Control of a Robotic Exercise Machine

by

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INTRODUCTION

Exercise devices provide a means of resisting user applied forces for purposes of improving physical performance. The characteristics of the device include its path of motion and the functional relationship between applied force and ensuing motion. The characteristics of machines have in the past been limited to those achievable with mechanisms whose motions are resisted by passive prings, masses and frictional devices. A great increase in the number practically achievable characteristics is provided by the servo controlled exercise machines of the type discussed in this paper. The benefits, objectives and prototype configuration are briefly described followed by a discussion of the control algorithms used on a prototype machine and the performance obtained.

While practicing coaches, therapists, and exercise physiologists do not agree on all of the aspects desirable in exercise, the following are thought to be desirable by a significant fraction of these people:

1. High resistance exercise is more effective at increasing muscular strength.
2. Exercising a muscle throughout its range of motion is preferred for increasing strength throughout the range.
3. Isolation of muscle groups during exercise increases strength faster.
4. To increase strength in a given motion the exercise should closely resemble that motion.
5. Inertial exercise resistance is not optimal since force throughout the range of motion is not required to complete the exercise.
6. Concentric (motion in the same direction as applied force) and eccentric (motion in the opposite direction of applied force) exercise are both effective in increasing strength. The relative value of each is debated.
7. Movement of a disabled limb powered by external means (therapist or machine) is useful in restoring its function.
8. Incentive is needed to encourage a person to continue exercise.

More detail in the discussion of these issues is found in reference (1) by the authors.

The Robotic Exercise Machine (REM) (U.S. Patent 4,325,437) was designed to enable the above aspects of exercise to be achieved in a versatile manner. The prototype machine has two degrees of freedom enabling motion of an exercise bar in a plane. The two axes are hydraulically powered and servo controlled. The two components of force applied to the bar in the plane of motion are measured and used to compute, via a resistance law, reference position commands to the axis servos. The force measurements are also used to provide the user with a measure of his performance, and to ascertain his strength potential throughout a range of motion and thereby provide an individually taylored resistance. The position of both axes are measured and used for feedback control. A microcomputer coordinates and controls the exercise machine behavior. Figure 1 shows the prototype machine. Additional details are found in the Appendix and references 1 and 2.

ROBOTIC EXERCISE MACHINE OPERATION

The Robotic Exercise Machine (REM) was designed to satisfy the following objectives:

1. Provide constrained paths of motion which are readily adaptable to the individuals needs.
2. Provide new resistance laws including non-inertial and eccentric characteristics.
3. Provide varying exercise resistance characteristics over the path of motion which can be readily adapted to the individual user's strength

ABSTRACT

The control schemes initially employed in a prototype two degree of freedom computerized resistance exercise machine are discussed. The performance obtained from the prototype machine is presented and discussed.

potential.

4. Provide for measurement of user performance for user incentive and progress evaluation.

To understand the control problems later discussed, the various phases of operation must be understood. On startup the machine is in the command mode. A keyboard is provided for modifying the various exercise parameters or for changing to the servo mode. The "Teach" command causes the change to the "servo" mode. In the servo mode the two axes are activated and their position is servoed to a desired position. The desired position is determined by one of five supervisors. The switch between supervisors is determined either on the basis of applied force, bar position, or a keyboard entry. These supervisors enable the user to successively 1. move to an initial point, 2. teach a path beginning at the initial point, 3. return to the initial point along the path, 4. teach the user strength potential along the path, 5. return to the initial point, and 6. exercise.

