

put torque, T_{in} , with a sensitivity of G then the resulting signal can be used as the input to a proportional controller. To simplify the analysis of this system it is assumed that the controller electronics can be designed to control motor current. Thus the motor current, i , can be set according to the equation $i = PGT_{in}$ where P is a proportional gain.

If the input mechanism is assumed to have negligible inertia, and the inertia of the mechanism and motor can be lumped into a single value J_o then the equation for torque balance applied at the output is $T_o + J\ddot{\theta} = T_m + T_{in}$. The expression $T_o = J\ddot{\theta}$ can be considered as representing both the force needed to move the mechanism in free space and the force applied during contact with the environment. By substituting for T_m in the above equation the torque gain can be expressed as follows

$$\frac{T_o + J\ddot{\theta}}{T_{in}} = 1 + K_T PG$$

Thus a net gain in torque is possible for the same mechanical advantage allowing the operator's input power to be amplified and applied to the mechanism's output.

Discussion

The variable stiffness spring and the torque amplifier form two component parts for the design of linkages to assist individuals with muscular dystrophy. A demonstrator variable stiffness spring was developed in the rehabilitation robotics group of the Applied Science and Engineering Laboratories and work is in progress to demonstrate a practical torque amplifier. Stability of such systems is a major concern and it is not yet clear what elements lead to instability although work by Colgate et al. [7] tends to indicate the primary concern is when the systems operate at a significant non-linearity such as changing the spring stiffness suddenly over a small distance, or when the

telemanipulator contacts the environment.

Several design criteria will also reflect on the feasibility of this approach. Lightweight components are vital for success to reduce the energy stored in the inertia elements, and likewise non-linearities introduced in the linkage or cables used to transmit power through the mechanism may lead to instabilities.

However providing modular actuation components may result in a flexible, customisable and adaptable approach for the design of simple teleoperator and powered orthoses for rehabilitation applications.

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This equation can be used to determine that the apparent stiffness of the system (once transient effects can be neglected) as $K_{equiv} = PK_T/R$. Thus the mechanism can establish a range of stiffnesses by adjusting P as needed. Further using the Routh - Hurwitz stability criteria the following inequality must hold for stability.

$$D > \frac{LP}{R} - K_g$$

Thus although the apparent stiffness of the mechanism can be set arbitrarily by choosing P , the value of D must also be adjusted to ensure that the system is stable and chosen so that the transient response is acceptable. A disadvantage of this arrangement is that excess power is dissipated as heat in the drive electronics and electric motor.

The effect of mechanical linear series impedance, such as that introduced by the linkage, is not detrimental to the stability of the overall system although it will tend to reduce the level of stabilisation that can be provided for the individual.

Torque amplification

The concept of torque amplification may

have some benefits in rehabilitation product design. A passive system, such as a pulley with mechanical advantage or a lever, can either amplify force or position, but with the proviso that power must be conserved. One advantage of a lever or cable system is that there is a direct connection from the input to the output of the mechanism and a change at the output due to the environment can be experienced by the operator. The concept of a torque amplifier is to permit power amplification from the input to the output of the system while maintaining the input/output relationship.

A mechanical arrangement for a torque amplifier is shown in Figure 2. The purpose of slip clutch is to avoid a non-passive environment applying excessive forces on the individual. This arrangement also protects the individual should the torque amplifier should fail or be switched off. The slip clutch has an additional advantage of allowing limited indexing of the mechanical system.

