A Robust and Low-Cost Linear Motion System for Precision Manufacturing Automation

Norbert C. Cheung
Department of Electrical Engineering,
Hong Kong Polytechnic University,
Hunghom, Kowloon,
Hong Kong SAR, China

***Abstract* - Most advanced manufacturing processes require precise linear motion for material transfer, packaging, assembly, and electrical wiring. To achieve precise linear motion, most of these high-performance manufacturing machines use X-Y sliding tables with permanent magnet rotary motors and rotary-to-linear couplers. Though this method is the most widely used, it has disadvantages of low accuracy, complex mechanical adjustments, high cost, and low reliability.**

This paper describes the use of variable reluctance technology to construct a novel linear direct-drive actuator system for high performance motions in manufacturing automation. The proposed actuator has a very simple structure and it can be manufactured easily. There is no need for magnets and no limitation on the travel distance. The actuator is extremely robust and can be used in hostile environment. A novel control method, using cascade control and force linearizing is developed and implemented for precise motion control of the actuator. Preliminary results of the motion system indicate that the system has fast response with good accuracy.

I. INTRODUCTION

Variable reluctance motor has never been a popular choice for high precision and high-speed motion actuator; because it is difficult to control and its output has high torque ripples. This is due to the fact that the actuator's characteristic is highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control. There is little in recent literature which concerns with high performance motion control of variable reluctance linear drive systems. It was only until recent years which we see a general surge of interest in the variable reluctance motor [1]. This was mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through advance control strategy".

The purpose of the project is to develop a novel, high performance, direct drive, and linear motion actuator system for precision manufacturing applications. The actuator is based on doubly salient variable reluctance technology [2]. The linear direct-drive actuator has a simple and robust structure with low inertia and direct drive capability, and is particularly suitable for high precision and high speed manufacturing machinery. Manufacturing of the actuator is simple, and it is suitable for precision travel over long distances. Unlike other types of motion actuators, mechanical couplings, lead screws, magnets, and brushes are not required in variable reluctance linear actuator [3]. Special mechanical adjustments or alignments are also not necessary. Comparing to permanent magnet linear motor, the proposed actuator has a much simpler structure and is less expensive. It is also more robust and more fault tolerant, and has less overheating problem.

II. CONSTRUCTION OF THE MOTION ACTUATOR

Figure 1 shows the appearance of the linear variable reluctance motion system. The variable reluctance linear actuator design is based on a "straightened-out" version of a 6/4-pole rotary switch reluctance motor. 3-phase coil windings are employed in the variable reluctance actuator. The actuator is optimised for (i) high power-to-size ratio, (ii) low force ripple, (iii) low leakage and eddy current loss, and (v) fast current dynamics. The variable reluctance motion actuator has the following characteristics:

Power output:	100W
Travelling distance:	300mm
Maximum Load:	20kg
Position Accuracy:	±25micron
Feedback device:	Optical Encoder
Accuracy of encoder:	1 micron

The motor is integrated on a precision ball bearing slider. A linear optical encoder is mounted on the motion actuator to observe the motion profile and provides the position feedback.

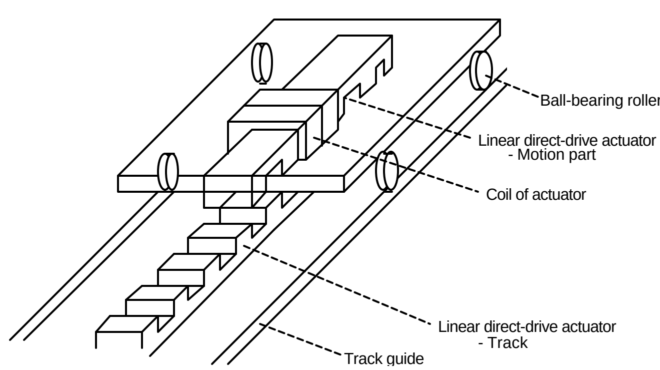

Fig. 1 Construction of the variable reluctance direct-drive linear drive

III MODELLING OF THE VARIABLE RELUCTANCE MOTION ACTUATOR

The variable reluctance linear drive system has a highly non-linear characteristic due its non-linear flux behaviour [4]. Below is the characteristics equation of the variable reluctance actuator:

$$[V_j]_{j=1\sim3} = \left[R_j I_j + \frac{\partial \mathbf{l}_j(x,i)}{\partial x}\frac{dx}{dt} + \frac{\partial \mathbf{l}_j(x,i)}{\partial i}\frac{di_j}{dt} \right]_{j=1\sim3} \quad (1)$$

$$F = \sum_{1}^{3} \frac{\partial \mathbf{l}_j(x,i)}{\partial x} i_j \quad (2)$$

$$F_{overall} = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + F \quad (3)$$

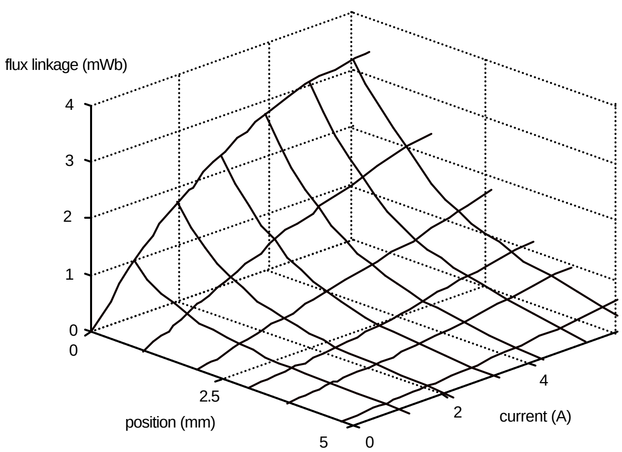

Fig. 2 Variation of flux linkage with current and position

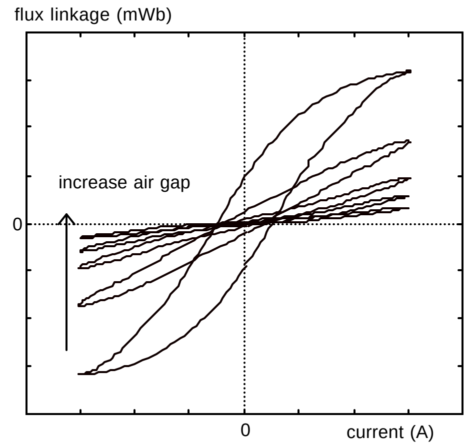

Fig. 3 Variation of hysteresis loop with air gap distance

Note that, in the above equation, the flux linkage has a nonlinear relation with current and position as shown in figure 2.

In addition to the nonlinearities of the flux linkage characteristics, the variable reluctance linear motor also suffers from hysteresis problems. As shown in figure 3, the area of the hysteresis loop varies according to air gap distance. The area of the loop is at its maximum when there is full alignment on the variable reluctance linear motor; it gradually changes its shape and decreases its area as the air gap increases.

Due to the irregular nonlinearities of the variable reluctance actuator, there is no generic scheme for the driving of the variable reluctance direct drive linear actuator. A novel driving scheme for linear actuator that has high speed, high accuracy, and low force ripple needs to be developed [5].