The manual move supervisor (MMSPV) initially commands the bar to move in the direction of applied force. This enables the user to place the bar in any desired starting position. The change to the Path Teach Supervisor (PTSPV) occurs when forces drop below a prespecified level or, under an option, when a keyboard command is entered. It is marked by a "beep" from the keyboard. Movement under PTSPV occurs as for MMSPV, but the positions of commanded path are stored at 1.27 cm (1/2 in) intervals along the path in an exercise file. When forces again drop to near zero (or the keyboard command is entered) the Return Supervisor (RTSPV) begins to specify the desired position. The initial position commanded is the last point saved under PTSPV. Movement under RTSPV and the remaining supervisors differ from MMSPV and PTSPV in that only the points along the path just taught can be commanded. RTSPV uses force component tangential to the path and commands a position which changes in accordance with the direction and magnitude of the tangential component. Thus the user can move back and forth along the path just taught, checking it for suitability, and eventually returning to the starting point which causes a change to the Force Teach Supervisor (FTSPV). FTSPV waits for a force along the path whereupon motion along the path at a constant tangential velocity is commanded. The average tangential force over each 1/2 inch interval is stored in the exercise file associated with the segment over which it occurred. RTSPV is again called to enable a return to the initial point and the user is ready to exercise. The Exercise Supervisor (EXSPV) commands positions based on tangential forces according to a resistance law. The resistance law used in the prototype is the Non-inertial, Positive, Negative, Speed limited (NPNS) resistance law.

According to NPNS, tangential velocity is specified according to the characteristics in Figure 2. This allows noninertial behavior and provides for concentric and eccentric exercise. The equilibrium for F_E is shifted in proportion to the strength potential at each point on the path to vary resistance. The propotionality constant is user specified. As an option the user can specify that F_E be scaled up or down for the eccentric motion by specifying NC.

DISCUSSION OF CONTROL ALGORITHMS

The control algorithms used in the REM fall into three separate categories: 1. Position servo control, 2. Command generating supervisors, and 3. filtering. These algorithms do not in many cases represent the final answer to the control problems presented by this application but represent a successful prototype demonstration of the concept and a basis for further improvement. To put in perspective some of the control problems experienced, a brief qualitative discussion of some of the dynamic characteristics of the prototype machine is given.

Dynamic Characteristics of Prototype REM

The cantilevered arrangement of the horizontal beam as shown in Figure 1 enabled free user access to the exercise bar. It resulted in massive moving parts (about 90 kg or 200 lb) being used to provide a fairly rigid structure. Significant compliance still appears, much of which occurs in the axis joints and in the stationary structure. Actuators of the "Geroller" type were chosen because of the high torque-low speed operation. Attendant backlash characteristics were minimized by preloading the axis drives. Aerospace quality four way hydraulic servovalves with high ($\sim$ 60 Hz) bandwidth were used.

Position Servo Control

The position servo most effective of those tested was a simple position feedback with a feed-forward velocity command. The feedforward velocity command to the servovalves enabled acceptable speed of response and steady state error with the low closed loop gain needed for stability reasons. The valve commands M_x and M_y were derivative limited forms (discussed later) of M_x' and M_y'. M_x', for example is computed as

$$M_x' = K_{px}(X_c - X) + K_{cx} V_{cx}$$

where

M_x' = valve command (before derivative limiting) for x (horizontal axis.

V_{cx} = velocity command in the x direction

X_c = position command in the x direction (from numerically integrating V_{cx})

X = measured position of x axis

K_{px}, K_{cx} = constant controller gains.

M_y' is computed analagously for the y axis.

Command Generating Supervisors

The command generating supervisors fall into two categories, the unconstrained, or free response mode and constrained or trajectory mode. The interaction between the supervisors and the position servo for these two categories is shown in Figure 3.

For MMSPV and PTSPV the supervisor serves primarily to compute the tangential force and issue proportional velocity commands. The velocity commands are then integrated to yield the force commands which are issued to the position servo. PTSPV additionally samples axis position, selects the first sample which is greater than 1.27 cm (1/2 in.) from the last point stored, and refines that point slightly to reduce numerical errors in later calculations, and stores the result. The important aspects of the unconstrained response is that the low force be smoothly translated into varying positions of the bar. A jerky response is undesirable because this is translated into the stored path. The subjective impression of the user is the most important aspect of performance in all cases.

