Grasping of Delicate Objects by a Novel Two-Finger Variable Reluctance Gripper

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Abstract – **Variable reluctance (VR) actuator has a simple and robust structure. VR actuator does not have a permanent magnet. It is low-cost, easy-to-manufacture, highly reliable, and can operate in hostile temperatures. However, it is inherently nonlinear, and it is difficult to operate as a proportional device. With the advancement of digital signal processing and power electronic drives in recent years, VR actuators have redrawn research interests.**

The paper describes the position and force control of a novel two-finger gripper using VR technology. Measurement and characterisation of the actuator is carried out. A novel motion and force control algorithm is implemented. The results show that the proposed actuator is suitable for high precision gripping applications.

I. INTRODUCTION

Position / Force control is one of the most fundamental but yet critical task [1]. They can be commonly found in semiconductor industries and factory automation. However, product requirement becomes tremendously demanding, in terms of quality, reliability, throughput, size and cost. This lay pressures to critical motion control axes. Product throughput, quality and reliability have increasingly demanding.

Traditionally, DC motor and voice-coil grippers were employed because they are simple, mature and compact in size [2]. However, with the presence of brushes and permanent magnets, system reliability and robustness are reduced. Besides, these machines tend to be relatively costly.

VR actuator is inherently simple and robust in structure, due to the absence of permanent magnet. It has high-energy conversion efficiency and it is capable to operate in hostile and extreme temperature situations [3]. Nevertheless, the non-linearity caused by its magnetic characteristics has been a major drawback, and has kept it from wide acceptance in industry. With the dramatic increase in the processing power of Digital Signal Processors (DSP) and reduction in price of these components, advanced control algorithm can be employed, and thus VR motors begin to regain interest.

This paper presents a novel two-finger VR gripper. The structure is described in section II. The modelling and the magnetic characterisation of the VR gripper are developed in sections III. A suitable control strategy for the VR gripper is proposed in section IV and V. The proposed control strategy and actual hardware implementation are described in section VI. The results shown in section VII confirmed that the VR gripper is suitable for high performance gripping motions.

II. CONSTRUCTION OF THE MOTION ACTUATOR

Fig. 1 shows the VR Gripper used in the project. It consists of two rotary elements, each attached to a finger. The actuator contains two coils with 400 turn windings each.

The moving rotors are mounted onto two individual shafts, whose axes are normal to the plane of the diagram, so that it may rotate freely between the poles of the stator. Both the rotors and stators are made up of laminated mild steel to reduce eddy current effects.

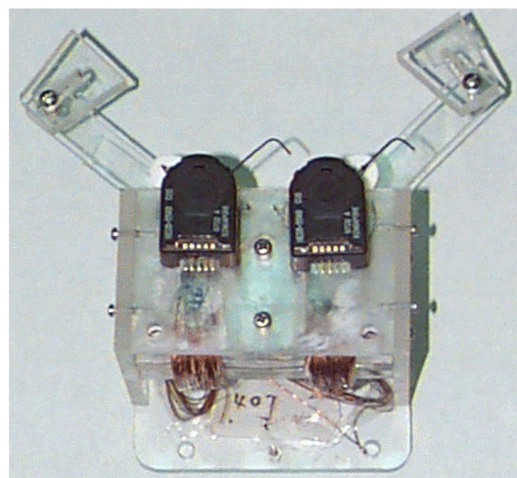

Fig. 1 The VR Finger Gripper

Fig. 2 shows the essential parts of the VR finger gripper. Both fingers (90mm long) are spring loaded, which allows bi-directional movement from the single direction excitation of the coils. When currents are applied to the stator windings, the rotors rotate away from initial positions to reduce their reluctance by alignment torque. The rotors eventually stay still when alignment torque comes into equilibrium with restraining torque provided by the spring. When the fingers rotate by 70°, the fingertips would be closed and the rotors are in fully aligned positions. Incremental rotary encoders are mounted on the shafts to measure rotor positions with a resolution of 0.09°.