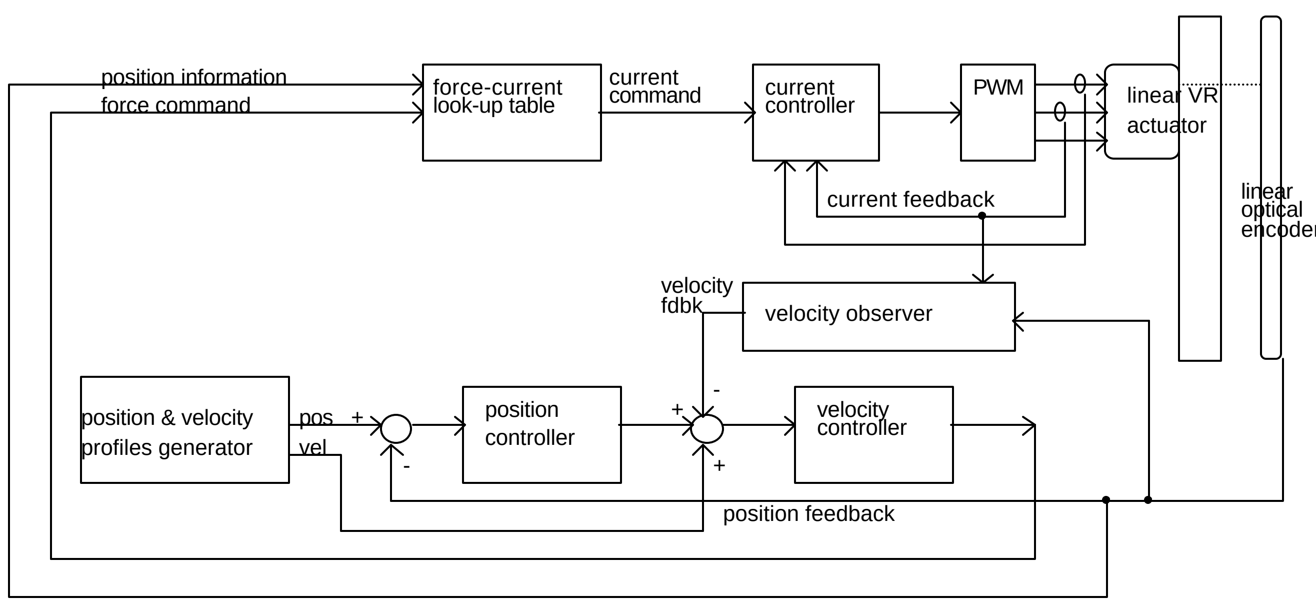

Fig. 4 Overall block diagram of the controller

IV THE CONTROL STRATEGY

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 non-linearity of the actuator, while a slower outer loop trajectory controller is used to control the mechanical dynamics. On top of this, a non-linear function is included to compensate the non-linearity of force against current and position. Figure 4 is the overall block diagram of the control system.

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. The non-linear function bridges the link between the trajectory controller and the current controller. It receives force commands and position information, and outputs desired current set points to the current controller.

The trajectory controller forms the essential part of the slow sub-system. It is a typical PID controller.

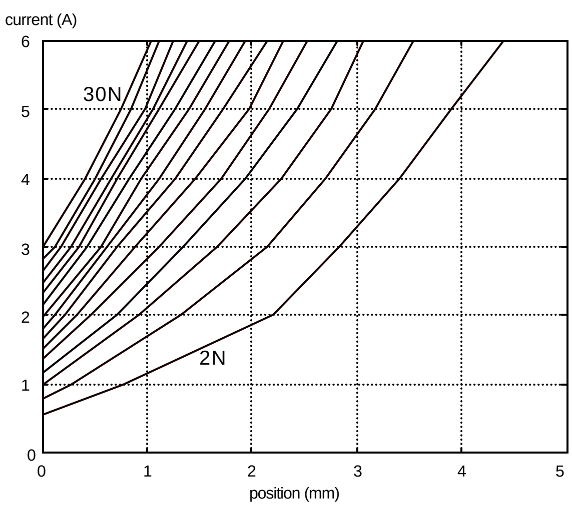

Fig. 5 The force to current look up table

Since the relations of force, current, and position are non-linear in nature, a 3D lookup table is used describe the force profile.