The remaining supervisors have several features in common due to the constrained path along which commanded trajectories must lie. The position commands, if exactly reproduced, would result in a series of straight line segments called the specified trajectory (ST) connecting the stored position points as shown in Figure 4. The procedure for calculating the position commands in the trajectory mode is described by the following steps. Portions in square brackets are required only in the exercise supervisor EXSPV.

1. Determine the present location relative to the ST. After the nearest ST segment has been found, segment endpoint coordinates [and force parameters] may be looked up in memory.

2. Using the segment endpoint cordinates obtained in step 1 and the current sample of force transducer output signals, compute the component of user-applied force tangent to the ST at the current location.

3. Using the tangential force obtained in step 2 [and the tabular force parameter from step 1,] compute commanded tangential velocity. This step determines the dynamic behavior of the machine as an exercise device.

4. Compute position commands for the servo controller by numerically integrating the tangential velocity command to get a commanded displacement along the ST. From this line integral compute position coordinates lying exactly on a segment of the ST.

Separate features for deceleration near the end of an ST have also been implemented to avoid significant overrun for high speed movements. More detail on the implementation can be found in reference [3].

The supervisors for return (RTSPV), force teach (FTSPV), and exercise (EXSPV) differ primarily in terms of the way the tangential velocity command is computed.

RTSPV computes a tangential velocity command proportional to the tangential force. Upper limits to commanded velocity exist, of course. The response under RTSPV is not critical, but should be smooth and sensitive to fairly low force levels.

FTSPV generates a constant tangential velocity command. The command is initiated when a threshold on tangential force is measured. Tangential force is averaged over each segment of the specified trajectory and stored with the position of the previous stored position point. The criteria of performance under FTSPV is precise tangential velocity and accurate path following.

EXSPV generates tangential velocity commands which are dependent on the exercise resistance law used for example the NPNS law described previously. The parameters of the resistance law vary with position along the specified trajectory. The criteria of performance under EXSPV are accurate tangential velocity (including transients) and path following. As with all the above cases, user "feel" is an important but difficult to quantify measure of performance.

<u>Filtering</u>

Two types of filtering are used to improve REM behavior. An averaging filter is used to smooth data received from the force transducer. The average of 13 samples of the force transducer at 100 samples/sec was used as the force measurement. In addition a derivative limiter, which limits the rate of change of a variable to a maximum was used. The derivative limiter was used on the force measurements and on the valve control signal.

PROTOTYPE PERFORMANCE

With the simple control algorithms implemented to date the dynamic characteristics leave much to be desired. User subjective evaluations have been fairly positive, however.

Figure 5 shows actual bar path during a commanded diagonal straight line motion covering the entire vertical travel and a large fraction of the horizontal travel. While significant variations from a straight line are obvious on the plot, these are not detectable to someone holding the bar. Figure 6 shows the bar's path for a typical exercise motion (a curl), including path teach, return, force teach, and exercise. The substantial variations from the exercise path are suprisingly unoffensive to the user. Deviation is especially large for the return and downward exercise motions when bar velocities become large and path curvature is substantial. Under these conditions the large inertia and low feedback gains result in large position errors.

Filtering of force measurements and commands also severely distorts the idealized NPNS resistance law. Figure 7 shows the measured force/velocity relationship for a horizontal path with a negative coefficient of 60%. The noninertial behavior is not accuately realized, especially for rapid changes in forces which should lead to sudden changes in velocity. These large accelerations are probably undesirable in exercise anyway and are atypical of actual exercise. Deviation from the ideal NPNS resistance law as prrviously shown are due to (1) starting and ending the exercise, (2) inadvertently encountering the end of the stored trajectory during exercise, (3) variation in stored force F_E over the exercise path, (4) discontinuity in the ideal course when changing from positive to negative tangential velocity, (5) "jerkiness" in the bar motions due to stick-slip valve and actuator behavior and (6) filtering of force and valve command signals.

CONCLUSIONS

While the prototype demonstrated the desired concepts much improvement is desirable. Work continues on improved control algorithms. A redesign of the mechanism with improved understanding of the tradeoffs will make the controller design easier.

