Abstract— This paper describes the design and operation of the Multi-Axis Cartesian-based Arm Rehabilitation Machine (MACARM), a new cable (wire) robot for upper limb rehabilitation. The prototype configuration is comprised of an array of 8 motors mounted at the corners of a cubic support frame that provides, via cables, 6 degree of freedom (DOF) control of a centrally located end-effector. A 6 DOF load cell mounted on the end-effector provides force measurement. Given its relatively simple architecture, the MACARM may provide an attractive alternative to serial robots for use in neurorehabilitation.

I. INTRODUCTION

Stroke is the leading cause of long-term disability in developed and developing countries. In the United States, over half of the approximately 750,000 individuals who suffer a new or recurrent stroke each year require physical rehabilitation, with a total direct cost exceeding 5 billion dollars [1,2]. Despite anticipated advances in preventative and acute therapies, the prevalence of stroke-related disability is projected to more than double by mid-century in association with a dramatic increase in the percentage of the population over 65 years of age. In the absence of significant changes in the delivery of rehabilitation services, the additional strain on the health care system is likely to negatively impact the quantity and quality of future care.

The automation of repetitive, labor-intensive aspects of physical rehabilitation has the potential for generating huge cost savings for the health care industry, increasing patient access to therapy, and enhancing functional recovery [3]. In recognition of this potential, several research groups have recently developed, evaluated and in some cases commercialized, advanced robotic systems for neurorehabilitation. With respect to the upper limb, work to date has focused predominately on adaptation or development of serial robots for physical rehabilitation [4-6]. However, cable robots, which actuate a centrally located end-effector via cables attached to a spatial array of motors, have a number of characteristics that make them attractive for use in physical rehabilitation. These attributes include: 1) the potential for large workspaces which may allow training of limb motion within the context of whole body movements; 2) structural efficiency which results in high force capacity relative to device weight; 3) ease of assembly, disassembly, storage and transportation; 4) modularity which facilitates repair or reconfiguration; and 5) economical construction and maintenance. Drawbacks of cable robots include: 1) moderate speed and accuracy; 2) potential interference between the cables and patient; and 3) an irregularly shaped load-dependent workspace.

This paper reports on the development of the Multi-Axis Cartesian-based Arm Rehabilitation Machine (MACARM) – a new cable robot for upper limb rehabilitation. The MACARM is founded on the Multipurpose, Multiaxial Isokinetic Dynamometer (MMID) technology developed by Intelligent Automation, Incorporated (IAI). The MMID technology, originally developed for NASA as a potential exercise system for astronauts onboard the International Space Station, is being adapted and evaluated for use in physical rehabilitation in conjunction with scientists at the Rehabilitation Institute of Chicago (RIC). The mechanical design, operation, and planned testing of the MACARM are detailed in the following sections.

II. MECHANICAL DESIGN

Figure 1 shows the prototype MACARM, configured with eight Active Modules anchored at the corners of a 234 cm (92 in) cube constructed of extruded aluminum tubing. The floor of the device is part of the frame and is raised to allow electrical cabling to pass underneath. The Active Modules generate forces that interact with the end-effector through cables, and in this manner, produce forces that...
interact with the user. It should be noted that depending on the application, greater or lesser number of modules could be used, as well as different end-effector configurations. However, a minimum of \( n + 1 \) cables are required to fully constrain an end-effector with \( n \) degrees of freedom (DOFs).

Each Active Module (Figure 2) consists of a high performance brushless DC motor, a 500 count quadrature encoder, a harmonic gearbox, a cable spool and a cable fairlead. The fairlead assembly allows the 1.6 mm (1/16 in) nylon-coated stainless-steel cable (2100 N (480 lb) load rating) to pivot without mechanically fatiguing as the end-effector is moved throughout the work volume. Each motor assembly is able to produce approximately 310 N (70 lb) of tension at up to 0.5m/s (20 in/s), although it is unlikely that forces this great would be needed in a clinical setting.