A major factor that influences the operation of the variable reluctance linear actuator is the resolution of the look up table. A higher resolution generally leads to better accuracy. In the implementation of the linear actuator control, it has been found that good continuity and smooth profile between points is more important than the accuracy of the look up table. To implement the force to current mapping by look-up table alone produces "chattering" in the travel of the linear motor, even when the size of the table is fairly large (100× 100 elements).

In this project, a small look-up table (20 x 20 elements, with increments of 0.3A and 1.5N) is employed to store the force compensation values. Two-dimensional linear interpolation is used to find the intermediate values. This produce a 5% worst-case deviation from the original nonlinear function and the output values always follow a smooth profile. Such an arrangement provides adequate description of inverse force function for the variable reluctance linear motor.

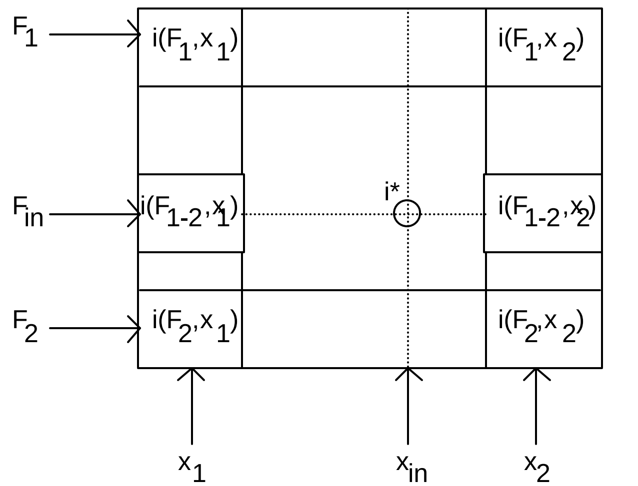

Fig. 6 Calculating *i** from the look-up table

Figure 6 shows the method of obtaining the required current i^* by bi-linear interpolation. Firstly, from the position x_{in} and force F_{in} inputs, two pairs of data in the look-up table $i(F_1,x_1)$, $i(F_2,x_1)$ and $i(F_1,x_2)$, $i(F_2,x_2)$ are located. For each pair, a linear interpolation is done, according to the ratio of F_1, F_2, and F_{in}. As a result two intermediate elements $i(F_{1-2},x_1)$ and $i(F_{1-2},x_1)$ are obtained. Finally, the output current command i^* is obtained by interpolating the two intermediate elements with x_1, x_2, and x_{in}.

The controller's operation is based on the assumption that the current controller has perfect tracking capability, and the non-linear force to current look up table generates the linearised current command to the current controller.

V. IMPLEMENTATION

The controller is implemented on a Digital Signal Processor based system. Figure 7 shows the set-up of the whole system. The Pentium II computer is used for program development and motion monitor during the real time execution.

The variable reluctance linear motor used in this project has a mechanical resonant frequency of about 250hz. When it is attached to the linear encoder and the dummy load, its resonant frequency decreases to 220hz. Due to this, a position controller with a sampling frequency of 1Khz was selected. This is more than adequate to accommodate the mechanical resonance of the variable reluctance linear motor. To ensure that the current loop is significantly faster than the position loop, a sampling frequency of 4Khz was used.

A Digital Signal Processor board, plugged into an ISA bus of a Pentium II computer, performs all control functions. The TMS320C31 Digital Signal Processor has a processing rate of 33M flops. Four simultaneous triggered Analogue-to-Digital Converters (two 16 bits, and two 14 bits) are included into the processor board. A TMS 320P14 slave fixed-point Digital Signal Processor, which is tightly coupled to the TMS320C31, generates pulse width modulation waveforms.

Note that the present set up is intended for development purpose only. The proposed control scheme can be implemented on a low-cost Digital Signal Processor or even on a micro-controller.