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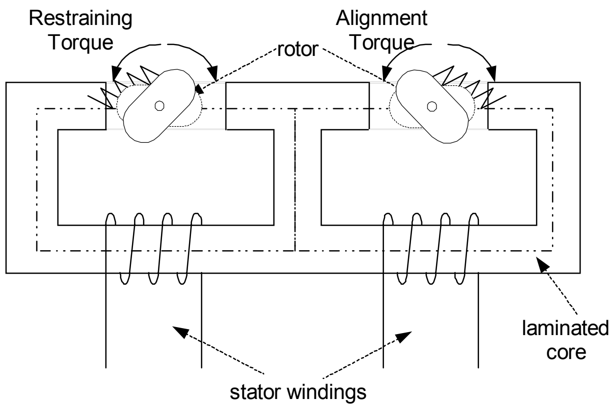

Fig. 2 Essential Parts of the VR Finger Gripper

III. MODELLING

The motor characteristics can be described by Equations (1-2):

$$J_j \frac{d^2\theta_j}{dt^2} = T_j - K_{sj}\theta_j \Big|_{j=1,2} \qquad (1)$$

$$T_1 = \frac{d\lambda_{jj}}{d\theta_j} i_j + \frac{d\lambda_{jk}}{d\theta_j} i_k \Big|_{j=1,2;k=2,1} \qquad (2)$$

where J_j, T_j, K_{sj}, θ_j, λ_{jj}, λ_{jk} and i_j are rotor inertia, motor torque, spring constant, rotor angle, self flux linkage, mutual flux linkage and stator current respectively. With accurate measurement of flux linkage λ and spring constant, i.e. λ_{jj} and λ_{jk}, an accurate model for the VR gripper can be obtained. Flux measurement method has been described in [4].

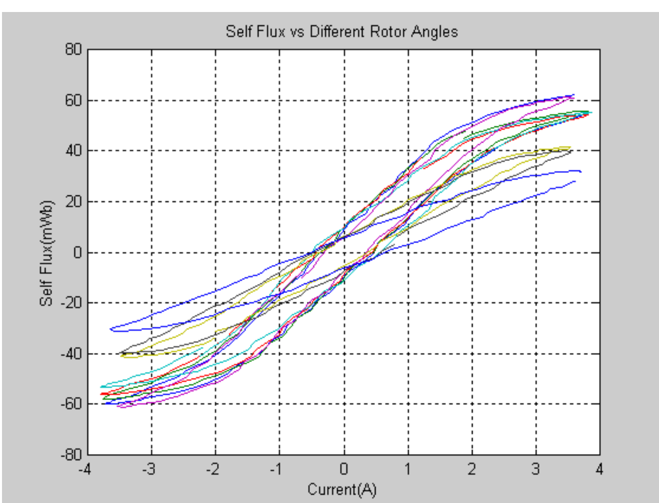

Fig. 3 Self Flux linkage versus different rotor positions

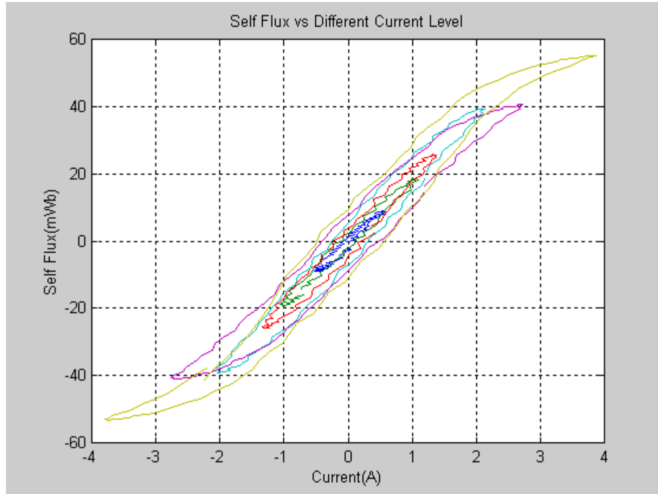

Figure 4. Self Flux linkage versus different current level

Fig. 3-4 show that the flux linkage varies quite significantly with current levels changes, but less so for rotor position changes. The VR gripper stays within the linear region below 2A, and no significant flux saturation is found. An exponential flux model employed is shown as Equation below (3). Then a least square nonlinear two-dimensional surface fitting method is applied to the flux-current chart so that the non-linear function λ can be represented by the following equation:

$$\lambda(\theta, i) = \lambda_s (1 - e^{-f(\theta)i}) \qquad (3)$$

where $f(\theta) = a + b\cos\theta + c\cos 2\theta + d\sin\theta + e\sin 2\theta$, θ is rotor angle and λ_s is a constant, of which the magnitude is equal or greater than the saturation flux of the motor [5].

