Development of a Low Cost Motion Actuator as an Artificial Joint for the Physically Handicapped Person

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Abstract- Traditionally, actuators for hinge motions are constructed from d.c. motors and reduction gears. This kind of motion actuator is simple to control, but it has a complex mechanical structure, and is it costly, expensive and requires maintenance. In this paper, a low-cost direct-drive motion hinge actuator based on variable reluctance principle has been developed. Variable reluctance actuator has a simple and robust structure, and it is widely used as low cost switching actuator in many applications. However, it has not gain widespread acceptance as a proportional actuator due to its inherent nonlinear control characteristics. In this paper, the problem is overcome by using a novel control strategy based on a nonlinear lookup table. The paper first describes the design, construction, fabrication and operating principle of the variable reluctance actuator. After the variable reluctance actuator has been fabricated, essential electrical and mechanical characteristics are measured. Then, a novel nonlinear control algorithm for the trajectory tracking of this actuator has been proposed. The proposed algorithm is implemented on a digital signal processor to control the motion of variable reluctance actuator in trajectory profile following mode. Results from the implementation show that the variable reluctance actuator can be controlled with high degree of speed and accuracy. This makes the actuator ideal for hinge motions of artificial limbs, and as a motion aid for the physically handicapped person.

Key Words: Variable Reluctance Actuator, Artificial Joint, Nonlinear Control.

1. Introduction

Variable reluctance actuator has a robust and simple structure and its manufacture cost is much lower than similar permanent magnet moving coil device. However, this kind of proportional actuator has not gain widespread acceptance, due to its nonlinear magnetic and electrical characteristics.

A variable reluctance proportional actuator is much more difficult to control than a moving coil actuator. During the past few years there has been a renewed interest in variable reluctance actuators [1], party due to the advancement of high-speed power switches, computing devices, and advanced control algorithms. In spite of these advancements, most publications are predominantly concerned with the velocity control of rotary multi-phase switched reluctance motors [2,3].

