Research article

Using variable-reluctance actuators in automated manufacturing machines

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Grippers, Actuators

Abstract

Most advanced manufacturing processes require high-speed and high-precision assembly machines for material transfer, packaging, assembly, and electrical wiring. To achieve the precise motion control, most of the machines use rotary electrical motors as their prime motion actuators, and couple their output shafts to mechanical motion translators. In this paper, the author proposes a new direction in high performance automated machine design, and suggests that the future high performance motion systems should be designed through the philosophy of "simplifying the mechanics through direct-drive actuators and advanced control methodologies". For this purpose, this paper investigates a class of direct-drive variable reluctance (VR) motion actuators for high performance motions, and also looks into a number of VR actuators suitable for robotic applications. It also highlights their features and advantages, and describes the challenges of controlling these devices.

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1. Introduction

Nowadays, manufacturing of electronic components and products (e.g. mobile phones, handheld computers, and hybrid IC modules) require high-precision and high-speed assembly processes. The manufacturing machines for this type of operation need to perform controlled trajectories of two-dimensional (2D) or three-dimensional (3D) motions. 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 costs are relatively expensive, due to its complex mechanical parts. Also, this type of machine also suffers from complicated alignment procedure, backlash problems, low reliability, and unable to operate in harsh environments.

Figure 1 shows the mechanical layout of a conventional linear slide, cascaded on top of each other to form a 2D *X*-*Y* table. This kind of arrangement may lead to inaccuracies and performance reductions. This is mainly due to the coupler alignment, the straightness of the ball screw, the coupling between the ball screw and nut, and the parallel alignment between the linear guides, the ball screw, and the motor. As the complexity of manufacturing product increases, the precision requirement of machines to manufacture these devices also needs to increase. Normally, the cost of a Cartesian robot increases exponentially with its precision. Most of the increase in cost goes to the higher precision mechanical components, the mechanical alignment procedure, and the regular maintenance effort. Therefore, the complexity in the mechanical translators and couplers lead to an expensive and hard to maintain machines. To increase the performance and reduce the cost of these automated machines, the most effective way

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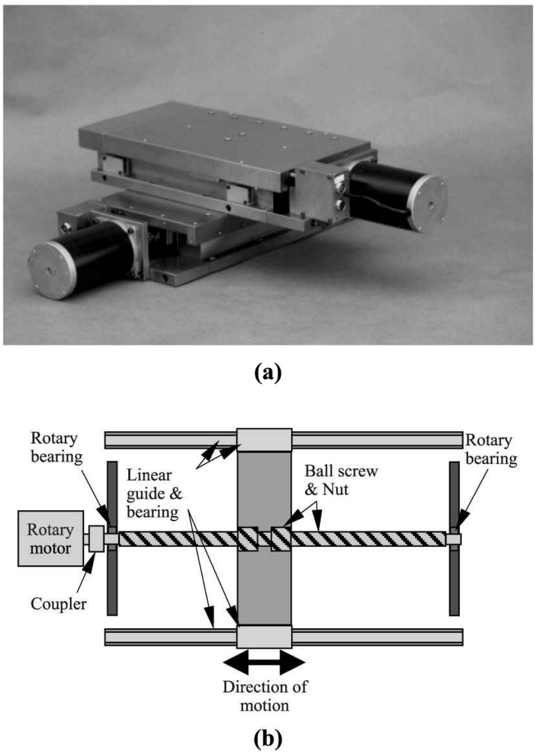
Figure 1 The conventional *X-Y* table: (a) its outside appearance, and (b) internal structure of the linear slide



is to eliminate the complex mechanical translators and couplers.

In this paper, the authors suggest a new direction in high performance automated machines design. For the future high performance machines, the following design directions should be considered:

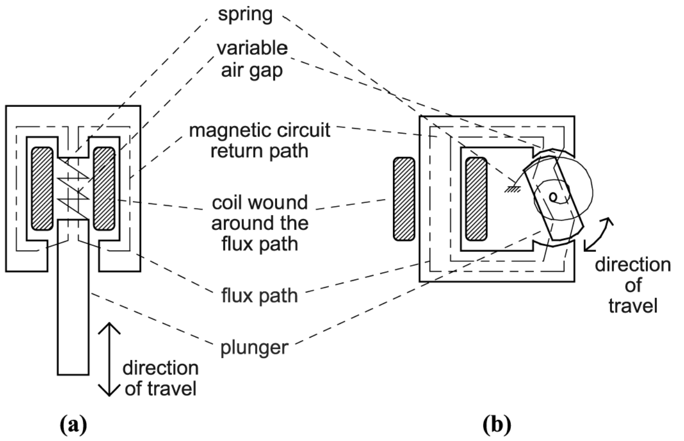
1. use direct drive motion actuators to eliminate the mechanical couplers and translators (Cheung and Cheung, 1997), even though it may be done at the expense of worse non-linear control characteristics;
2. use intelligent and robust control techniques to overcome the mechanical and electrical non-linearities (Chung *et al.*, 1997).

