A New Type of Direct-Drive Variable-Reluctance Actuators for Industrial Automation

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Abstract

Most advanced manufacturing processes require high-speed and high precision motion control for material transfer, packaging, assembly, and electrical wiring. Examples are surface mounting of electronic components, wire bonding of semiconductor chips, and assembly of watches and hard disks. To achieve precise motion control, most of these high-performance manufacturing machines use rotary d.c. or a.c. motors as the prime motion actuator, and couple their output shafts to mechanical motion translators (e.g. reduction gear, belt, ball screw, etc.). Though this is the most widely used method, it has disadvantages of reduced accuracy, complex mechanical structure, difficult adjustments and alignments, high production cost, and low reliability.

In this paper, the author proposes a new direction in high performance machine design, and suggests that future high performance motion systems should be designed through "simplifying the mechanics through specialized direct-drive actuators and advanced control methodologies". For this purpose, this paper investigates a class of variable reluctance (VR) direct-drive motion actuators for high performance machines. The paper looks into several specialized motion actuator systems designed by the author, (including limited stroke actuator, gripper, artificial limb, linear motion device, and planar motion device), highlights their features and advantages, and describes the challenges of controlling these devices.

Keywords:
Variable Reluctance, Actuators, Direct-Drive, Motion Control, Automation

1. Introduction

Nowadays, most electronic components and products (e.g. mobile phones, handheld computers, and hybrid IC modules) require high precision and high-speed assembly processes. To produce machines for this type of operation, high performance two-dimensional (X-Y axis) motions or three-dimensional motions (X-Y-Z axis) are required. Most of these machines require high position accuracy, high repeatability, and high accelerations and decelerations. To achieve these tasks, most machines employ rotary permanent magnet brushless motors, shaft couplers and rotary/linear mechanical translators, and reduction gear to design the machine. The control of this type of machine is relatively easy, and in most cases, standardized motion components are used. However, its manufacturing and maintenance cost are relatively expensive, due to its complex mechanical parts. Also, this type of machine also suffers from high alignment cost, backlash problems, low reliability, and unable to operate in harsh environments.

This paper suggests a new direction in precision and high performance machines design. This paper proposes the following solutions for the future direction of high performance machines design:

1. Use specialized direct drive motion actuators to eliminate the mechanical couples and translators [10].
2. Use advanced control techniques to overcome the mechanical and electrical nonlinearities [11], rather correcting the nonlinearities by electrical means.

To further reduce cost and ease the production of specialized motion actuators, this paper proposed to use Variable Reluctance actuators as the prime motion actuator. 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 VR 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 VR 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]. In this paper the author looks at a few types of VR motion actuators (limited stroke linear VR actuator, the VR finger gripper, linear VR motor, and planar VR motor), and investigates their suitability in high performance motion system applications.

2. Control Characteristics of the VR Actuators

VR actuators display nonlinear electrical characteristics, and its nonlinear behaviour is highly dependent on the actual construction of the actuator [4]. However, it can generally be expressed as a set of state equations below:

This paper is an extension of the previous work done by the author in the area of motion control for VR actuators [1,2,3].

$$\frac{dx}{dt} = v \tag{1}$$

$$\frac{dv}{dt} = \left(\frac{\partial\lambda(x,i)}{\partial x}\cdot i - K_s x - m_p g\right)\cdot\frac{1}{m_p} \tag{2}$$

$$\frac{di}{dt} = \left(V - Ri - \frac{\partial\lambda(x,i)}{\partial x}\cdot\frac{dx}{dt}\right)\cdot\frac{1}{L_e + \frac{\partial\lambda(x,i)}{\partial i}} \tag{3}$$

For most VR actuators, the flux linkage λ behaviour and the force profile F will display a hilly profile like the measurements in Fig. 2 and Fig. 3.