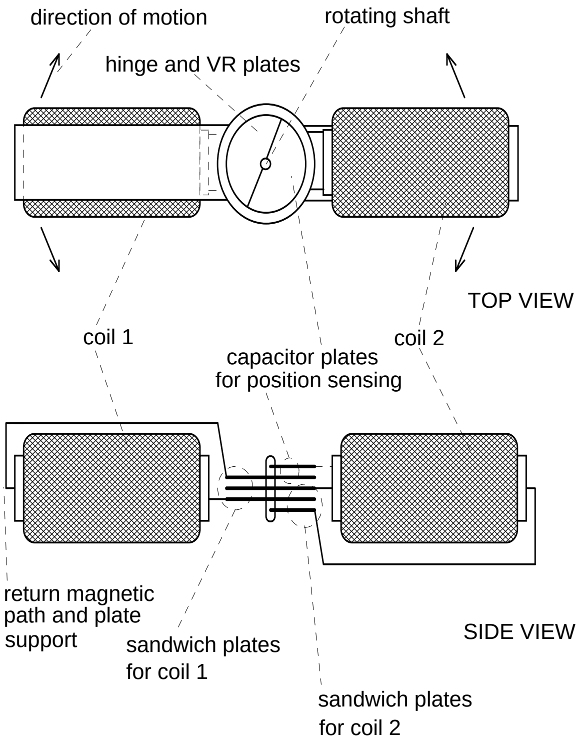

Fig.1 Construction of the Artificial Joint

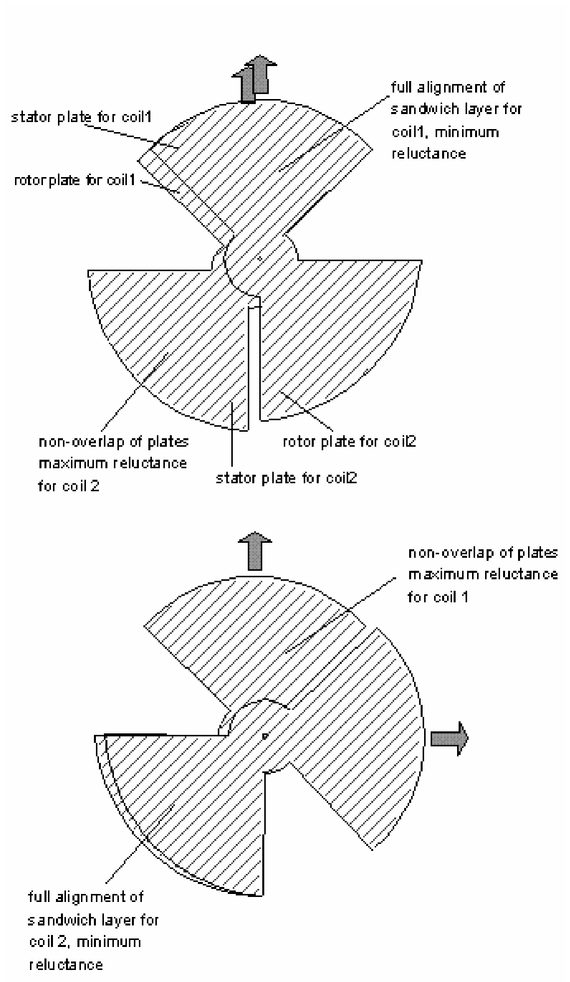

Fig. 2 The Moving Plates of the Artificial Joint

The author has previously conducted some work on the modelling, control, and position estimation of variable reluctance solenoid actuators [4,5,6]. This paper is an extension of the previous work done by the author in the area of motion control for variable reluctance actuators. In this paper, a direct-drive joint actuator based on variable reluctance principle is developed. Sandwich layers iron path construct the magnetic path of the actuator, and two coils are used to energize the actuator. The rotation angle is sensed by another layer of parallel plates, which acts as a variable capacitor. The whole structure is robust, easy to construct, and it does not contain any delicate brushes or permanent magnets.

The variable reluctance joint actuator has been fabricated and tested, and its essential electro-mechanical characteristics have been measured. To provide effective motion and force control for the actuator, a novel nonlinear control strategy has been developed. The developed control algorithm is then implemented on a low cost digital signal processor, which energizes the two coils, and controls the movements of the actuator.

Testing results show that the variable reluctance actuator has a high-speed response with good position accuracy. Comparing with moving voice coils or d.c. motors with reduction gears, the variable reluctance actuator provides equal performance levels, while at the same time gives additional advantages of low cost, simple construction, and robust construction.

Presently only one variable reluctance actuator joint is constructed and studied. However, there is no limitation on the number of joints used for a single application. Three variable reluctance actuators can be stacked to mimic a 3-joint human finger. Due to the small and convenient size of the joint actuators, combining two or more variable reluctance joints in robotics applications can be achieved without substantial modifications.

2. Construction of the Artificial Joint

Fig. 1 is a diagram of the variable reluctance joint actuator. It consists of two coils with sandwiched laminated plates at the centre. The plates act as the motor and the hinge for the variable reluctance actuator. There are two variable reluctance magnetic paths controlled by two coils, each producing torque in the opposite direction. The maximum rotation angle is 90°. In actual practice, the maximum angle of rotation is limited to 80° because the torques produced at the two ends is very irregular.

Fig. 2 shows the operating principle of the variable reluctance actuator. The plates consist of two portions; one portion is responsible for the clockwise torque, while the other portion is responsible for the anti-clockwise torque. Individual coils energise each portion separately. The return magnetic path is machined from annealed "Carpenter 430FR" metal sheet. Note that each portion is designed as a sandwich layer, with a fixed stator on one side, a moving rotor sandwich in the middle, and another magnetic return path plate on the other side, which bears the same shape as the stator.

To provide feedback for the variable reluctance joint actuator, a moving plate variable capacitance is mounted on the top part of the joint actuator. The capacitance forms part of an LC tuning circuit, which provides variable frequencies according to different angular positions of the actuator. The frequency output is then fed into the counter of the Digital Signal Processor. Since the frequency does not vary linearly with position, an interpolated look-up table is employed to convert the frequencies into actual positions. Figure 3 shows the construction of the position interface circuit.

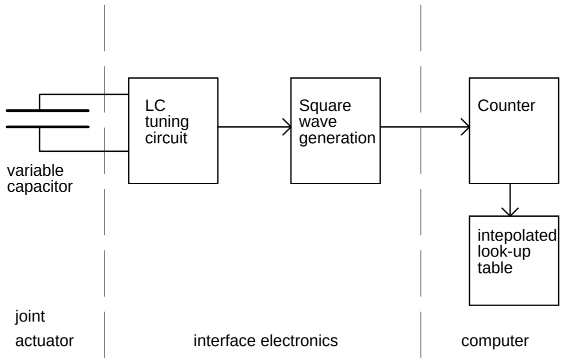

Fig. 3 The position interface

3. The Control Characteristics of the Joint Actuator

Unlike, d.c. voice coil actuator, the variable reluctance joint actuator's characteristics is highly dependent on the nonlinear behaviour of its magnetic circuit. Before effective control of the variable reluctance joint actuator can be achieved, a study on the actuator's magnetic flux behaviour is required.