REFERENCES

1. Book, Wayne, David Ruis, and Russell Polhemus, "Microprocessor Controlled Robotic Exercise Machine for Athletics and Rehabilitation", Proceedings of the 1979 Joint Automatic Control Conference, Denver, Colorado, pp. 771-776.

2. Ruis, David A., Russel, W. Polhemus, and Wayne J. Book, "Robotic Exercise Machine and Method", U.S. Patent 4,235,437, November 25, 1980.

3. Ruis, David A., "Design and Testing of a Microcomputer-Controlled Robotic Exercise Machine for Athletic Training and Rehabilitation", M.S. Thesis School of Mechanical Engineering, Georgia Institute of Technology, March, 1981.

APPENDIX - Prototype REM Specifications

Mechanical

Travel: Horizontal - 1.2 m (4 ft.)
Vertical - 1.7 m (5.5 ft.)

Speed: 1.2 m/s (4 ft/s) maximum

Force: 300 N (700 lbf) maximum

Hydraulic Power Supply: Pressure - 10,340 kPa (1500 psi) maximum

Hydraulic Accumulator: 15ℓ (4 gal.) with 15ℓ (4 gal.) gas bottle with precharge of 5171 kPa (750 psi)

Actuators: Geroller type hydraulic motors

Drive: Redundant chain drives

Electrical

Computer: Texas Instruments 990/4 with 12K words (16 bit)

Position Transducers: Conductive plastic potentiometers

Force Transducers: Semiconductor pressure transducer and bellows

Analog to Digital Converters: 12 bit accuracy with multiplexer speed is 55μ per channel

Digital to Analog Converters: 12 bit accuracy

Sample Rate: 400 Hz

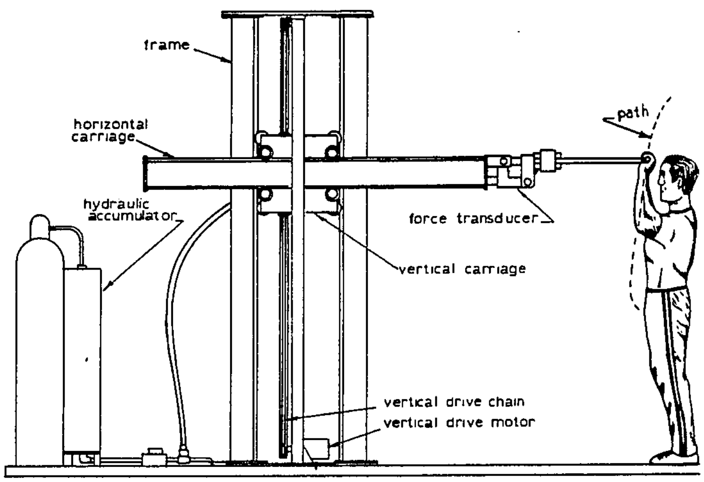

Fig. 1. The Robotic Exercise Machine Prototype Shown in the Plane of Motion.

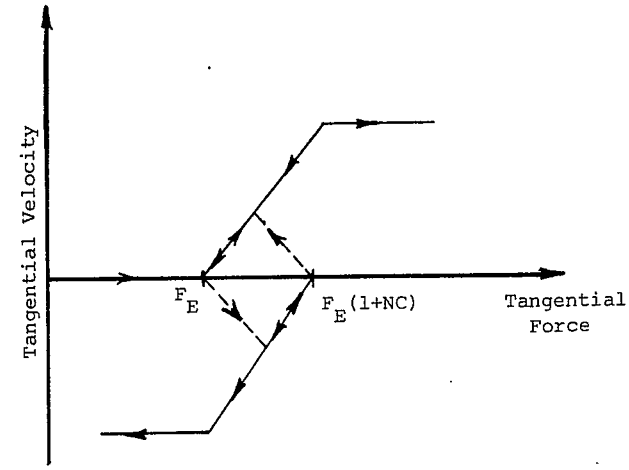

Fig. 2. NPNS Resistance Law with Negative Coefficient NC.