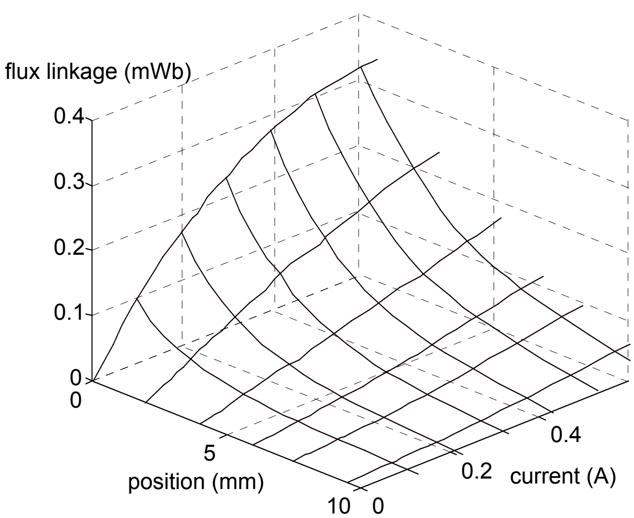


Fig. 2 λ against current and position

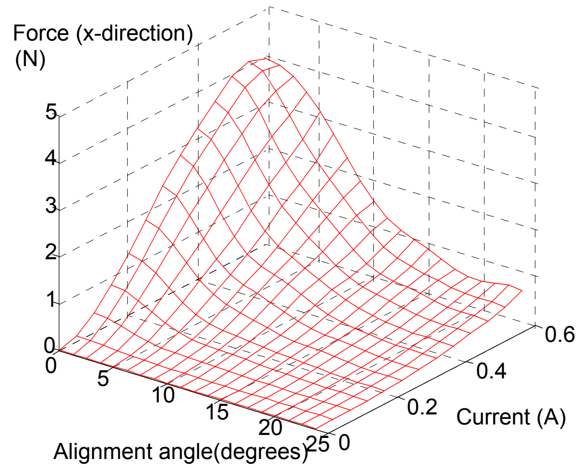


Fig. 3 Force against current and position

To overcome these nonlinear behaviours, suitable nonlinear decoupling control strategy based on the actuator's nonlinear geometries needs to be developed [5].

3. The Direct Drive VR Actuators

In this paper, five types of actuators will be examined. They are:

(i) Linear limited stroke VR actuator,
(ii) VR finger gripper,
(iii) VR linear motor,
(iv) VR artificial joint, and
(v) VR 2D planar motor

Each device has its control characteristic, advantages, application areas, and control strategy.

3.1 The Limited Stroke VR Actuator

Fig. 4 shows the diagram of a limited stroke VR solenoid. Primarily it is used for on off control of fluids. The structure is very robust, and the cost of such a device is very low. However, this device can be used as a proportional valve in hydraulic servo systems, if it is controlled in a proportional manner.

By measuring the nonlinear characteristics, and embed these nonlinear control characteristics into the control strategy, the above proposition can be accomplished [6]. Furthermore the position of the plunger can be estimated by a sensorless position technique [7], and the feedback position sensor can be eliminated from this device.
By using advanced control method [6], the low-cost on-off solenoid can replace some types of proportional valves that have much higher costs and less reliability.

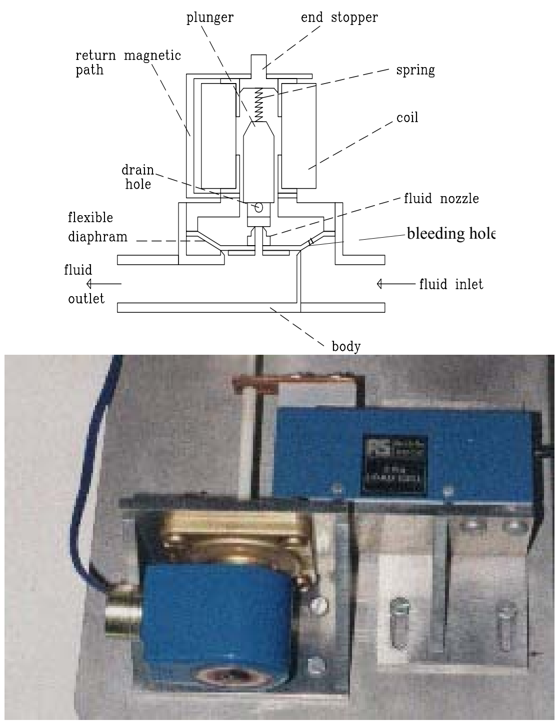
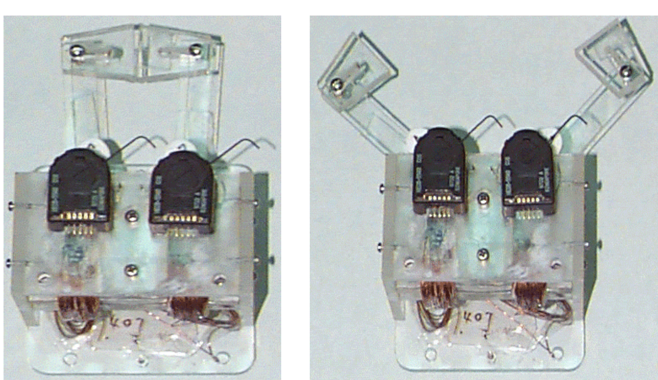