The voltage equation of the actuator can be written as:

$$V = Ri + \frac{d\lambda}{dt} \qquad (1)$$

where V is the voltage applied to the coil. R, i, and λ are coil resistance, current of coil, and flux linkage respectively. Since λ is dependent on current of the coil and the angle of alignment θ, (1) can be expanded as:

$$V = Ri + \frac{\partial\lambda(\theta,i)}{\partial i}\cdot\frac{di}{dt} + \frac{\partial\lambda(\theta,i)}{\partial\theta}\cdot\frac{d\theta}{dt} \qquad (2)$$

On the mechanical side, the variable reluctance joint actuator can be represented by a second order system:

$$I\ddot{\theta} = T - K_s\theta \qquad (3)$$

K_S is the torque constant produced by the spring on that particular attachment location, T and I are the torque and inertia of the actuator.

The torque produced by the moving element can be calculated from the co-energy W' of the actuator, as (4) below:

$$T = \frac{\partial W'(\theta,i)}{\partial\theta} \quad \text{and} \quad W'(\theta,i) = \int_o^i \lambda(\theta,i)\,di \qquad (4)$$

From (4) the instantaneous torque can be rewritten as:

$$T = \frac{\partial\lambda(\theta,i)}{\partial\theta}\cdot i \qquad (5)$$

From (1)-(5), a set of state equations can be formed:

$$\frac{dx}{dt} = v \qquad (6)$$

$$\frac{dv}{dt} = T(\theta,i) - K_s\theta \qquad (7)$$

$$\frac{di}{dt} = \left(V - Ri - E(\theta,i)\cdot\frac{d\theta}{dt}\right)\cdot L(\theta,i)^{-1} \qquad (8)$$

where $E(\theta,i)$ and $L(\theta,i)$ are the back e.m.f. constant and the incremental inductance of the actuator, and are expressed as:

$$E(\theta,i) = \frac{\partial(\theta,i)}{\partial\theta} \quad \text{and} \quad L(\theta,i) = \frac{\partial(\theta,i)}{\partial i} \qquad (9)$$

Note that equations (1) to (9) apply to both the coils and their magnetic circuits. Also, there is no inter-coupling between the two magnetic circuits. Each magnetic circuit is responsible to produce one direction of rotational torque.

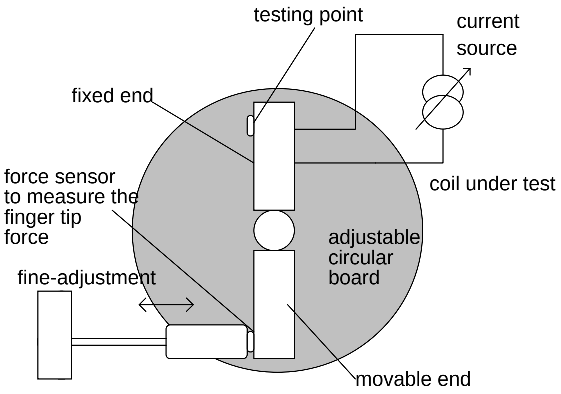

Fig.4 Setup for the measurement of static force

To determine the torque $T(\theta, i)$ of the joint actuator at different angles and currents, a special set-up, shown in figure 4, is used to measure the static force of the joint actuator versus its angular-position and current. This result is used in a current look-up table to control the motion of the joint actuator. Figure 5 shows the measured force at the testing point vs current and angular position.

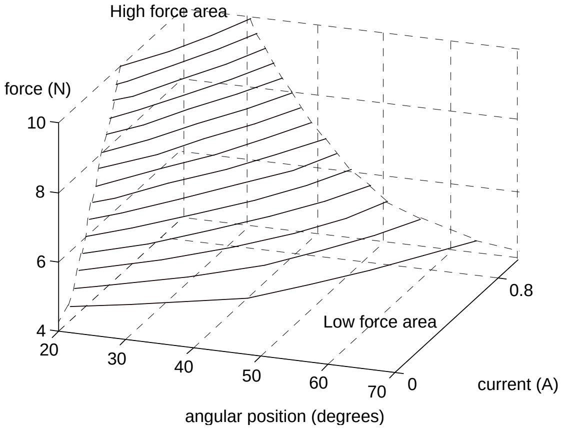

Fig. 5 The force profile

The incremental inductance $L(\theta,i)$ of the joint actuator at various angles and currents are obtained from the phase differences between currents and voltages measurements of the actuator. The measurement setup is similar to the measurement of the static force described in the previous page. The only differences are (i) clampers are used to station the moving element during the measurements, and (ii) a d.c. biased a.c. voltage is fed to the coil, to provide an a.c. signal with d.c. current offset.