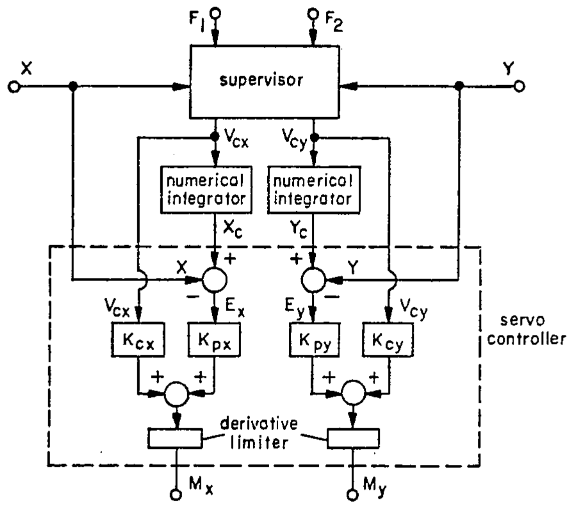

Fig. 3a. Block Diagram of Supervisor and Servo Interaction. Free Response Mode.

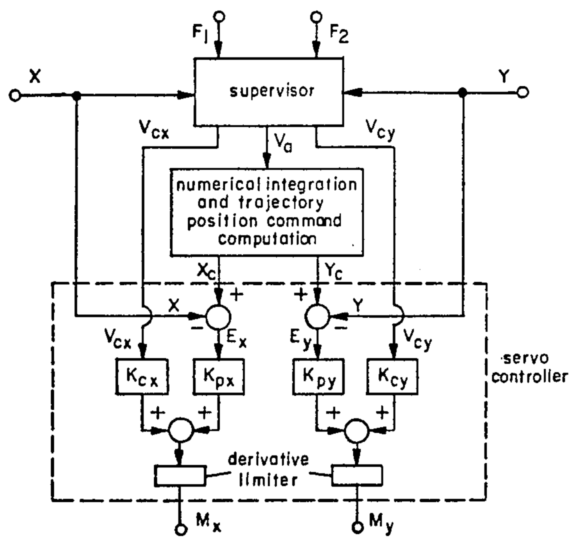

Fig. 3b. Block Diagram of Supervisor and Servo Interaction. Trajectory Mode.

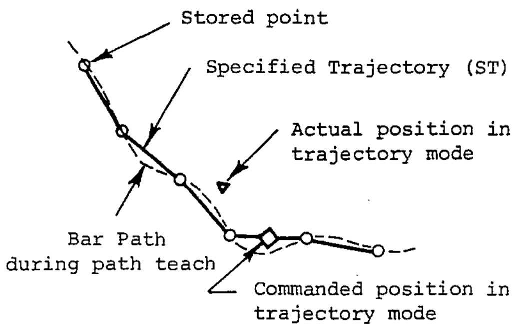

Fig. 4. Specified Trajectory (ST) as Obtained from Bar Path and Stored Points.