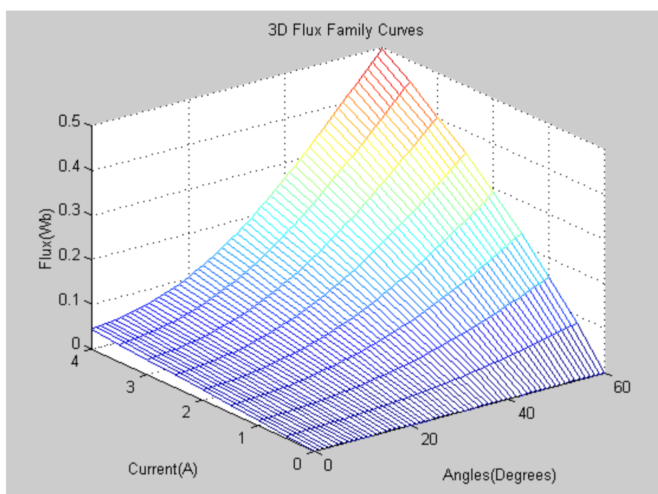

Fig. 5. 3D-Flux linkage profile of VR Gripper

Fig. 5 shows the 3D flux linkage profile, which is constructed by minimizing the sum-square error of its norm. Due to the symmetrical structure of the actuator as the equivalent VR Gripper magnetic circuit representation shown

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in Fig. 6, the excitation currents in gripping motion in both stator windings are assumed to be equal [6].

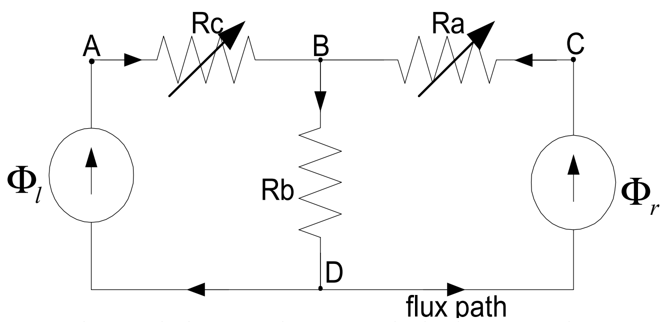

Fig. 6 Equivalent VR Gripper magnetic circuit representation

Thus, the motor force model can be expressed as Equation (4) below.

$$F = \frac{i\lambda \sin(2\theta)}{l} \qquad (4)$$

where F, i, λ, l and θ are motor force at finger tip, excitation current, self flux linkage, finger length and rotor angle [7]. With the experimental data obtained previously, force profile can be constructed from Equation (4) as shown in Fig. 7.

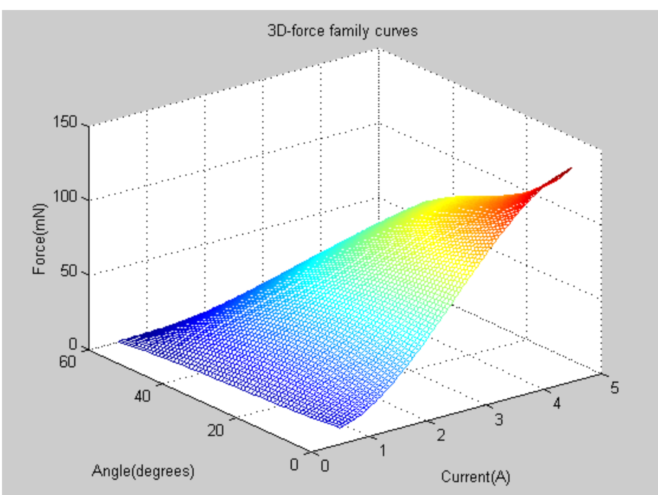

Fig. 7 3D Force profile of VR Gripper

IV. CONTROL STRATEGY

Fig. 8 is the overall block diagram of the control system.

