Employing Variable Reluctance Direct-drive Motion Actuators in High Performance Manufacturing Machines

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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 system design, (including limited stroke actuators, embedded artificial limb, linear motion devices, and planar motion devices), highlights their features and advantages, and describes the challenges of controlling these devices.

Key Words: Variable Reluctance Motors, Precision Motion Systems

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) is 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. Fig.1 is a typical example of this type of 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 error, low reliability, and unable to operate in harsh environments.

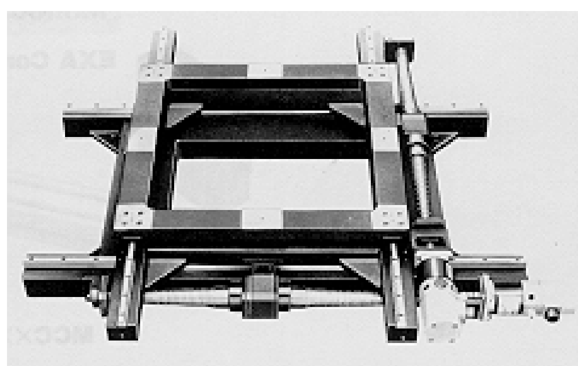

Fig. 1 A conventional planar motion mechanism

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 specialised direct drive motion actuators to eliminate the mechanical couples and translators [6].
2. Use advanced control techniques to overcome the mechanical and electrical nonlinearities [7], rather than correcting the nonlinearities by electrical or mechanical means.

To further reduce cost and ease the production of specialised 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].

$$\frac{dx}{dt} = v \qquad (1)$$

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

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

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.

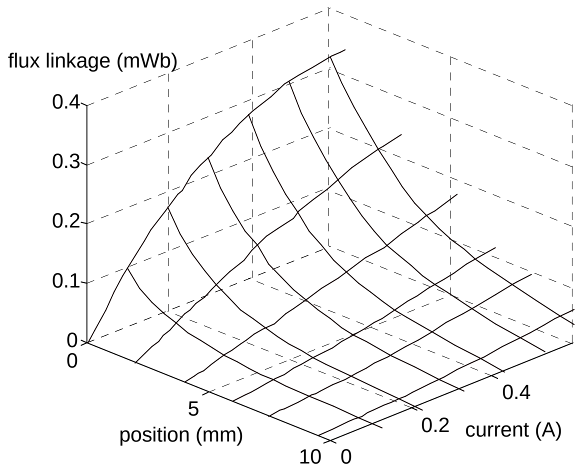

Fig. 2 λ against current and position

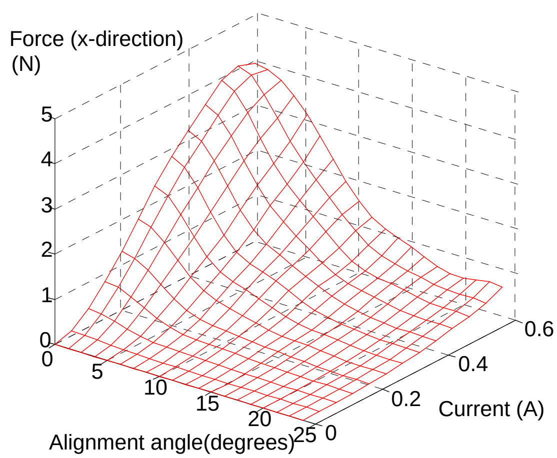

Fig. 3 Force against current and position

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, four types of actuators will be examined. They are:

(i) the linear limited stroke VR actuator,
(ii) the VR finger gripper,
(iii) the VR linear motor, and
(iv) the VR 2D planar motor

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

3.1 The Limited Stroke VR Actuator

Figure 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 [6], and embed these nonlinear control characteristics into the control strategy, the above proposition can be accomplished [8]. Furthermore the position of the plunger can be estimated by a sensorless position technique [9], and the feedback position sensor can be eliminated from this device.

By using advanced control method, the low-cost on-off solenoid can replace some types of proportional valves which have much higher costs and less reliability.