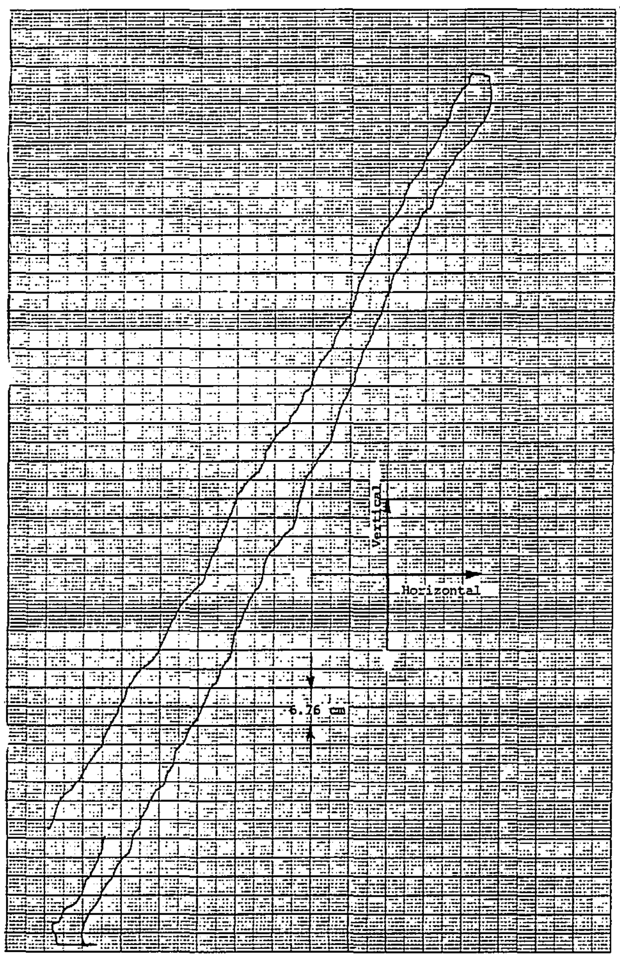

Fig. 5. Bar Path During Parallel Straight Line Commanded Motion.

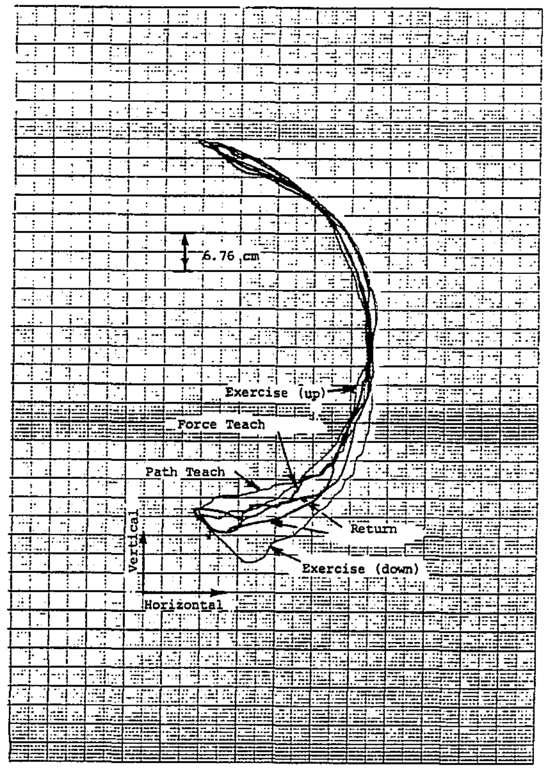

Fig. 6. Actual Bar Motions During All Phases of Curl Exercise.

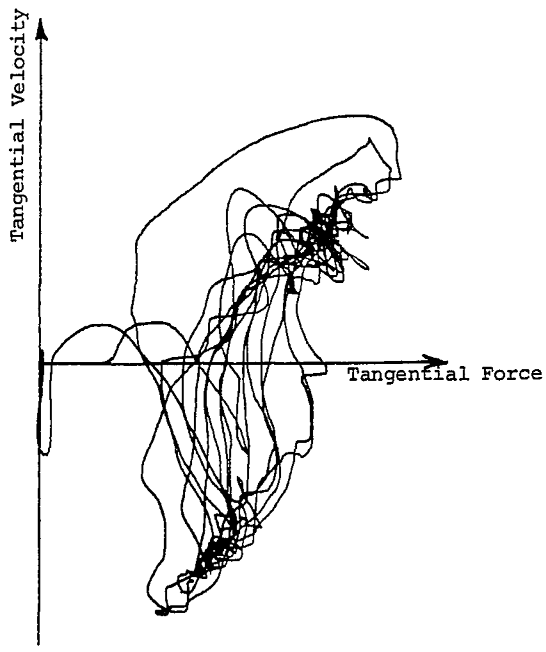

Fig. 7. Actual Measured Resistance Law with NC = 60%.