Fig. 4 The limited stroke VR actuator

3.2 The VR Finger Gripper

The VR principle can also be used to design finger grippers for robotic applications. Fig. 5a and 5b show the construction of the two-finger VR gripper [8]. It consists of two rotary elements, each attached to a finger. The actuator contains two coils, each with a 400-turn winding. The moving rotors are mounted onto two individual shafts, whose axes are normal to the plane of the diagram, so that the moving elements may rotate freely between the poles of the stator.



aligned (grasp) position unaligned (release) position

Fig. 5a The opening and closing of the VR gripper

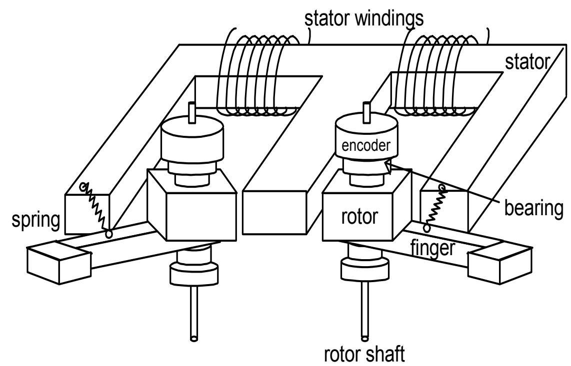


Fig. 5b The VR finger gripper

3.3 The Linear Switch Reluctance Motor (LSRM)

Fig. 6 shows the schematic diagram of the LSRM and its actual appearance [9]. The motor is optimised for (i) high power-to-size ratio, (ii) low force ripple, (iii) low leakage and eddy current loss, and (iv) fast current dynamics. The motor is integrated on a precision linear motion slider. Three phase coils are assembled on a moving platform with 120 electrical degree separations. As the motor windings are flux de-coupled, the three phase circuits are completely independent and there is no mutual inductance between phases. This novel feature simplifies the model analysis and enhances the robustness of the whole system.

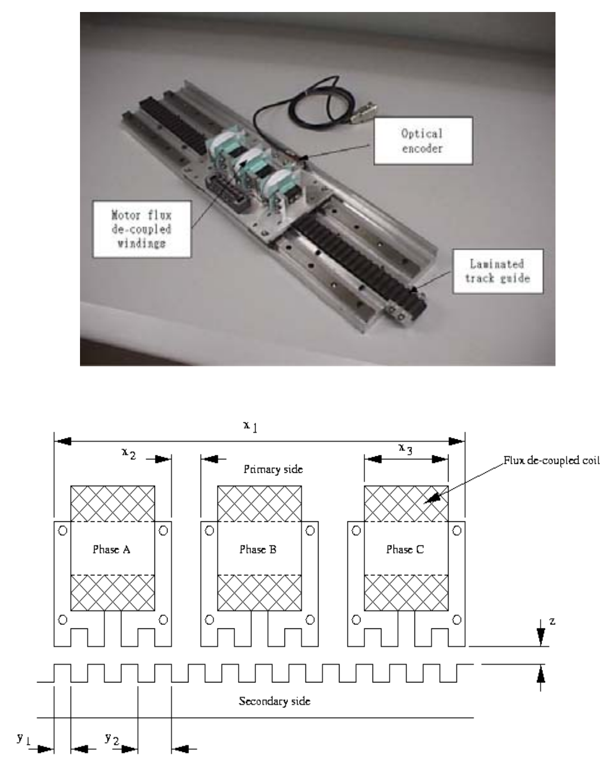


Fig. 6 The VR linear motor

3.4 The VR Artificial Joint

Fig. 7 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°. The plates of the VR artificial joint 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.

