extension **30** of the third element **22** to define a fourth articulation **32** having an axis "D" which is substantially perpendicular to the third axis, C. A fifth free rotary element **34** is mounted on a generally outwardly radially disposed extension **36** of the fourth element **28** to define a fifth articulation **38** having an axis "E" which is substantially perpendicular to the fourth axis, D. Lastly, a sixth free rotary user connection element **40** in the form of a stylus configured to be grasped by a user is mounted on a generally outwardly radially disposed extension **42** of the fifth element **34** to define a sixth articulation **44** having an axis "F" which is substantially perpendicular to the fifth axis, E.

[**0032**] Instead of using mechanical linkages, gears, or other force transmission components, the interface **10** employs three dedicated actuators fitted with capstans and corresponding cables to power rotary axes A-C. Cable drives provide good force transmission characteristics with low weight; however, backlash can be a problem, especially in high precision, high resolution haptic interfaces. Backlash or play in a rotary mechanical transmission, such as those employed in the interface **10**, is most evident when direction of rotation is reversed. One method of reducing backlash is to provide a manual adjustment feature to adjust the position of one or both of the cable ends relative to ground so that slack in the cable can be reduced. Further, the cable can be preloaded in tension so that there is minimal slippage between the cable and the actuator capstan as the capstan rotates. However, as the cable stretches and the components of the mechanism wear over time, cable tension is reduced and must be periodically adjusted to prevent slippage. Additionally, cable tension is difficult to measure and excessive tensioning can lead to deformation of the structural elements and accelerated, premature wear in the articulation bearings.

[**0033**] **FIG. 2A** is a schematic view of an automatic cable tensioning device **46** which overcomes many of the limitations of known cable drives and is useful in the powered axes of the haptic interface **10** in accordance with one embodiment of the present invention. The tensioning device **46** automatically loads the cable to a predetermined tension and maintains that level of tension over time, even in the event of cable stretching and component wear. The tensioning device **46** includes a cable **48** fixed at proximal and distal ends directly or indirectly to a ground surface, shown generally at **50***a*, **50***b*. A non-rotating clutch post **52**, also fixed to ground, is located along the cable path. A spring **54** is disposed along the cable path between the clutch post **52** and ground **50***b*. Lastly, an actuator capstan **56** is provided along the cable path between the clutch post **52** and ground **50***a* on the side opposite the spring **54**. As depicted in **FIG.** 2A, the cable **48** extends from ground **50***a*, circumscribes both the actuator capstan **56** and the clutch post **52** at least once each, and is connected to the spring **54**, which is in tension and connected to ground **50***b*.

[**0034**] A non-rotating post, such as clutch post **52**, may be used to amplify or multiply an applied cable tension to resist or offset tension applied to the cable downstream of the post. As is known by those skilled in the art, the amplification factor is a function of post diameter, wrap angle of the cable around the post, and the coefficient of friction between the cable and the post. Accordingly, for a given spring tension, as wrap angle and/or friction increases, a larger downstream cable forces can be offset or resisted.

[**0035**] In a static state, the tension induced in the cable **48** by the spring **54** causes the cable to be pulled to the right, eliminating any slack or looseness in the cable **48**, cable tension being a function of the spring constant, k, and the linear displacement, x, of the spring ends from a rest state. In operation, as the actuator capstan **56** rotates in a clockwise direction, as depicted, tension is applied to the portion of the cable **48** between the capstan **56** and ground **50***a* and the capstan **56** moves to the left relative to ground **50***a*. Any looseness or slack in the cable to the right of the capstan **56** is automatically taken up by the spring **54**, the cable **48** sliding around the clutch post **52** whenever the spring force overcomes the frictional drag of the cable **48** around the clutch post **52**.

[**0036**] Alternatively, when the capstan **56** rotates in a counter-clockwise direction, the capstan **56** applies tension to the cable portion between the capstan **56** and the clutch post **52**. As long as the spring tension enhanced by the clutch post effect exceeds the tension induced by the capstan **56**, the cable **48** will be effectively locked **48** to the clutch post **52** and will not slip around the post **52**. The spring **46** will be effectively isolated from the capstan loading. Accordingly, the tensioning device **46** automatically self-adjusts and maintains cable tension at a predetermined magnitude, taking up any slack when the capstan **56** rotates in a first direction and locking when the capstan **56** rotates in a second direction.

[**0037**] FIGS. 2B-2E depict several applications of the principles of the tensioning device **46** in the powered axes of the haptic interface **10**. For example, **FIG. 2B** is a schematic plan view of an automatic cable tensioning device **146** employed in the first articulation **16** of the haptic interface **10**. Depicted is a generally circular hub portion of the first element **14**. A cable **148** is fixed to the element **14** at a first ground location **150***a* and circumscribes the element **14** in a clockwise direction. The cable **148** wraps an actuator capstan **156** disposed substantially tangentially to the circumference before wrapping several times around a clutch post **152**. Thereafter, the cable is attached to a spring **154** in tension which is grounded to the element **14** at **150***b*. Since the actuator (not depicted) is fixed in the housing **12** of the interface **10**, as the actuator rotates the capstan **156**, the first element **14** is caused to rotate about first axis A. As may be readily seen, tabs, slots, and other guide features are provided in the element **14** to facilitate routing and retention of the cable **148** in the proper location and orientation throughout the range of motion of the element **14**.

[**0038**] **FIG. 2C** is a schematic plan view of an automatic cable tensioning device **246** employed in the second articulation **20** of the haptic interface **10**. Depicted is a generally circular hub portion of the second element **18**. A cable **248** is fixed to the element **18** at a first ground location **250***a* and circumscribes the element **18** in a counterclockwise direction. The cable **248** wraps an actuator capstan **256** disposed substantially tangentially to the circumference before wrapping several times around a clutch post **252**. Thereafter, the cable is attached to a spring **254** in tension which is grounded to the element **18** at **250***b*. Since the actuator (not depicted) is fixed to the first element **14**, as the actuator rotates the capstan **256**, the second element **18** is caused to rotate about the second axis B.

[**0039**] **FIG. 2D** is a schematic plan view of a first automatic cable tensioning device **346** employed to drive a