The above-mentioned design directions are based on the fact that the powerful servo controllers are getting cheaper and more readily available, while high-precision components and experienced craftsmanship are getting more and more expensive. It is always more effective to implement the complex motion requirements on the software than on the mechanical hardware.

To further reduce the cost and complexity of designing a specialized direct drive motion actuators, this paper proposes to use a variable reluctance (VR) motion actuators as the prime motion actuator. VR motor has a robust and simple structure and its manufacture cost is much lower than similar brushless DC or AC motors. It is primarily a direct-drive device, due to its ability to accommodate large pole numbers with small pole pitch (Miller, 1993). Better still, its structure and shape can be adapted to different applications, and there is no need to conform to the traditional rotary motor structure.

Figure 2 shows the construction of a rotary and a linear VR actuator. When a current is passed through the coil, magnetic flux will be created around the magnetic circuit of the actuator. Flux behaves like "invisible rubber bands of force", it will try to reduce the air gap between the plunger and the magnetic circuit return path. As a result, a torque is produced and the rotor will turn clockwise until it is fully aligned with the magnetic core. For the case of linear VR actuator, the plunger will go upwards until it hits the upper end travel. The VR actuator is actually the simplest and most robust form of electric motor, it does not contain permanent magnet, copper cage, and commutator. Presently, VR actuators are mostly used as on-off devices in low cost domestic applications (e.g. central car lock, washing machine water valve, etc.). The main reason why VR actuators cannot gain widespread acceptance as proportional actuators is mainly due to its non-linear magnetic and electrical characteristics.
A VR proportional actuator is much more difficult to control than brushless DC or synchronous actuators. The characteristics of VR actuators are highly dependent on their flux behaviors, and flux behavior is

Figure 2 The operating principle of VR actuators (rotary and linear)



essentially non-linear in nature. However, during the past few years, there has been a renewed interest in proportional VR actuators (Goldenberg *et al.*, 1994), partly 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 switch reluctance motors (Taylor, 1991). For the past few years, the Power Electronics Research Centre of the Hong Kong Polytechnic University has been developing a series of high performance direct-drive VR actuators for various applications of motion; these include the VR finger gripper, the VR artificial joint, the linear VR motor (LVRM), and the planar VR motor (PVRM). In this paper, the authors report on the latest developments of these direct-drive VR motion actuators, look at their performances and investigate their suitability in high performance robotic applications. Finally, this paper also reports on the developed control strategies for the effective control of direct-drive VR actuators.

2. Control characteristics of the VR actuators

VR actuators display non-linear electrical characteristics, and its non-linear behavior is highly dependent on the actual construction of the actuator (Rahman *et al.*, 1996a, b, c). However, it can generally be expressed as a set of state equations as follows:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v \qquad (1)$$

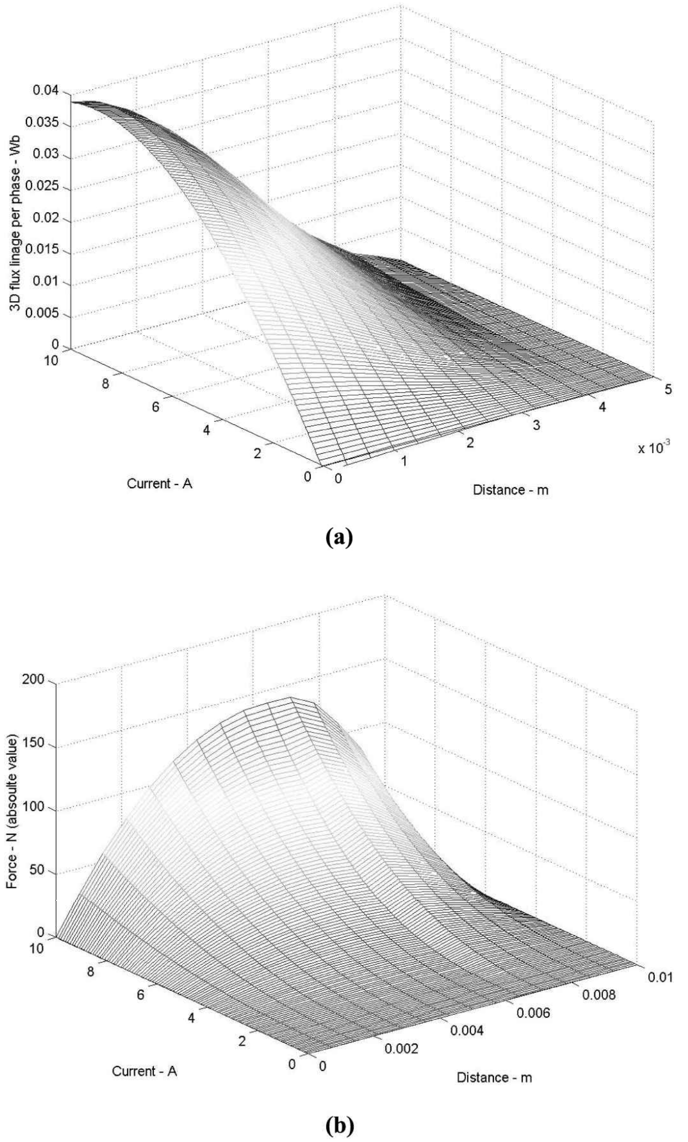
$$\frac{\mathrm{d}v}{\mathrm{d}t} = \left(\frac{\partial\lambda(x,i)}{\partial x}\cdot i - K_s x - m_p g\right)\cdot\frac{1}{m_p} \qquad (2)$$

