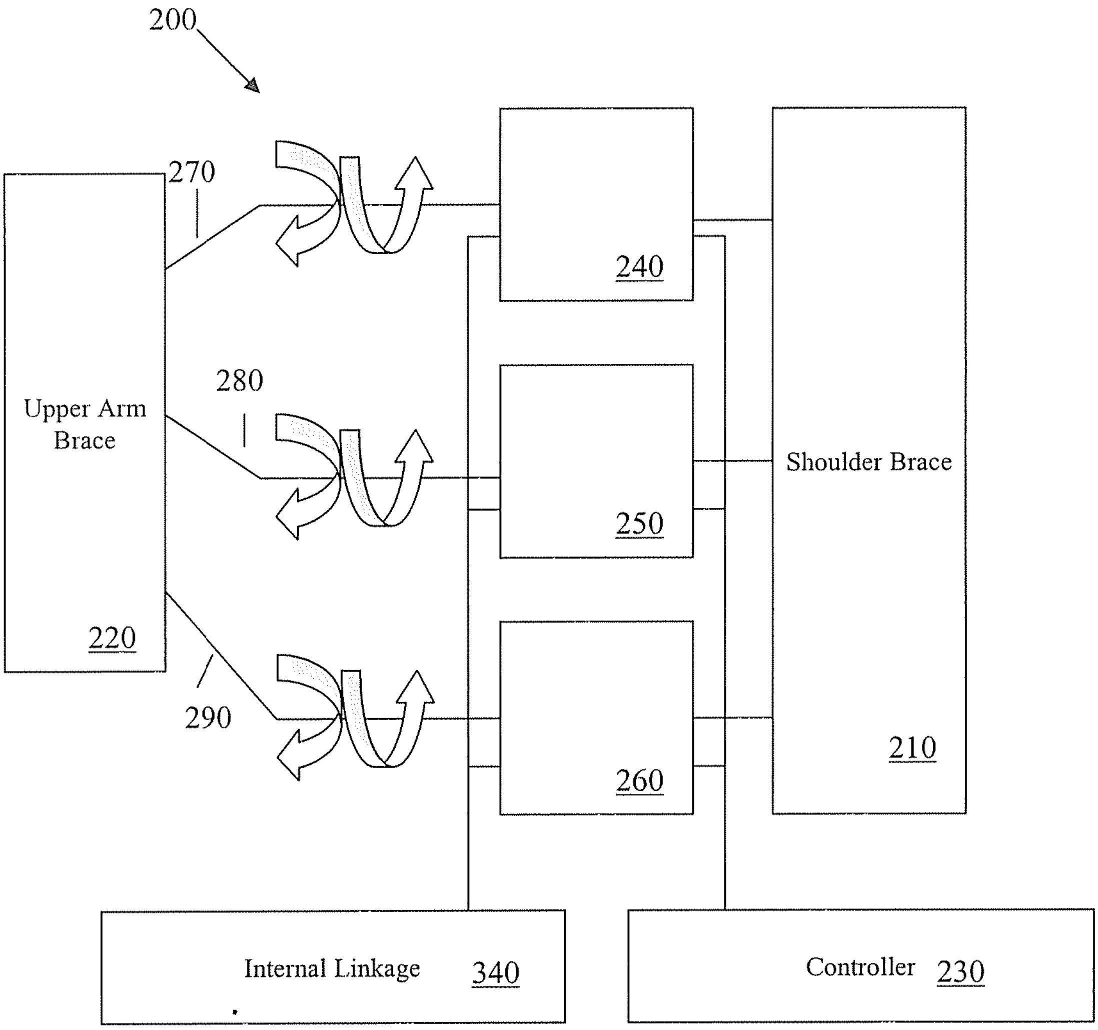

Figure 17

Haptic Exoskeleton
File No. 27211.04283
Inventors: Paul Bosscher, Eric LaFay

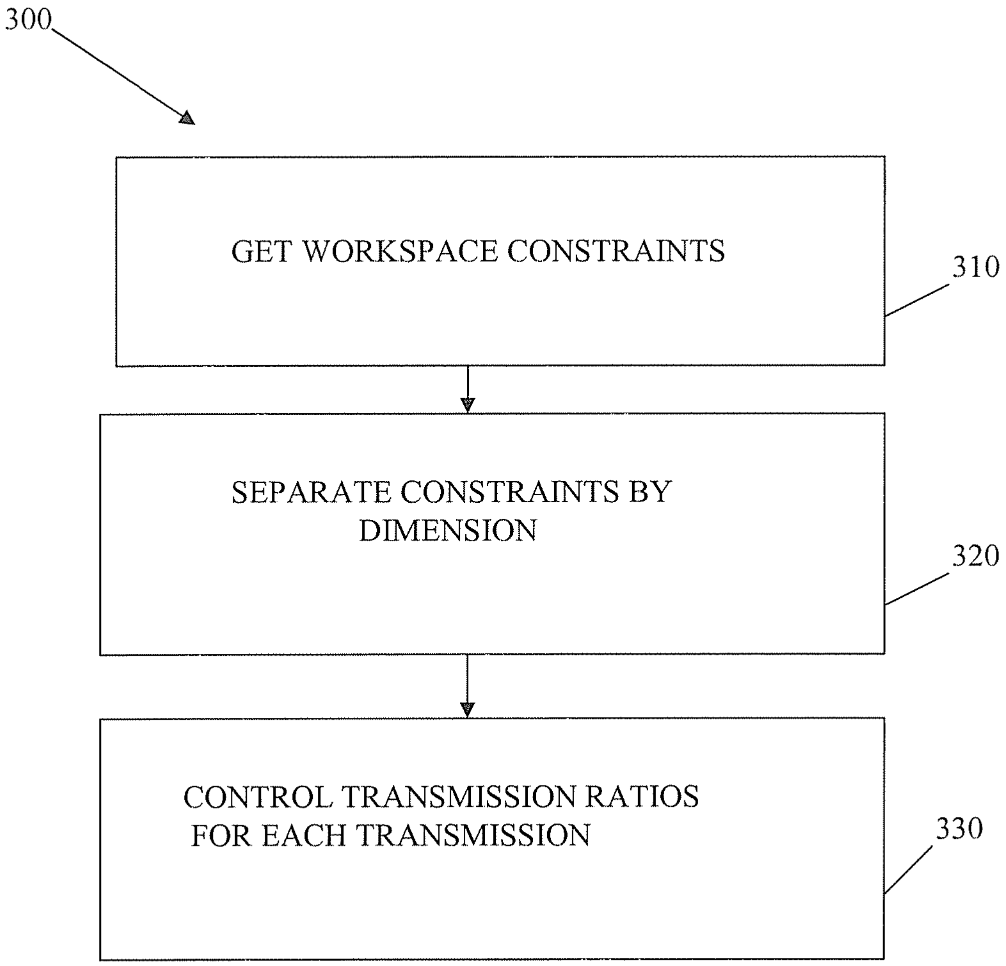

Figure 18