If the sensor, S_a , measures the person's in-

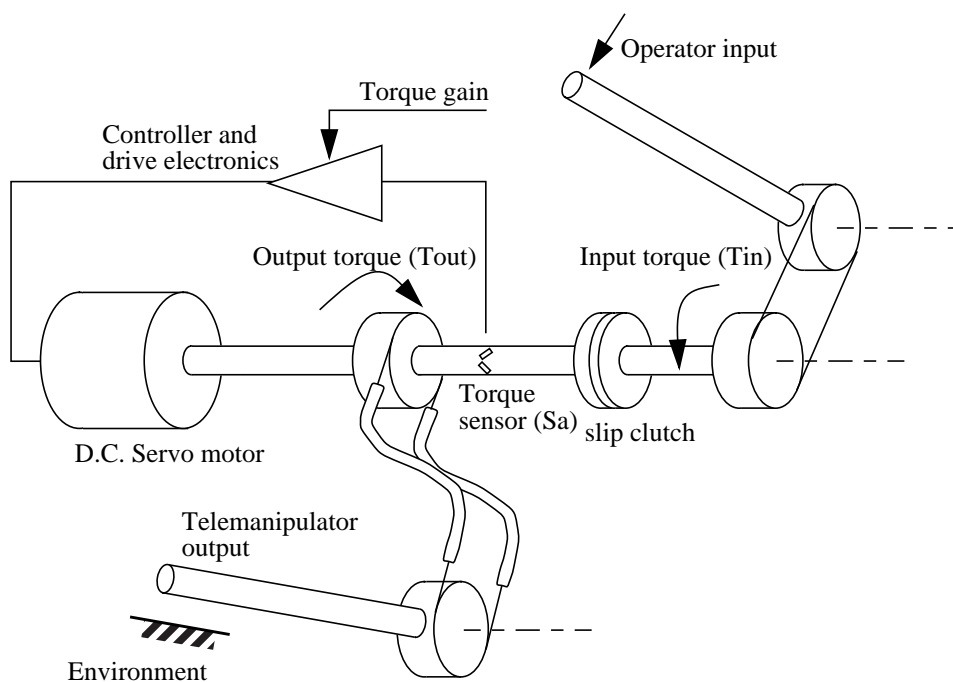


Figure 2. Mechanical configuration for a torque amplifier

Rahman [4] is exploring novel mechanisms to allow head control of a general telemanipulator similar in principle to the Magpie whereas work by Bajcsy et al. [5] is exploring issues relating to the customisation and flexible design of rehabilitation linkages. In both instances the investigators have assumed that the resulting mechanism will be passive with a possibility of adding actuation at a later stage if needed. Similarly an initial approach to the design of a powered orthosis considered a passive approach with the possibility of adding actuation at a later stage [6]. The concept of a variable stiffness impedance makes this approach relatively straight forward.

Position stabilisation for a powered orthosis

For individuals with tremor such as cerebral palsy it may be desirable to stabilise the person's arm in a prescribed region to allow fine manipulation to occur. Likewise individuals with weakened muscles may wish to utilise their arms but have insufficient strength to maintain arm position. In both instances active control of position may provide a means of maintaining position.

A mechanical arrangement for the stabilisation mechanism is detailed in Figure 1. Assuming a model for the D.C. servo motor in the following form:

$$V_{in} = \dot{\theta}K_g + iR + L\frac{di}{dt}$$

$$T_m = iK_g$$

where V_{in} and i are the voltage and current applied to a D.C. motor having a torque constant of K_T , a generator constant of K_g , and an armature resistance and inductance of R and L .

If the output shaft angle θ is measured and used as the input to a PD controller of the form $-V_{in} = P(\theta - \theta_{ref}) + D\dot{\theta}$ the resulting system can be tuned to have a variable impedance.

Assuming the torque imposed on the system by the person or environment is T_{in} and the overall system inertia is J then by Newton-Euler's equation $T_{in} + T_m = J\ddot{\theta}$.

