the tubular aluminum posts may be eliminated altogether, the molded post in the element being used as the clutch post at the same or a different diameter. The hardness and surface finish of the clutch post may also affect performance of the automatic tensioning device due to wear and resultant changes in the effective coefficient of friction.

[**0058**] As stated above, in order to reduce the cost and size of a cable drive in the haptic interface **10**, while maintaining the desired force reflecting characteristics, it is desirable to use relatively small actuators and capstans to generate the desired torques and forces. By increasing the reduction ratio of a cable drive transmission, the same moment can be provided at an articulation and the same amount of force can be provided at a radially outwardly disposed extension therefrom with less power. Accordingly, cost and design complexity can generally be reduced.

[**0059**] For example, in the case of a single stage cable drive transmission, selected for relatively high efficiency at low cost, where the drive pulley or capstan is bounded by the envelope of the articulation, the radius of the capstan is a fundamental limit on the reduction ratio of the transmission. Accordingly, the smaller the capstan, the more efficient and less costly the cable drive transmission.

[**0060**] As stated hereinabove, conventional metal cables, such as stainless steel cables, fail rapidly at capstan diameter to cable diameter ratios of about 15 or lower. It has been determined, however, that a cable manufactured from tungsten exhibits unexpectedly good drive and life characteristics in this lower ratio range.

[**0061**] According to one embodiment of the invention, the tungsten cable has a nominal braided diameter of 0.015 inches, swaged to a final diameter of about 0.014 inches. Cable construction is 8×19 class, utilizing a 7×7 core wrapped by eight 1×19 filament strands. As known by those skilled in the art, cable or wire rope, as it is sometimes known, is designated by two figures, the first indicating the number of strands and the second, the number of wires or filaments per strand. In this embodiment, each filament is nominal 0.0008 inch diameter tungsten material, such as that used in the manufacture of light bulb filaments. This is a much smaller nominal diameter than that of stainless steel filaments which can usually only be drawn as fine as about 0.003 inches in diameter.

[**0062**] This particular tungsten cable has a nominal breaking strength of about 37 pounds; however, higher breaking strengths have been measured, depending on how the load is applied to the cable. For example, a breaking strength of about 42.5 pounds has been measured by grabbing the cable, and a breaking strength of about 47 pounds measured using a capstan. The cable is available from Alan Baird Industries, located in Hohokus, N.J. as manufacturer's part number ALA8908LD1.

[**0063**] Because the tungsten cable can be manufactured from very small diameter filaments, the cable can be quite flexible so as to tightly wrap small diameter capstans. Capstans used with a tungsten cable may have a minimum diameter less than 0.25 inches at the base of the groove. In one example, the capstan diameter is 0.175 inches at the base of the groove. The above referenced 0.014 inch cable used with a 0.175 inch capstan yields a 12.5:1 ratio. Accordingly, whereas a stainless steel cable shows signs of fraying and wear after some 750,000 cycles, a tungsten cable of the same nominal diameter subjected to the same loading and test conditions exhibits no visible signs of wear after 5,500,000 cycles. Lubrication applied to a cable will decrease fraying and wear of the cable. In one embodiment using tungsten cable, lubrication is not absolutely required, as the tungsten cable contains residual carbon resulting from hydrocarbon lubricant burned during the swaging process.

[**0064**] The tungsten cable can also offer certain advantages over the polymer composition cable discussed hereinabove. For example, the tungsten cable has a nominal breaking strength of 37 pounds, over twice the 17 pound breaking strength of the polymer cable. Further, the cable is relatively stiff in the longitudinal direction. Accordingly, there is near zero hysteresis during use, due in part to the swaging process which imparts a residual stress in the cable. The tungsten cable also is contemplated to exhibit negligible creep over the useful life of the cable, based on observations during the aforementioned cyclic testing.

[**0065**] The tungsten cable also grips clutch posts and capstans securely, due to the surface characteristics of the cable. Accordingly, the cable may be used with or without the grounded capstans discussed hereinabove with respect to **FIGS. 3A and 3B**, as well as with or without metal sleeves on the clutch posts. Also, the cables can be manufactured to accurate lengths, for example within a tolerance of about plus or minus 0.03 inches for a 15 inch cable, for example, by crimping the ends to form loops for attachment to the transmission elements. The tungsten cable is also quite stable at elevated temperatures of 200° F. or higher, which can occur in haptic interfaces.

[**0066**] Accordingly, a tungsten cable can be used advantageously in a haptic interface transmission drive to achieve the benefits of each of standard stainless steel cables and the above described polymer composition cables, without the inherent shortcomings of each. One embodiment uses tungsten cables in the first and second axis drives and a portion of the third axis transfer drive.

[**0067**] Referring now to **FIG. 4**A, depicted is a schematic perspective view of the transfer drive, shown generally at **74**, for powering the third articulation **26** of the haptic interface **10** in accordance with one embodiment of the present invention. **FIG. 4B** is a schematic perspective view of the actuator end of the transfer drive **74** depicted in **FIG. 4**A. Several covers of the haptic interface elements have been removed to expose the components.

[**0068**] Mounted on the first element **14** are second axis actuator **76** and third axis actuator **78**. The first axis actuator is disposed in the housing **12** and cannot be seen in this view; however, the capstan **156** thereof is partially visible. As the capstan of the third axis actuator **78** rotates, the transfer drive element **58** rotates about second axis B, converting rotary motion to linear motion of first and second transfer drive rods **60**, **80** disposed along the radial extension **24** of the second element **18**. As best seen in **FIG. 4**A, the drive rods **60**, **80** terminate in looped braided tungsten or stranded stainless steel cable ends which are hooked onto a raised ground tab of the third element **22**.

[**0069**] Accordingly, the second transfer drive rod **80** is directly grounded through looped cable ends to each of the drive element **58** and the third element **22**; whereas, the first