[0130] It is expected that the software may evolve into a stimulating "gaming scenario", perhaps associated with some form of "scoring" providing the subject with additional incentives. This is even more important if the subjects are children reorienting the concentration from the rehabilitation aspects to more "fun and games".

[0131] In order to create a realistic training environment for individuals with stroke, 3-D visual feedback is incorporated into the system. We have used a 3-D virtual reality world displayed on a large flat panel monitor, as is seen in **FIG. 9**. The display includes an avatar of the subject's arm and hand providing a direct link from the task to the virtual world. **FIG. 9**, an exemplary display of a VDU screen image, shows a virtual environment comprising a surface (table-top; dark grey), the area delimited by the reach of the individual's arm (wall; red), several targets in the vicinity if the individual's reach (hemispheres; blue), an avatar of the individual's virtual arm consisting of movable joints (hand, elbow, and shoulder, orange) and limb bones (forearm and upper arm; blue-green), the starting position of the hand (hemisphere; light grey), and the track/path of the hand to one of the targets (lines; green). Different colors may be chosen to represent different objects or avatars in the display according to the subject's preference. Subjects with color-blindness may also have a choice of color schemes.

User Interface Software

[0132] With an application programming interface (API), the user creates the virtual model on the haptic server. The real-time operating system on the haptic server interprets the virtual model and generates the trajectories for the robot, based on the force sensor input. The haptic server also incorporates issues like safety guards, communication protocols, and collision detection with virtual objects. In one embodiment, the HAPTICAPI, which is a C++ programming interface, is used by the programmer to define or modify the virtua haptic world via an Ethernet connection to the robot that controls the internal state machine (FCS Control Systems). Through the robotic control, haptic effects can be created (like dampers and springs), and spatial geometric primitives can be defined (like spheres, cones and cubes). Simple virtual worlds can be created using these effects and primitives. When more complex virtual worlds are required, e.g. with meshed surfaces or deformation, another rendering method needs to be applied. A local mass model will be rendered on the haptic server, and the forces acting on this mass due to interaction with the virtual world are rendered from a host computer. When the end effector collides with a virtual object, an appropriate force and displacement are presented to the user. The relationship between force and displacement is given by the object properties of the virtual model (for example, stiffness, damping, friction, or the like). With a penalty-based method, the appropriate relation between force and displacement is calculated by the real-time operating system and incorporated in the position, velocity, and acceleration signal.

Control Algorithm

[0133] The robot uses an admittance control algorithm. A force sensor measures the interaction force between the user and the system. From these forces, a virtual mass model calculates position, velocity, and acceleration (PVA), which an object touched in the virtual world would obtain as a result of the applied force. An example of such an admittance control algorithm is currently used and available in FCS Control Systems' devices (see U.S. Pat. No. 4,398,889 herein incorporated by reference in its entirety).

[0134] The virtual world defines the space in which the object lives (for example, gravity, environmental friction, position of the object, etc.) and the object properties (for example, mass, stiffness, damping, friction, etc.). The virtual mass model will typically contain a mass larger than zero, to avoid commanding infinite accelerations and causing system instabilities. The PVA-vector serves as a reference signal for the robot, realized by a PID servo control servo loop.

[0135] With proper feedback gain settings, this control loop will compensate the real mass of the manipulator up to a factor of six, and terminates its internal friction up to the accuracy of the force sensor. So, if the mass of the manipulator behind the actuator is 15 kg, the operator feels only 2.5 kg at the end effector.

[0136] Since gravity can also be almost eliminated, the perception of the user is that they are moving a mass much less than 2.5 kg. The admittance control algorithm is shown in **FIG. 4**.

Robot Control Software

[0137] The robot control software allows specification of the following features from the user interface:

[0138] a) Inclination angle of the virtual table imposed by the robot arm, which can be varied while exercising the paretic limb.

[0139] b) Virtual environment imposed by the robot: the environment can be made to feel like a hard constraint onto a plane, allowing no movement above or below it with free or guided motion on that plane; or like a one-sided upper or lower constraint. These abilities will allow individuals with stroke to lift their arm from the virtual table with or without a downward "virtual gravity" force and away from the virtual surface.

[0140] c) Virtual objects: generation of mechanical effects when manipulating a virtual object on the plane or addition of the "virtual gravity" force when a subject attempts to lift and move objects of different weights. See U.S. Pat. No. 4,398,889 incorporated herein by reference in its entirety.

Training

[0141] Following an injury to the brain, gravity introduces limitations to a compromised system and restricts arm movements in stereotypical ways. These limitations are associated with the activation of anti-gravity shoulder muscles used to lift the arm, and associated overflow into elbow/wrist and hand flexor muscle activation. This in turn reduces elbow extension capabilities, because it is necessary to overpower the flexion activation in order to reach outward away from the body. Furthermore, flexor activity in the wrist and hand are expected to increase as well resulting in very disabled upper limb. The phenomena of synergies (shoulder abduction involuntarily coupled with elbow/wrist and finger flexion) is seen in a variety of cases of brain injury; it has been most extensively studied in adult hemiparetic stroke, but it is also seen in cerebral palsy (CP) and head trauma. Using a state-of-the-art haptic system such as, but not limited to, the current ACT 3D robot prototype or the like, can investigate how subjects are able to interact in an