4. Controlling the Joint Actuator

There is little in recent literature that deals with proportional control of joint actuators. For the related problem of rotary switched reluctance motors, M. Illic-Spong *et al* [7,8] used feedback linearizing technique to tackle the problems of nonlinearity. Though it has produced promising results in simulation, the method is too complicated to implement in real time. D.G. Taylor [9] used reduced order composite control for the variable reluctance motor; however, external analogue hardware is required to linearise the current voltage relation of the switched reluctance motor.

Exploiting the fact that the current dynamics is at least an order faster than the mechanical dynamics, this paper proposes a dual rate cascade control approach. A fast inner loop current controller is employed to regulate the current-voltage nonlinearities of actuator, while a slower outer loop trajectory controller is used to control the mechanical dynamics. On top of this, a nonlinear function is included to compensate the nonlinearities of force against current and position. Figure 6 is the overall block diagram of the control system.

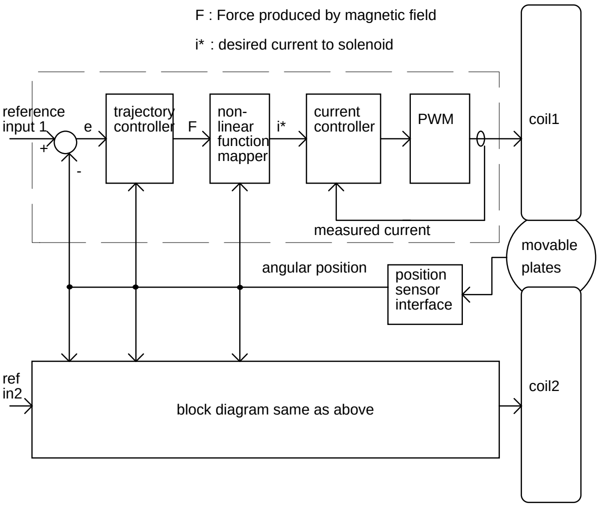

Fig.4 Block diagram of the control system

4.1 The Current Controller

A current controller is employed to linearise the current-voltage relation of the actuator. A simple PI controller is proposed. Position can be assumed to be stationary during the control time frame of the current controller, since current dynamics are much faster than mechanical dynamics. Under normal operation, position change constitutes very little to the overall current control. Thus, a PI controller is sufficient to control an actuator which essentially has a resistive-inductive loading. Standard Ziegler Nichols procedure can be used to tune the controller. Figure 5 shows the worst-case response of the current controller.

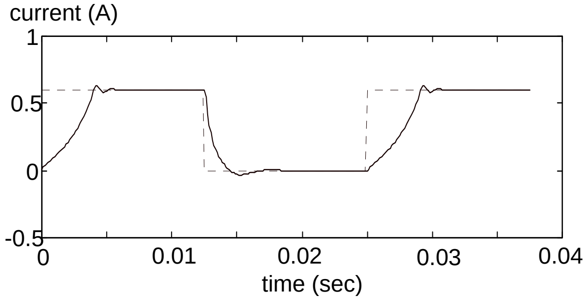

Fig.6 Worst-case response of the current controller (angular position is stationary)

4.2 The Force Look-Up Table

The nonlinear force compensation mapper bridges the link between the trajectory controller and the current controller. It receives force requirements from the trajectory controller and outputs desired current set points to the current controller. As shown in figure 5, the relations of force, current, and angular position are nonlinear in nature; a lookup table is used to translate the force and position inputs to desired current outputs. This information is stored as a two-dimensional look up table. A 20×20 elements look up table with two-dimensional linear interpolation is sufficient to describe the force profile with an accuracy of ±5%.