Rather than using a single switching element for the pulse width modulation of individual coil, this project uses three half-bridge IGBT inverters to drive the variable reluctance linear motor. This structure allows bi-directional supply to be applied across the winding and resulting in high dynamic response of the current loop. Since the pulse width modulation driver needs to have a chopping frequency that is substantially higher than the current loop frequency, a chopping frequency of 12.5Khz was selected. A voltage of 90V is employed to supply the three half-bridge IGBTs. The higher voltage ensures that the overall drive system has a better current dynamics.

A cross over protection circuit is used to protect the power supply from short-circuiting. Since the worst-case turn off time for the IGBTs are 3μS, a 5μS delay is introduced to the turn on of the IGBTs. The average voltage applied to the solenoid follows the equation below:

$$\overline{V} = \sigma(+V) + (1-\sigma)(-V) = (2\sigma - 1)V \quad (4)$$

where σ is the duty ratio of the PWM output, and has the range of $0<\sigma<1$.

The two currents through the coils of the variable reluctance linear motor are sensed by two highly sensitive Hall effect elements. Two second-order analogue active filters, with cut off frequencies of 500hz are used to filter out the high frequency components of current sensor.

VI. RESULT

Figures 8, 9, 10, and 11 show the motion performance of the variable reluctance linear drive. Overall, the actuator can follow the command path quite closely. It also shows that the drive system has high stiffness and it can recover from external disturbances quickly.

Figure 8 shows the trajectory path of the actuator for a large distance travel of 125mm. Overall there is very little difference between the command path and the actual trajectory path. There is only a time lag of about 0.05s between the two profiles. The command path is a third order profile; this type of profile limits the maximum amount of acceleration and deceleration.

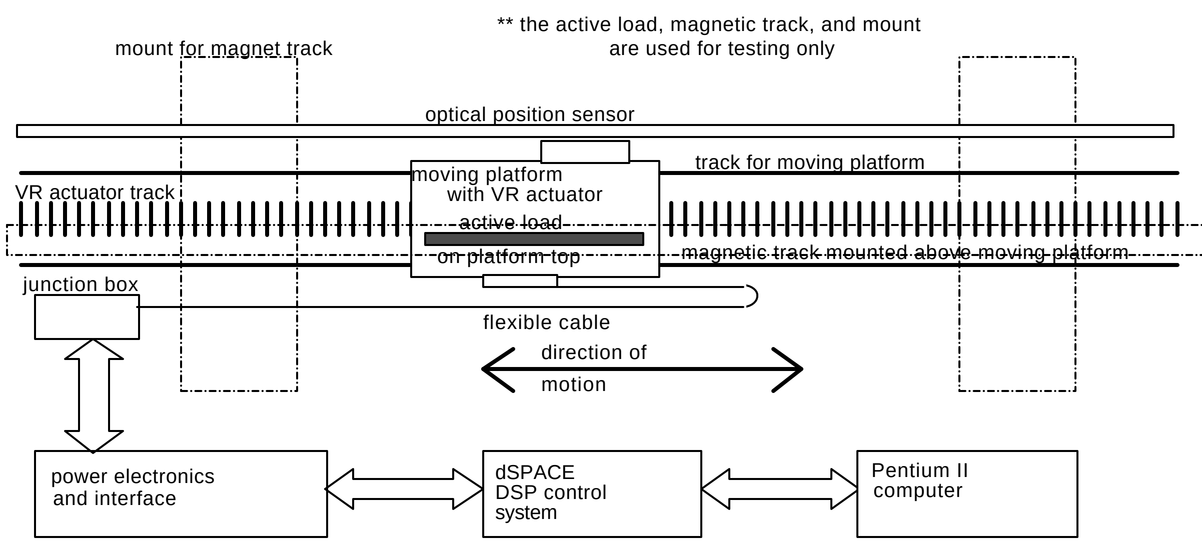

Fig. 7 A overall setup of the linear motion system

Figure 9 shows the trajectory path of the variable reluctance linear actuator for short distance travels. For the trajectory path, the maximum deviation from the command path is less than 25 microns.