In this equation T_{in} can be considered as the independent variable. By eliminating the intermediate variables i, T_m, V_{in} and converting the equation to the Laplace variable, s , the admittance of the system (the inverse of impedance) can be calculated as

$$\frac{\theta}{T_{in}} = \frac{R + sL}{s^3JL + s^2JR + sK_T(K_g + D) + PK_T}$$

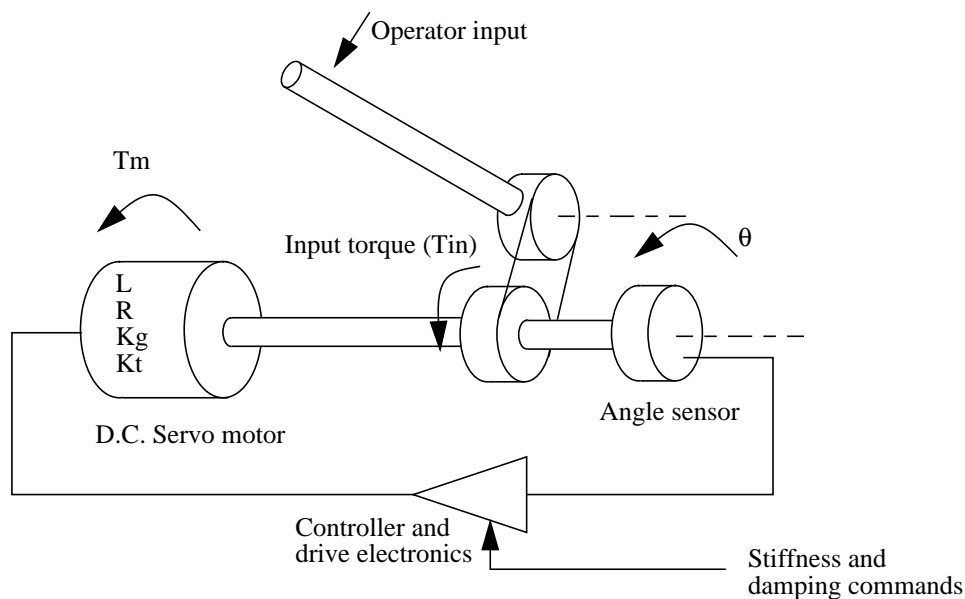


Figure 1. Mechanical arrangement for a variable stiffness impedance

Theoretical Considerations for the Design of Simple Teleoperators and Powered Orthoses

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Abstract

This paper describes theoretical considerations for actuators of a modular system to implement simple telemanipulators and power assisted orthoses. The stability criteria for a variable impedance spring and gain of a torque-amplifier are developed. A successful implementation of such modules could provide a method for the flexible design of linkages to assist individuals who have specific manipulation needs.

Rationale

The application of robotic technology to alleviate problems encountered by individuals with disabilities has yet to demonstrate economic feasibility. Although the cost-benefit considerations are well known it has been difficult to establish the infrastructure to allow widespread use of expensive equipment. Techniques in robotics still have a part to play in assisting individuals with disabilities, particularly people who require assistance with manipulating and controlling elements in a general environment. A recent trend is to use techniques in robotics to design flexible and potentially lower cost linkage systems. Although such systems will be unable to meet the needs of all individuals who experience difficulty with manipulation, these linkages may be a suitable and cost effective solution for individuals who have well defined needs for assistance with manipulation.

Several assumptions are implicit in this approach. The first is that the individual needs

to enhance existing manipulative skills, either by stabilising his or her arms in suitable locations in the environment, or by transferring and amplifying movements from a non traditional body site. The concept of augmenting existing motor skills is not appropriate for certain individuals who would require the robotic systems to respond to commands and operate unsupervised while a task is in progress.

The approach also assumes that the actuator will be based on electric motors and, to keep weight to a minimum, power will be transferred from the human via the actuator to the environment through cables or simple linkages.

Finally it is assumed that the individual has adequate proprioception to be able to utilise the principle of extended physiological proprioception [1]

Background

The costs of robot assistance intended for individuals with disabilities is highly correlated to the number of degrees of freedom[2]. An exception to this trend is the Magpie [3], a foot operated eating assistant, which is entirely mechanical and is optimised to perform a single function - assisting with eating - based on a single input mode - four orthogonal movements of the individual's leg. These two limitations have resulted in a low uptake of this type of manipulation assistance.

The lack of flexibility and the need for customisation is a major weakness in the principle demonstrated by Magpie. Work by