A. *Current Control*

A fast inner loop digital current controller is employed to linearise the current-voltage relation of the actuator with 5kHz sampling rate. An adaptive PI controller is adopted to improve current response [8]. The chopping frequency is set at 24kHz to ensure good current dynamics.

B. *Nonlinear Lookup Table*

The non-linear lookup table 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.

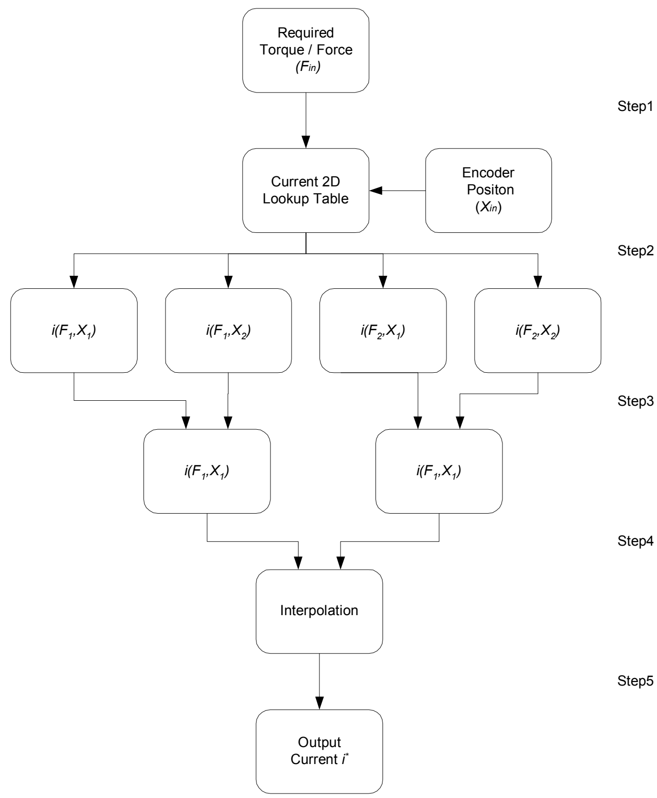

Fig. 9 Flowchart for Calculating i^*

Fig. 9 shows the method of obtaining the required current

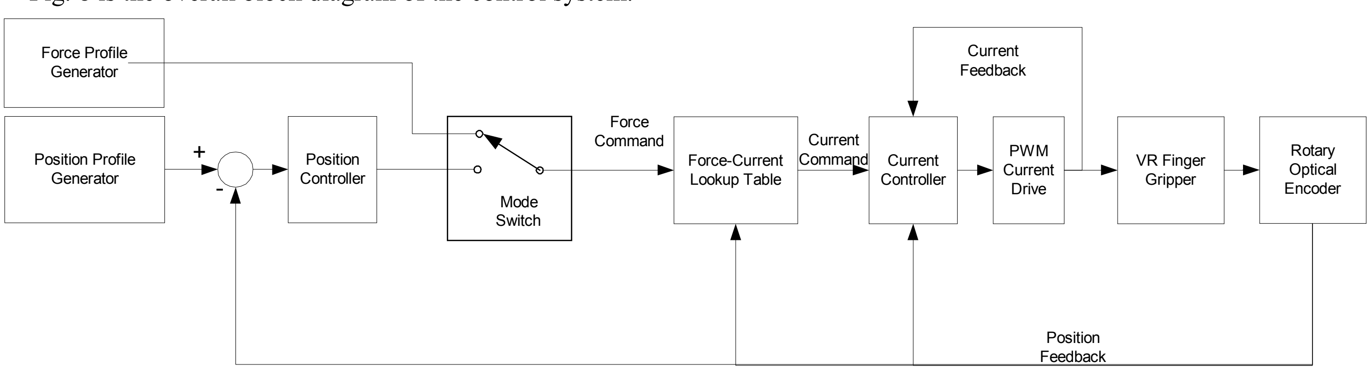

Fig. 8 An overall control block diagram

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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 $i(F_{\equiv\text{-}1},x_1)$, $i(F_{\equiv\text{-}2},x_1)$ and $i(F_{\equiv\text{-}1},x_2)$, $i(F_{\equiv\text{-}2},x_2)$ 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 $i(F_{1\text{-}2},x_1)$ and $i(F_{1\text{-}2},x_2)$ are obtained. Finally, the output current command i^* is obtained by interpolating the two intermediate elements with x_1, x_2, and x_{in}. Fig. 10 shows the linearized current profile of the VR finger gripper.