The measured result that represents the stiffness of the control system is shown in figure 10. The restoring force acting on the motion platform is measured when it is deviated from its original set point position of 150 mm. The force-position profile is a familiar S-shape curve. There is a large force change around the ±25-micron region, and then the force change becomes more gradual outside this region. The reasonably high stiffness of the system indicates that the system can be controlled to a high degree of accuracy.

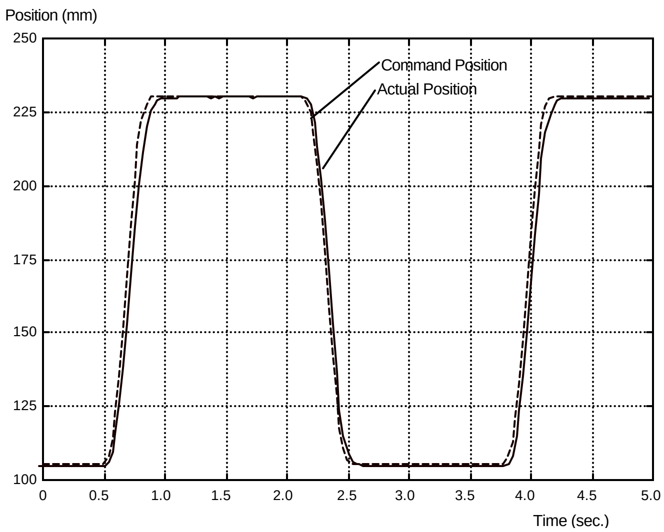

Fig. 8 Trajectory path of the linear drive for large distance travel

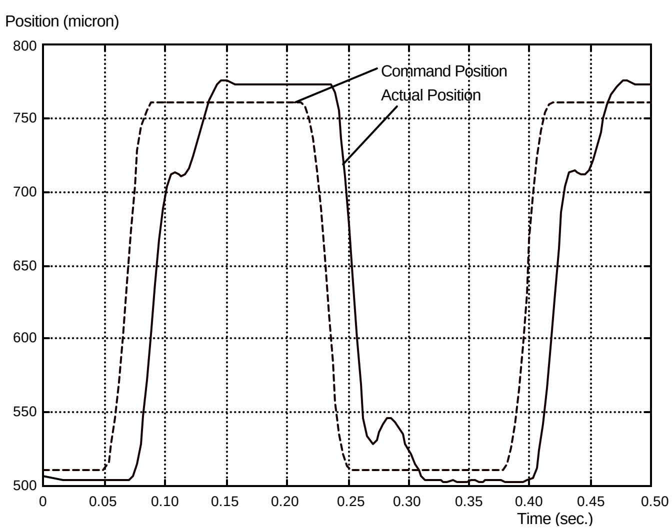

Fig. 9 Trajectory path of the linear drive for small distance travel

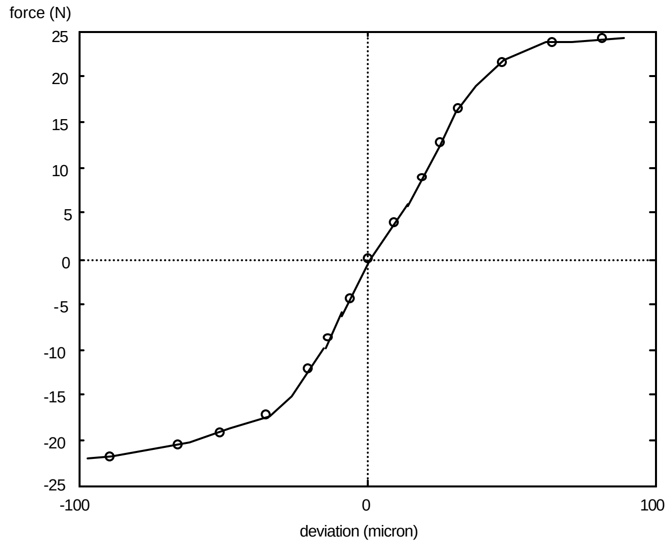

Fig. 10 Stiffness of the control system around a set point of 150 mm

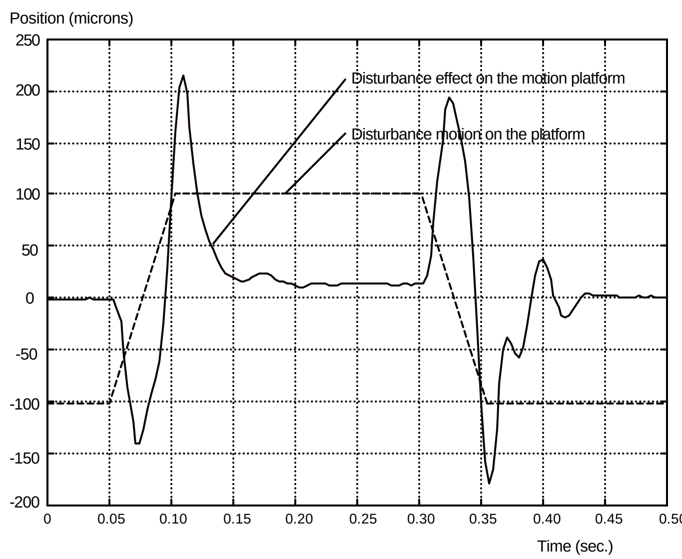

Fig. 11 Recovery from external disturbance

Figure 11 shows the disturbance motion of the moving platform when it is subject to external disturbance. A moving coil actuator, which drives a separate load, is attached to the moving platform of the variable reluctance linear motor. The load is energised to move and its disturbance to the stationary moving platform is recorded. Result shows that the linear motor can quickly recover from external disturbances of both directions (low to high step change and high to low step change). The settling time for the variable reluctance linear motor is within 0.05 seconds.

VII CONCLUSION

The variable reluctance linear motion system described in this paper is robust, reliable and has little mechanical adjustments. Due to its performance and low manufacturing cost, the actuator can be applied to many new and high-end applications which require high precision and high-speed motions. It will also have a tendency to replace many traditional X-Y tables that operate by rotary motors and mechanical lead screws.