4.3 The Trajectory Controller

The trajectory controller forms the essential part of the slow sub-system. It is a typical PID controller. The controller's operation is based on the assumption that the current controller has perfect tracking capability, and the non-linear function look-up table generates the linearised current command to the current controller

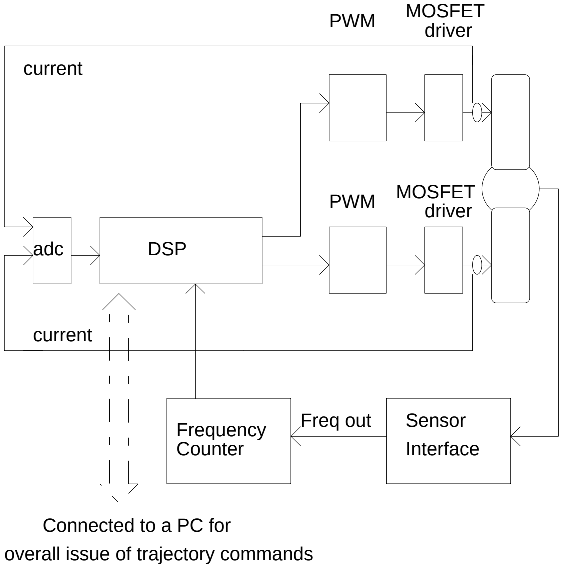

Fig. 7 Overall set-up of the control system

5. Control Implementation

Figure 11 shows the setup of the whole system. A floating-point digital signal processor TMS320C31 is used to implement all the control functions, while a fixed point digital signal processor TMS320C14 is used for PWM waveform generation. The inner current loop has a sampling frequency of 10Khz, and the outer loop samples at 2Khz. The PWM driver has a chopping frequency of 25khz. ±50V is supplied to the PWM driver, which is 2.5 times the normal supply voltage of the original design value. The higher voltage is used to increase the current dynamics of the actuator.

6. Results

Figure 8 shows the result of the trajectory following performance of the variable reluctance joint actuator. As shown in the figure, the actual motion path can follow the command path very closely, and there is no noticeable deviation error. Figure 9 shows the step response of the joint actuator. The step response performance is limited by mass of the moving part and the torque of the actuator. Though there is overshoot, the joint actuator can settle within 0.3 seconds.

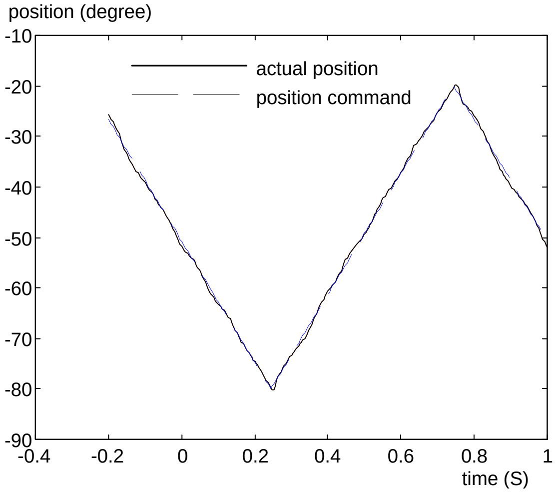

Fig. 8 Actual trajectory following performance

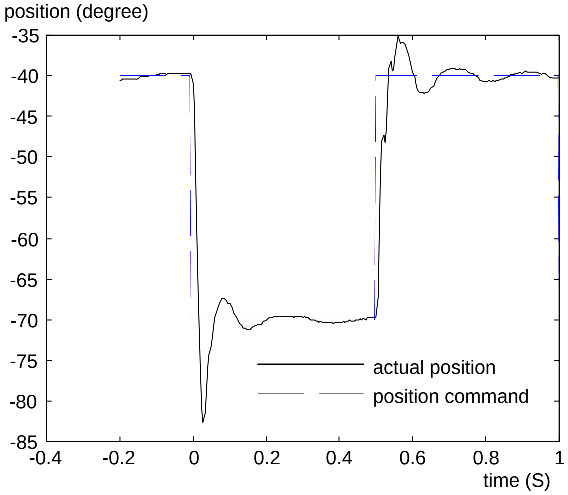

Fig. 9 Actual step response performance

This is already very adequate for the joint motions of artificial finger or wrists. Overall, the performance is adequately fast, stable, and accurate.

7. Conclusion

This paper has presented a novel variable reluctance artificial joint suitable as a motion aid for handicapped people. The actuator has a compact, simple and robust construction. In this investigation project, the actuator has been fabricated, and its electrical and force characteristics have been measured. A novel but simple control algorithm is implemented to drive the actuator. The proposed control algorithm is implemented on a single chip computer to drive the actuator. Preliminary results show that the motion actuator system has reasonably good control and motion characteristics.

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