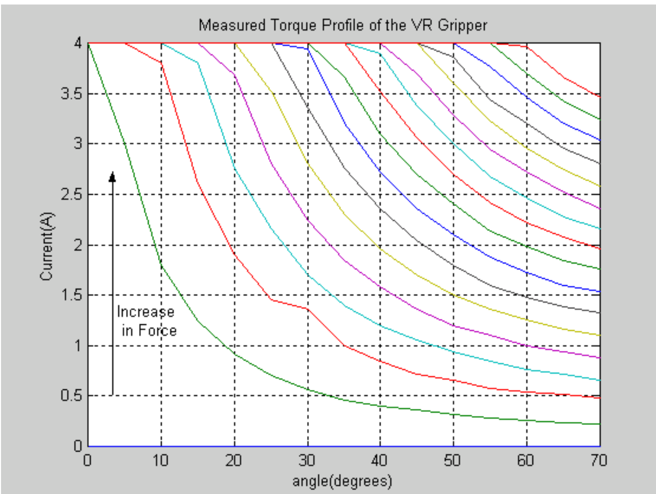

Fig. 10 Linearized Current Profile

C. *Control mode Switch*

The essential component is the control mode switch, which selects the force command input between the trajectory controller and force profile generator. Upon contact, control mode switch changes its force command input to a separate force profile generator while the force exceeds a threshold.

D. *Trajectory Control*

Trajectory controller employed is a typical PID controller when the finger is under motion. The trajectory profile is generated by a third-order low-pass filter. This can reduce the excitation to the mechanical parts and increase in reliability comparing to a step response. This also prevents the control signals from saturation.

E. *Force Profile Generator*

The force profile generator is a step profile, which lasts for a certain period of time.

The VR finger gripper torque and force relationship can be described as $F \cong T \times K$ where T, F, K are motor torque, force and constant. Both trajectory and force control modes can share the same nonlinear lookup table while introducing an error of less than 5%.

F. *Low Impact Force Profile*

In force sensitive industrial process, maintaining a low impact force is always desirable. In this paper, a dedicated motion profile is proposed to reduce the impact force upon contact.

Fig. 11 shows the low impact force velocity profile. The main idea is to reduce the impact force upon contact with a low constant velocity. It consists of a smoothed-profile motion and a low velocity search.

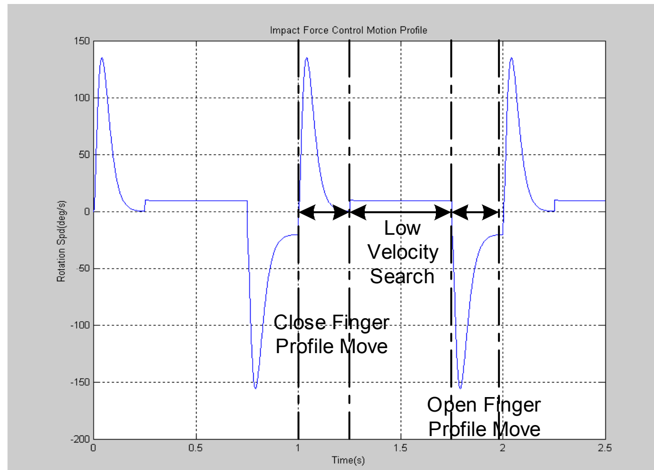

Fig. 11 Low Impact Force Velocity Profile

To reduce the impact force upon contact, one can reduce the level of change of momentum by reducing the moving mass or the velocity upon contact. With the low velocity motion, at contact, a small change of momentum and thus a low level of impact force can be expected.

Initially, the finger gripper rests at an *initial position*. Then, it closes and moves towards a *search position*, which has no contact with the object being grasped. Then the finger moves towards it at a low velocity. Once contact is found, force control is switched on and the fingers stay for a certain period of time. Finally, the fingers open and return to its *initial position*. With this profile strategy, system can maintain a low impact force for all force sensitive applications.