The Active Modules are driven from two centrally located Auxiliary Boxes, which contain the power supplies and motor amplifiers. The Power Aux Box houses two 48-volt, 20-amp power supplies (each power supply provides power to four of the Active Modules). The Amplifier Aux Box contains eight motor amplifiers that adjust the current to each of the Active Modules according to the ±10 voltage output from the motor controller. The motor controller is an 8-axis PCI motor controller from Galil Motion Control, which is located inside the control computer.

The cables from each of the Active Modules attach to the corners of a custom designed end-effector in the center of the work volume. The end-effector (Figure 3) for the prototype system is effectively a 0.51m x 0.33m x 0.05m (24in x 13in x 2in) rectangular prism constructed from tube stock to minimize weight. These dimensions were chosen based on computer simulations to provide the largest range of stable translational and rotational motion under the widest range of user-applied forces and moments.

In the original NASA MMID system, forces and moments generated by the user were not measured directly, but were calculated based on the vector summations of force data provided by uniaxial load cells mounted behind the Active Modules. This method of calculating user-applied forces had a number of serious drawbacks that resulted in relatively large (> 10%) inaccuracies in load measurement for some regions of the workspace. For the MACARM, user-applied forces are measured directly with a 6 DOF load cell from JR3, Inc., mounted under the end-effector. Digital data from the load cell are routed to a PCI DSP card in the control computer. Attached to the load cell is either a simple post handle (as seen in Figure 1) or a more advanced gimbaled handle (Figure 3) that allows for free rotation of the patient’s hand during movement. The final configuration of the user interface will be optimized based on the feedback obtained from stroke patients during testing of the device at RIC.

### III. SOFTWARE

The MACARM control software is written in C++ on a Windows XP platform. The software consists of a layered hierarchical design with an asynchronous event subsystem, as depicted in Figure 4. Most of the operator interaction occurs through the Graphical User Interface (GUI) layer, although some inputs (such as handheld e-stop buttons) are input to the lower-level software through the motion control board. The next level down, the Routine Manager, is responsible for accepting commands from the GUI layer, accessing the Routine Database, and assembling Routines in the appropriate form for the Routine Controller to process.

The Routine Controller runs at a fixed interval of 8ms and performs the pseudo-real-time 3D control of the system. It is not truly real-time because a real-time kernel is not used. Instead, the high-speed multimedia timer services of Windows are utilized, which generally has sub-millisecond accuracy. The Routine Controller operates according to the exercises assembled by the Routine Manager and the current state of the system (user-applied force, end-effector position, etc.), and sends commands to the Motion Controller. The End-Effector Configuration block is responsible for performing the mapping from Cartesian to cable length coordinates, and vice versa.

The Motion Controller software block provides an interface to the motion control hardware for the Routine Controller. The Motion Controller block also maintains

Fig 2: Active Module

Fig 3: End Effector and gimbaled handle
information about the current state of each of the axes, what mode each axis is in (torque control, position control, etc.) and other such information. The motion controller hardware (the Galil PCI card) performs the real-time PID control for each of the 8 axes at 1 kHz.

All of the software components, except for the GUI, are written in platform-independent C++ code. The GUI layer of the software was implemented in Visual C++ using Microsoft Foundation Classes (MFC), a set of software classes distributed by Microsoft designed to facilitate GUI implementation on the Windows platform. Real-time data, such as position, velocity, user-applied force and moment, cable length, etc. are displayed on 2D plots using an ActiveX strip chart control. A 3D view of the system during runtime can also be displayed. The MACARM software incorporates the Open Scene Graph library for 3D visualization. Open Scene Graph is an open source library that builds on the OpenGL standard and provides high-level functionality for real-time 3D scene rendering. There is also limited support in the MACARM software for designing new functional routines in a virtual 3D environment. A screen capture of the GUI is shown in Figure 5.

Fig 4: Software Hierarchy

IV. OPERATION

The MACARM uses a very flexible architecture to represent its behavior during runtime. Rather than force one particular way of operating the MACARM, the software allows the operator the flexibility to program its behavior in very simple or very elaborate ways. In the simplest approach, the operator can specify a path (in 6 degrees of freedom) that the end-effector is to follow through the work volume. The path can be any geometric path (such as a line or an arc) or a trained segment (a path input by the operator moving the end-effector by hand). More complex paths can be made by assembling simple paths in a sequence. Paths can also be put in a loop to perform repetitions of motions. Furthermore, additional constraints can be placed on the path motion, such as “only move if the user-applied force is above 10 N”.

