the crest **160** of the channel **72**. The crest to crest distance (X) should be greater than the cable **558** diameter (Y) by up to about 50 percent. For example, a channel **72** with a trough radius of 0.010 inches nesting a cable with a diameter (Y) of 0.014 inches yields an X dimension 42 percent greater than the cable diameter (Y). Accordingly, at increased loads, the cable may deform slightly and increase surface contact between the cable and the channel. The increased surface contact may obviate the need for a grounded capstan, in which case, the aperture **66** would not be required. In conventional capstans and sheaves, trough radius T_R is no more than about 5% to 10% greater than the radius of the cable.

[0048] Instead of providing a flat **68** on the actuator shaft **64**, a groove may be formed in the capstan bore **62**. Also, instead of capturing the knot **70** inside the bore **62**, a window or other cutout may be provided in the capstan **456** longitudinally spaced from the aperture **66** to provide space for the knot.

[0049] 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. Cables which undergo repeated and severe bending around small diameter capstans or clutch posts, however, must have a high degree of flexibility to prevent premature fraying, breakage, and failure due to fatigue, picking, or other failure mechanisms. For example, conventional steel cables typically require a capstan diameter to cable diameter ratio of about 15 to 50 or more, depending on the diameter of the individual steel fibers used to manufacture the cable and the construction of the cable. While cable tension can be increased to prevent slippage when using insufficiently flexible cables with smaller than recommended capstan diameters, such actions tend merely to accelerate degradation and failure of the cable.

[0050] In additional to flexibility, parameters such as yield strength, elastic modulus, and creep characteristics are important in selecting a cable for use in a haptic interface **10**. Creep, as opposed to elastic stretching, is the relatively slow, permanent plastic deformation of the cable which results from continued exposure to elevated levels of stress. For many materials, creep is exacerbated at increased temperatures. A cable with poor creep strength characteristics will permanently stretch and loosen over time, absent manual or automatic tension compensation.

[0051] The polymer composition cables which can be used in the first and second axis drives and a portion of the third axis transfer drive may be a fused blend of a high modulus polyethylene (HMPE) material and a liquid crystal aromatic polyester-polyarylate (LCAP) material which, in combination, has been shown to exhibit low creep, high strength, and long life.

[0052] Commercially available gel spun HMPE material in filament, fiber, and yarn forms, such as that manufactured by DSM, N.V. located in the Netherlands and sold under the marks Dyneema™ or Fireline™, has a high elastic modulus, but is relatively inflexible and exhibits excessive creep. Accordingly, performance of a cable manufactured solely from this material is compromised when subjected to bending around small diameters or loading over time.

[0053] Alternatively, commercially available LCAP material in similar forms, such as that manufactured by Hoechst Celanese, a division of Hoechst AG located in the Netherlands, and sold under the mark Vectran™, exhibits low creep, but is relatively brittle and prematurely frays after repeated cycling, making a cable manufactured solely from this material generally unsuitable for use in the cable drives discussed hereinabove.

[0054] A polymer composition cable suitable for use in the haptic interface cable drives can be manufactured by twisting or braiding together filaments, fibers, or yarns of HMPE and LCAP and subjecting the composite cable to an elevated temperature in the range of the respective melting points of the two materials for a period of time to at least partially fuse the two materials together. The heated composite cable may also be drawn under tension while at the elevated temperature to more intimately consolidate the two component materials and improve the mechanical properties of the cable once cooled. An example of a suitable manufacturing process is disclosed in U.S. Pat. No. 5,540,990 issued to Cook et al., the disclosure of which is herein incorporated by reference.

[0055] In one embodiment the polymer composite cable may have a composition of between about 20 percent to about 80 percent HMPE, balance LCAP. In a preferred embodiment, the polymer composite cable may have a composition of between about 30 percent to 70 percent HMPE, balance LCAP. In a more preferred embodiment, the polymer composite cable may have a composition between about 40 percent to 60 percent HMPE, balance LCAP. The aforementioned compositions relate solely to the relative amounts of HMPE and LCAP. Other constituents such as coloring agents, fillers, and coatings may be employed to color the resultant cable, provide magnetic or electrical properties, increase wear life, improve performance at elevated temperatures, or enhance fusing during manufacture of the cable.

[0056] In one embodiment, the clutch posts **152**, **252**, and **352** adapted to be used with the polymer composition cable are made of 6061 T-6 aluminum and have an outer diameter of about 3/16 inches. The aluminum posts are tubular, being permanently bonded to posts molded in the respective elements manufactured, for example, from carbon filled polycarbonate. The clutch post **452** wrapped by the stranded stainless steel cable is larger, having an outer diameter of about 0.22 inches due to differences in flexibility of the cable and coefficient of friction between the cable and the clutch post **452** relative to the polymer cable drives.

[0057] Cable tension in each drive is on the order of about 10 pounds force. The polymer composition cable has a nominal diameter of about 0.014 inches with a breaking strength of between about 20 and 30 pounds force, although other sizes with different strengths can be used depending on the application. The cables may be wrapped around respective clutch posts typically between about 1.5 to 4 times. Automatic tensioning spring forces are on the order of about 1 to 4 pounds force. As discussed hereinabove, the number of wraps and spring force can be selected as desired, depending on the anticipated maximum cable tension to be encountered during operation of the actuator, the diameter of the clutch post, and the coefficient of friction between the cable and the clutch post, in accordance with conventionally known mathematical relationships. Additionally, other materials may be used for the clutch posts. In one embodiment,