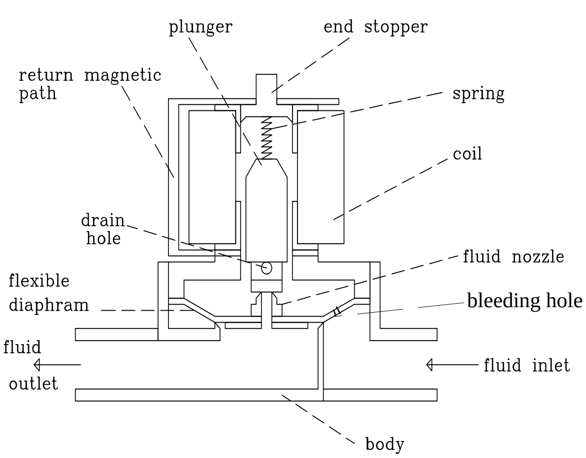

Fig. 4 The limited stroke VR actuator

3.2 The VR Finger Gripper

The VR principle can also be used to design finger grippers for robotic applications [10]. Figure 5 shows the construction of a VR finger Gripper. It consists of a coil with a laminated magnetic core at the centre. The moving element hinges on the upper end of the laminated core, and is spring loaded to allow the fingertip to move outwards when it is unenergised. The spring also ensures good magnetic circuit contact between the moving part and the stationary element. A miniature rotary optical encoder is mounted behind the VR grasping finger to sense the position of the moving element.

Presently only one VR grasping finger has been studied. However, there is no limitation on the number of fingers used in coordination for a single application. Due to the small and convenient size of the grasping fingers, combination two or more VR fingers in robotics grasping applications can be achieved easily.

Comparing to its permanent magnet counter part, the VR finger gripper can be machined more easily, and it is more reliable and robust. Unlike, d.c. voice coil actuator, the VR actuator's characteristics is highly dependent on the nonlinear behaviour of its magnetic circuit. Before effective control of the VR grasping finger can be achieved, a study on the actuator's magnetic flux behaviour is required.

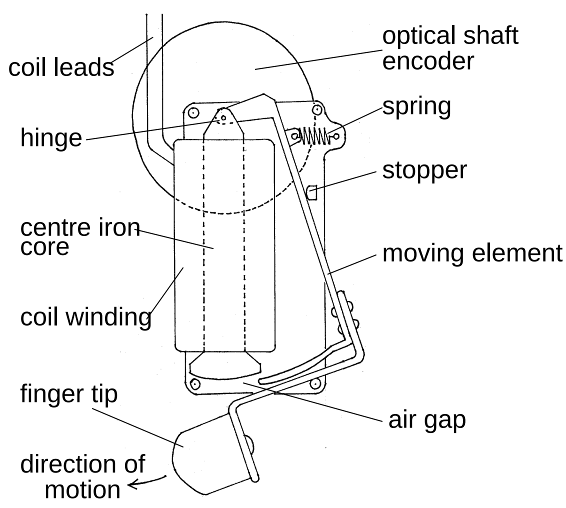

Fig. 5 The VR finger gripper

3.3 The VR Linear Motor

Unlike the VR limited stroke solenoid and the VR finger gripper, the VR linear motor shown in figure 6 is a multi-phase actuator. The direct-drive VR linear actuator has a robust structure, with low inertia and direct drive capability. Therefore, it is particularly suitable for high precision and high speed manufacturing machinery [11].

Manufacturing of the actuator is simple, and it is suitable for precision travel over long distances. Unlike other types of linear motion systems driven by rotary motors, mechanical couplings, lead screws, magnets, and brushes are not required in the VR linear actuator. Special mechanical adjustments or alignments are also not necessary.

Comparing to permanent magnet linear motor, the VR linear actuator has a much simpler structure and it is less expensive. It is also more robust and more fault tolerant, and has less overheating problem.

The key technology issue for VR linear drive system is to acquire the nonlinear characteristics of the linear motor and to use an effective nonlinear control algorithm to decouple the nonlinear behaviour from the force output.