The routine types that the MACARM supports are not limited to paths, however. The MACARM can be operated in a bounded free-motion mode, where the end-effector moves according to some basic rules (e.g. move in the direction of user-applied force, move according to joystick input, etc.), but is subject to virtual boundaries. Virtual boundaries can be defined by any geometric surface, such as a plane, sphere, or cone. The MACARM software also makes use of the Open Dynamics Engine (ODE) software library for real-time dynamics simulation. The ODE library is an open-source library that is capable of dynamics simulation, collision detection and collision response. Using this library, the MACARM software can simulate any dynamic environment, with the user interacting with the simulated environment via the end-effector. The virtual environment can contain any number of fixed or moveable objects acting according to the physics rules in place and subject to gravity (or zero-gravity).

The MACARM software and electronics incorporate many levels of safety features. At the lowest level, the maximum allowable torque from the motors can be adjusted via potentiometers on the motor amplifiers. The MACARM software continuously monitors the feedback from the motor controller for error signals. In particular, a large position following error reported by the motion controller can indicate a failure in any of several components in the system. If such a condition is detected, the software will immediately terminate the running routine and remove power from the motor amplifiers.

The software also monitors higher-level trajectory parameters for errors during runtime. If a commanded trajectory attempts to move the end-effector faster than is allowed, the software will terminate the routine. Stability of the end-effector pose (position and orientation) is evaluated in real-time by attempting to solve for a set of cable tensions given a desired pose and measured user-applied forces. At any point in time, the sum of forces and moments at the end-effector can be expressed as a set of linear equations. For the MACARM, there are 6 equations (3 sum-of-force equations and 3 sum-of-moment equations) and 8 unknowns.
(the 8 cable tensions), yielding an underdetermined system of equations. Additional constraints, such as minimum and maximum permissible cable tensions, allow a solution to be obtained using linear programming algorithms. The MACARM software uses the lp_solve library, a freely available library for solving linear programming problems. If a valid solution to the problem can be found, then the commanded end-effector pose is considered stable, and the required movement is permitted. If a valid solution cannot be found, then the pose is considered unstable, and the software does not allow the move. In effect, this creates a 6-dimensional (3 translational and 3 rotational) surface within the work volume that bounds the motion of the end-effector.

V. Evaluation

An extensive series of tests are planned to evaluate the technical performance of the MACARM. Static and dynamic positional performance will be evaluated throughout the workspace and under various conditions of applied loading. Single-axis performance targets for the MACARM are summarized in Table 1.

Work completed to date has focused on determination of the wrench-feasible workspace [7,8] for various assumed load conditions. Preliminary analyses indicate that in the absence of user-applied loading the theoretical workspace for the prototype system is approximately 1.4m x 1.6m x 2.0m (55in x 63in x 79in) in the X, Y and Z (up/down) directions, respectively (either the X or Y axis can be considered the side-to-side direction). The workspace changes shape and contracts with applied loading. For an extreme wrench consisting of 222 N (50 lb) along each axis and 102 Nm (75 ft-lb) about each axis, the shape of the workspace is similar to an ellipsoid of revolution with maximum dimensions of 0.8, 1.0, and 1.4m (31in x 39in x 55in) in the X, Y, and Z directions, respectively. Allowable rotations of the end-effector exceed 0.7 rad (40 deg), depending on the position in the work volume. In principle, however, the frame could be made larger to enlarge the work volume, and either the end-effector could be modified or additional Active Modules could be added to increase the rotational range of motion.

Testing of the MACARM with human subjects (both healthy and stroke-impaired) will be completed in 2006. In the interest of safety, these initial tests will be conducted with the gimbaled handle rather than with 6 DOF control of the limb. The first phase of testing will focus on validation of force and positional performance during use with human subjects, and refinement of the software and hardware based on user feedback. This will be followed by a pilot study (10 subjects) that will capitalize on the MACARM’s versatility to address the difficulty individuals with chronic hemiparesis have integrating reaching with postural support of the limb [9].

![Table 1](image)

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REFERENCES