The variable reluctance linear drive system uses a simple machine structure but a complex control method. In this paper, an effective control method based on a cascade structure, a non-linear look-up table, and dual rate sampling is proposed and implemented. Preliminary results show that the linear variable reluctance actuator can be operated at high acceleration/deceleration rate with high precision.

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REFERENCES

[1] T.J.E. Miller, "Switched reluctance motor and their control", Magne Physics Publishing and Clarendon Press, Oxford, 1993.

[2] G.S. Buja, M.I. Valla, "Control characteristics of a SRM motor drives - Part II, operation in the saturated region", IEEE Trans. on Industrial Electronics, Vol 41, No 3, p316-325, June 1994.

[3] S. Bolognani, G.S. Buja, M.I. Valla, "Switched reluctance motor performance analysis based on an improved model of its magnetic characteristics", Electrical Machaines and Power Systems, July/August, Vol 19, Iss 4, p425-438, 1991.

[4] M.F. Rahman, N.C. Cheung, K.W. Lim, "Modelling of a nonlinear solenoid towards the development of a proportional actuator", Proc. of the 5th International Conference on Modelling and Simulation of Electrical Machines Convertors and Systems, ELECTRIMACS'96, Saint Nazaire, France, Vol 2, p695-670, Sep 1996.

[5] M.F. Rahman, N.C. Cheung, K.W. Lim, "Converting a switching solenoid to a proportional actuator", Trans. of IEE Japan, Vol I16, Pt D, No 5, p531-537, May 1996.

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