A driving scheme for VR linear actuator that has high speed, high accuracy, and low force ripple is required.

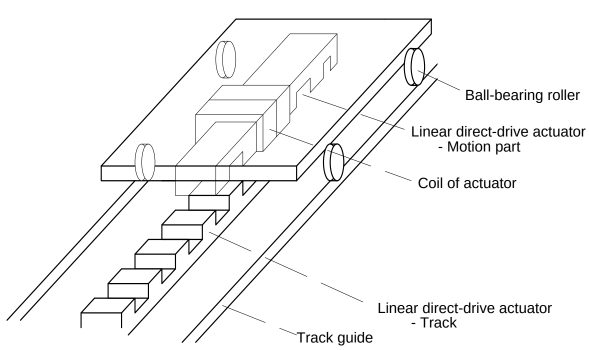

Fig. 6 The VR linear motor

3.4 The 2-D VR Planar Motor

Presently, the Sawyer motor [12,13] is the only form of 2D planar motion actuator available in industry. However, this kind of actuator is based on open-loop stepping motor principal, and it cannot achieve very high speed and acceleration. Also, it is susceptible to loss of steps and it is unable to provide high stiffness.

There have been attempts to add feedback control [14] or use composite magnetic material [15] for the Sawyer motor, but the improve in performance (especially on acceleration/deceleration) is not substantial, due the inherent stepping motor structure of the Sawyer motor. There have been attempts from Japan to build a 2D planar motor using the induction motor principle [16], however, the motor is not suitable for high speed and high precision motions; it is more suitable for moving large loads.

Up till now, there has been virtually no publication or research literature regarding high performance 2D planar motor using Variable Reluctance (VR) driving principle. Nearly all publications regarding VR drives are on rotary device only.

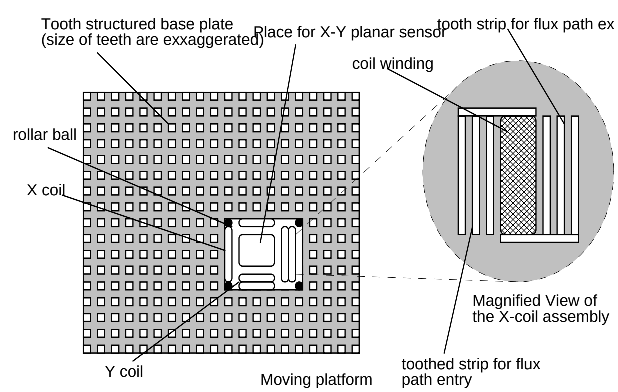

Fig. 7 The VR planar motor

The construction of the "toothed structure" 2D planar motor is shown in figure 7 and 8. At this stage, the full control of the 2-D planar has not yet been tested. But, according to previous experience with VR linear motor, the 2-D planer VR motor is expected to have the following performance:

Power output (X & Y axis)	80-100W
Accuracy of planar encoder	10 micron
Travelling distance	300mm × 300mm
Acceleration/deceleration	>3G at 0.5kg load
Position Accuracy (X & Y axis)	±50 micron
Maximum Load	5kg
Rotational Deviation Error	<2~3 degrees
Size of base plate	450mm × 450mm

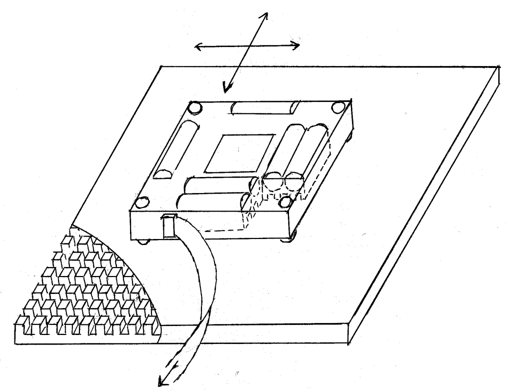

Fig. 8 The 2-D planar VR motor

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 jewelleries). 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 labour/overhead costs, and on lean budgets

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