drive rod **60** is directly grounded through a looped cable end to the third element **22** and indirectly grounded to the drive element **58** through the clutch post **452** and spring **454** depicted in **FIG. 2E**. The drive rods **60**, **80** minimize cable lengths and therefore enhance the stiffness and rigidity of the transfer drive **74**. The cables are used solely at the grounding points, with one cable end of the first drive rod **60** being routed through the automatic cable tensioning device **446** depicted in **FIG. 2E** to substantially eliminate backlash in the third axis drive. The tension achieved with the automatic cable tensioning device also provides added stiffness and rigidity in the drive system.

[**0070**] Referring again to **FIG.** 4B, it can be seen that by nesting the transfer drive **58** and the second element **18** commonly on the second axis B, a significant portion of the mass and weight of the third axis cable drive is supported directly by the first element **14**, instead of being cantilevered out at the end of the extension **24** of the second element. As a result, the imbalance of the second element **18** due to the radial extension **24**, as well as the weight of the third element **22**, fourth element **28**, fifth element **34**, and stylus **40**, can be readily counterbalanced using a circumferentially loaded spring **82** disposed concentrically with the second axis B. A counterweight **164**, rigidly attached to member **18** can be used to assist the spring **82** in counterbalancing those elements which rotate about the second axis B. A counterweight **166**, rigidly attached to transfer drive element **58** moves with element **58** in a manner that counterbalances the motion of remotely located members such as the third element **22**, fourth element **28**, fifth element **34**, and stylus **40** as they move about axis C.

[**0071**] Further, **FIG. 4B** depicts the substantial structural ribbing of the interior portion of the second element **18**, especially the extension **24** thereof. The haptic interface **10** is designed such than the elements themselves provide the structural integrity or skeleton of the interface **10**, rather that having mechanical frames and the like merely encased in cosmetic covers. Accordingly, the skeleton of the interface may be considered as an exoskeleton, with the cable drives, articulation bearings, and other transmission components attached thereto.

[**0072**] Light weight, low cost, high stiffness, and high strength are preferred characteristics for the moveable portions of the haptic interface. For these reasons, injection molded 40% carbon fiber filled nylon or similar compositions may be selected for the structural elements such as second element **18**, second element extension **24**, third element **22**, third element extension **30**, fifth element **34**, and sixth element **40**. Other glass and carbon fiber filled, injection molded plastics may be used as well. Desirable characteristics for the base portion, or housing **12**, of the haptic interface also include low cost, high strength, and high stiffness; however, because the base structure may also serve as a heat sink for the internal electronics, it is desirable that the base structure be significantly thermally conductive. Finally, to avoid the requirement of rigidly attaching the haptic interface to a desktop or otherwise grounded surface, the haptic interface should have enough weight to prevent movement during the application of forces to a user. For these reasons, a plaster cast or die cast zinc material may be used in the construction of the housing **12**. Other suitable materials include cast iron, bronze, and aluminum.

[**0073**] In order to track the location of the powered axes, each of the actuators is fitted with an optical encoder **84** having an encoder disk **86** and an emitter/detector pair **88** as depicted in **FIG. 5**. Instead of conventionally tracking actuator rotation by mounting the encoder disk **86** on a shaft extension extending from the actuator **90** remote from the capstan **456**, the encoder disk **86** is mounted on the actuator shaft **64** using a collar **92** disposed proximate the capstan **456**. Accordingly, the overall volume required for the actuator **90** in the haptic interface **10** can be minimized for a given size actuator **90**. The emitter/detector pair **88** straddles an edge of the disk **86**, outputting pulses as the shaft **64** and disk **86** rotate so that the angular orientation of the powered articulation can be determined.

[**0074**] The haptic interface **10** may include automatic work volume calibration components for use in combination with computer software such that the haptic system, as a whole, has the capability to initialize position of the haptic interface **10** when the system is energized and geometrically center the user reference point in both the workspace volume and virtual or remote environment.

[**0075**] As mentioned hereinabove, each of the actuators for axes A-C includes an encoder **84** for tracking the angular orientation of the first element **14**, second element **18**, and third element **22**. Since the relative encoders, however, provide indications of relative angular rotation, an absolute reference is needed to define a "home" position for each element. As best seen in **FIG.** 4B, the second element **18** includes three axially disposed flags **94***a-c* forming gaps **95***a-c* having different circumferential lengths. As the second element **18** is rotated about axis B, either manually by a user or under system control by the second axis actuator **76**, the flags **94***a-c* and gaps **95***a-c* sequentially pass through an emitter/detector pair **96**. Based on the number of encoder pulses counted during passage of any given flag **94** or gap **95** through the emitter/detector pair **96**, the specific flag **94** or gap **95** and angular orientation of the second element relative to the home position can be determined.

[**0076**] In one embodiment, the first element **14** and second element **18** each have three flags and the third element **22** solely one, due to space constraints. Although one flag or gap is sufficient, a plurality of flags and gaps with different lengths located at several circumferential locations permits determining the absolute angular orientation of the element more readily, with lesser manual or automatic angular rotation of the element being required. The angular location of each of the fourth element **28**, fifth element **34**, and sixth user connection element or stylus **40** about respective axes D-F may be tracked using respective potentiometers.

[**0077**] When the haptic interface system is energized, a user can be directed to manually move the stylus **40** and connected elements through respective ranges of motion within the work volume of the haptic interface **10** to geometrically calibrate the workspace. Alternatively, under control of system software, the three actuators may be used to automatically drive the powered axes through their range of motion to achieve a similar result. In addition, the system may adjust itself through monitoring during normal use to compensate, for example, for system wear or cable stretch. Instead of using an optical emitter/detector pair **96**, other devices such as a microswitch or proximity switch could be used. Alternatively, potentiometers or absolute encoders