The controller's operation is based on the assumption that the current controller has perfect tracking capability.

VI. IMPLEMENTATION

A dSPACE DS1102 card is used as the motion controller. Fig. 8 shows the overall experimental setup. The card has an on-board 60MHz TMS320C31 DSP for real-time computation and interfaces with the PC through the ISA bus. It consists of two 24bits incremental encoder input channels, two 12 bits ADC channels and six PWM channels. In connecting with MATLAB real-time workshop and SIMULINK, real-time control C-code can be generated with a SIMULINK diagram. Assembly codes can be compiled and downloaded to the DSP.

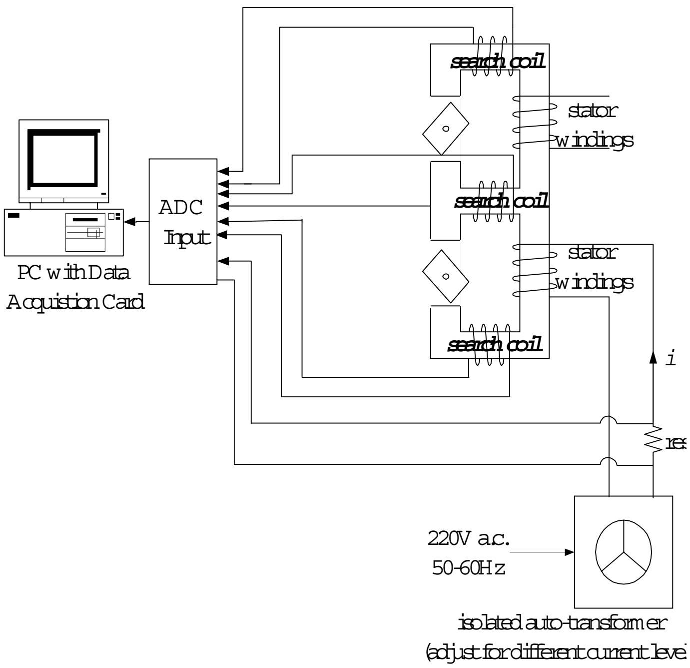

Fig. 12 Experimental Setup

VII. RESULTS

Actual profile and force (50-300mN) responses are shown in Fig.13-15.

Seven degrees of offset is added to the trajectory profile for avoiding the finger from hitting towards the hard limit. As the force exceeds 10mN, control mode switches from trajectory control to force profile generator.

Fig. 13 shows the force response for 50mN. After contact detection, it takes 200ms for force response to settle.