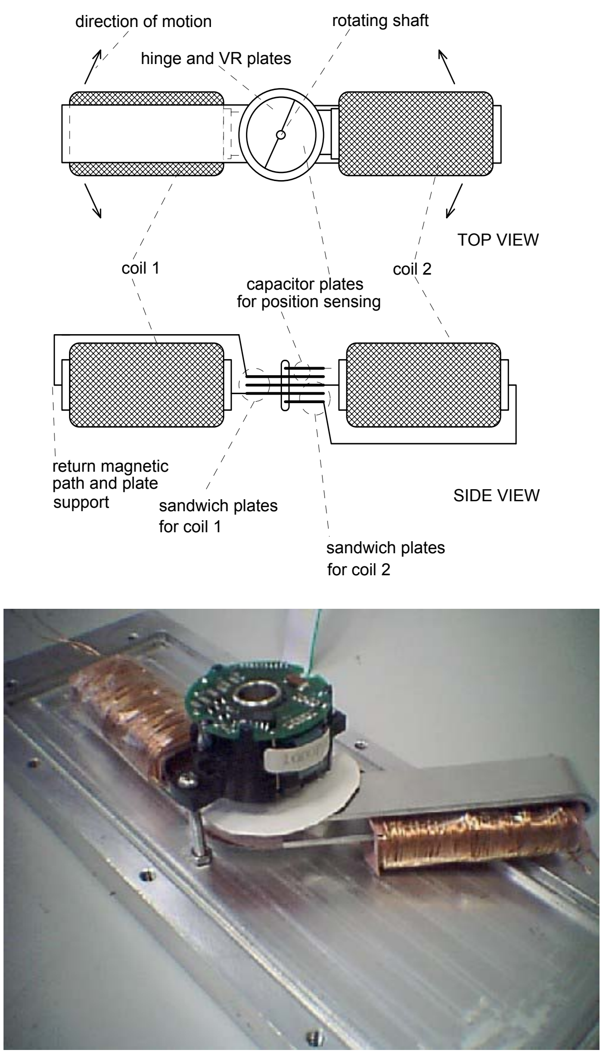


Fig. 7 The VR artificial joint

3.5 The 2-D VR Planar Motor

To achieve precise 2D planar motion, most of manufacturing machines use X-Y tables with rotary d.c. motors and rotary-to-linear mechanical couplings. Though this is the widely used method, it has disadvantages of complex mechanical structure, frequent mechanical adjustments, high manufacturing/maintenance cost, and low reliability. Disadvantages of traditional X-Y tables have indirectly led to the high cost and difficult maintenance of these machines.

By using a novel 2D Variable Reluctance (VR) planar drive technology, a 2D direct-drive planar motion system can be constructed to replace traditional X-Y tables. The proposed actuator has a very simple structure with few mechanical parts, and it can be manufactured easily. Since the motion system is a self-aligned direct drive system, there is no need for X-Y alignments, rotary-to-linear couplings, and linear roller slides.

The real challenge of this project lies not only on the 2D VR planar actuator design, but also on the 2D position sensing, the nonlinear control methodology, and the PWM current drive. Figure 8 shows the layout and the actual photo of such a system.

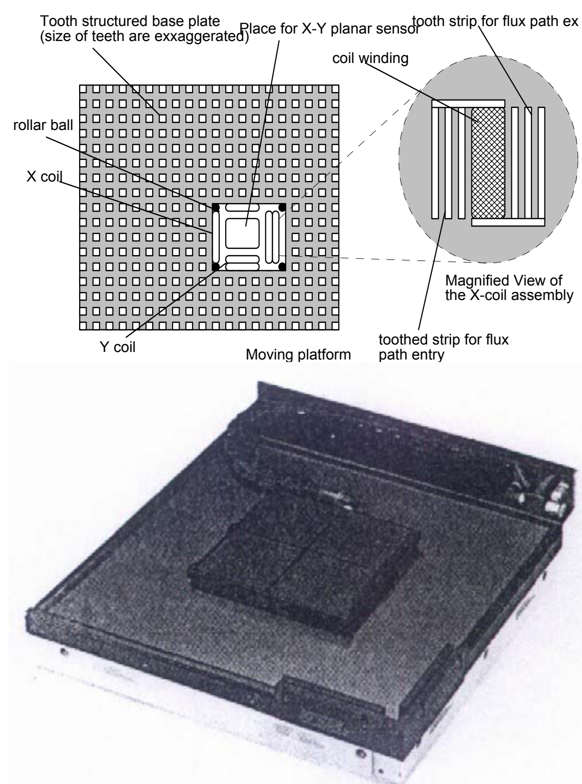


Fig. 8 The VR planar motor

4. Conclusion

Higher Performance and lower cost machines can be developed by using VR direct drive actuators, and by following the philosophy “Simplifying the mechanics through specialized actuators and advanced control methodologies”. The special VR actuators described in this presentation are low-cost, robust, and reliable. They contain little mechanical adjustments, and can be easily manufactured. These advantages will enable these actuators to replace many traditional X-Y tables driven by rotary motors and mechanical lead screws.

The manufacturing cost of many electronic products (handheld computers, semiconductor devices, etc.) can be made cheaper when the machineries that produce the above products can be purchased and operated at a lower cost. The advantages of the direct drive motion systems will also open up many new applications in low cost and high performance motion drive that are not feasible before (e.g. crafting Chinese characters on jewelry). The proposed ideas can be a valuable contributor to the High Tech industry, when its present emphasis is on the development of high-tech/high value-added products, with minimum labor/overhead costs, and on lean budgets

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