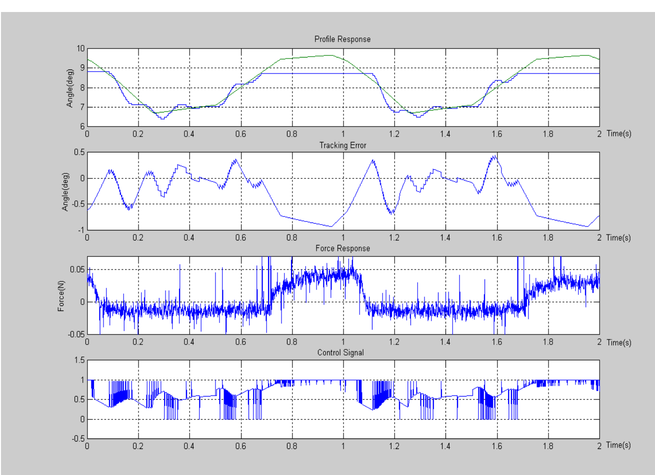

Fig. 13 Force response for 50mN

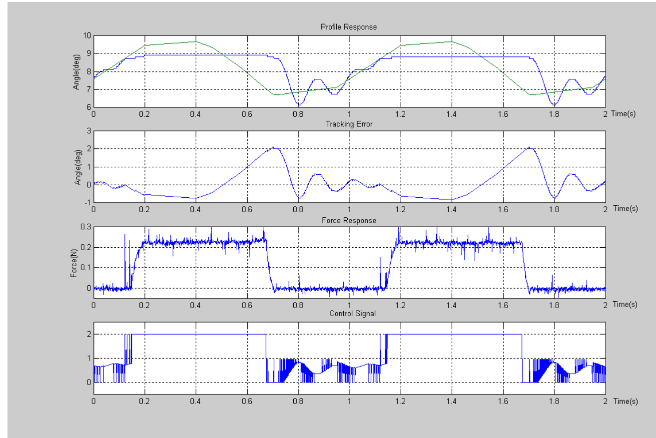

Fig. 14 Force Response for 0.2N

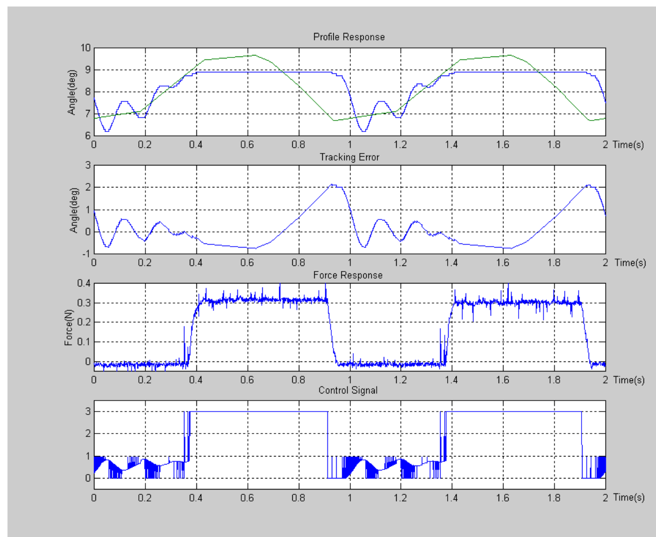

Fig. 15 Force Response for 0.3N

Fig 14 and 15 show force response for 200mN and 300mN. Results show the force responses are fast and stable. Force settling time is less than 50ms and ripple free.

VIII. CONCLUSION

A novel two-finger gripper based on variable reluctance technology has been designed and fabricated. The resulting actuator is robust and simple, and it is suitable for hazardous environment. With the absence of permanent magnet, the manufacturing cost and difficulty are much reduced.

The variable reluctance finger gripper inherits a simple machine structure but a complex control method. In this paper, an effective dual control mode strategy based on a trajectory control and force control structure is proposed. Detailed control strategies were described and implemented on the project VR finger gripper.

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Force control responses of 50mN, 200mN and 300mN were shown. Results show for forces larger than 200mN has rise time less than 50ms with ripple free.

Experimental results show that the proposed actuator can be controlled with reasonably good accuracy. It is an ideal replacement for the higher-cost and less-robust permanent magnet actuators for force control applications. Proposed method is simple, low-cost and easily implemented in any industrial controllers.

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REFERENCES

[1] K. Kiguchi, T. Fukuda, "Intelligent Position /Force Controller for Industrial Robot Manuipulators - Application of Fuzzy Neural Networks", IEEE. Trans. of Indust. Electronics, Vol. 44, No. 6, p753-761Dec 1997.

[2] R.D. Lorenz, J.J. Zik, D.J. Sykora, "A Direct-Drive, Robot Parts, and Tooling Gripper with High-Performance Force Feedback Control", IEEE Trans. on Indust. Appl., March/April, Vol. 27, No. 2, p275-281, 1991.

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

[4] K. K. Chan, N. C. Cheung, "Modelling and Characterisation of a Novel Variable Reluctance Finger Gripper", Sixteenth Annual IEEE Applied Power Electronics Conf., P1116-1122, March 2001.

[5] K. K. Chan, N. C. Cheung, "Modelling and Characterisation of High Performance Variable Reluctance Finger Gripper", The Fifth Int. Power Eng. Conf., P370-375, May 2001.

[6] G.R. Slemon and A. Staughen. *Electric Machines.* Addison Wesley, 1982.

[7] S. Mir, I. Husain and M. E. Elbuluk. Switched Reluctance Motor Modelling with On-Line Parameter Identification *IEEE Trans. on Ind. App.*, Vol. 34, No. 4, pp776-783, Jul./Aug. 1998.

[8] K. K. Chan, S. W. Tam, N. C. Cheung, "Adaptive Current Control of Variable Reluctance Finger Gripper", The Fifth Int. Power Eng. Conf., P370-375, May 2001.