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

For most VR actuators, the flux linkage λ behavior and the force profile F will display a hilly profile like the measurements shown in Figure 3(a) and (b).

To overcome these non-linear behaviors, suitable non-linear decoupling control strategy based on the actuator's non-linear geometries needs to be developed (Lim *et al.*, 1994). This subject is reported in Section 4 of this paper.

Figure 3 (a) Flux linkage λ versus current and position, and (b) force versus current and position



3. The direct-drive VR actuators

One of the key advantages of direct-drive VR actuator is its ability to mould its shape to a particular application requirement. As long as the VR principle is observed, the actuator will operate effectively and efficiently. In this paper, four types of direct-drive VR actuators are examined. They are:

(1) the VR finger gripper,
(2) the VR artificial joint,
(3) the LVRM, and
(4) the PVRM.

Each device has its own unique structure, control characteristic, and application areas. However, all of them operate on the

VR principle, and can be controlled in a similar manner.

3.1 The VR finger gripper

The VR principle can be used to design the finger grippers for the robotic applications (Cheung, 1998). Figure 4 shows the actual appearance of the VR finger gripper. The VR finger gripper consists of two rotary elements, each attached to a finger shape end effector. The actuator contains two coils, each providing gripping torque to one finger of the device. 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. The overall construction of the VR finger gripper is shown in Figure 5.

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. During the development of the VR finger gripper, the self and mutual flux linkages were measured and the 3D-flux linkage profile was generated with a 3rd order polynomial surface fitting. The actuator inherits a non-uniform force profile as a reluctance actuator. A dual mode position/force control strategy was applied to the finger gripper. Presently, the finger gripper has a position accuracy of 0.5° and force accuracy of 5 mN. Its maximum gripping force is around 8 N. The finger gripper has been applied to grip the various delicate objects with high speed and low force impact.

3.2 The VR artificial joint

The VR actuator principle can also be applied to design the artificial joints. Direct-drive rotary joint is very useful to construct the robotic arms and fingers. Figure 6 shows the overall construction and the actual appearance of the variable reluctance joint actuator. It consists of two coils with sandwiched laminated plates at the center. The plates act as the motor and the hinge for the VR actuator. There are two VR 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. The overall structure is extremely simple, and it can be mould to

Figure 4 The opening and closing of the VR gripper

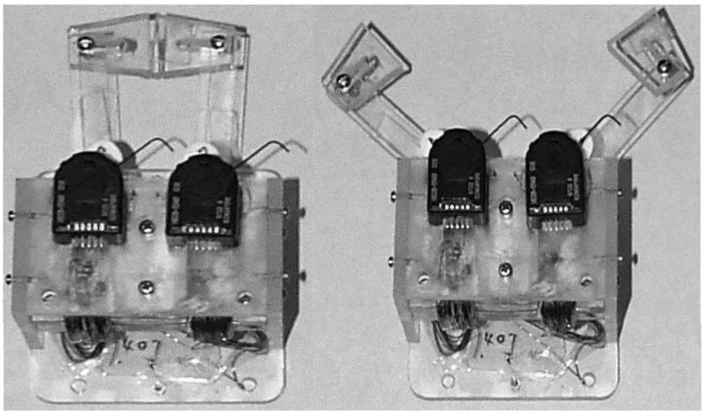


Figure 5 Essential parts of the VR finger gripper: (a) top view, and (b) side view

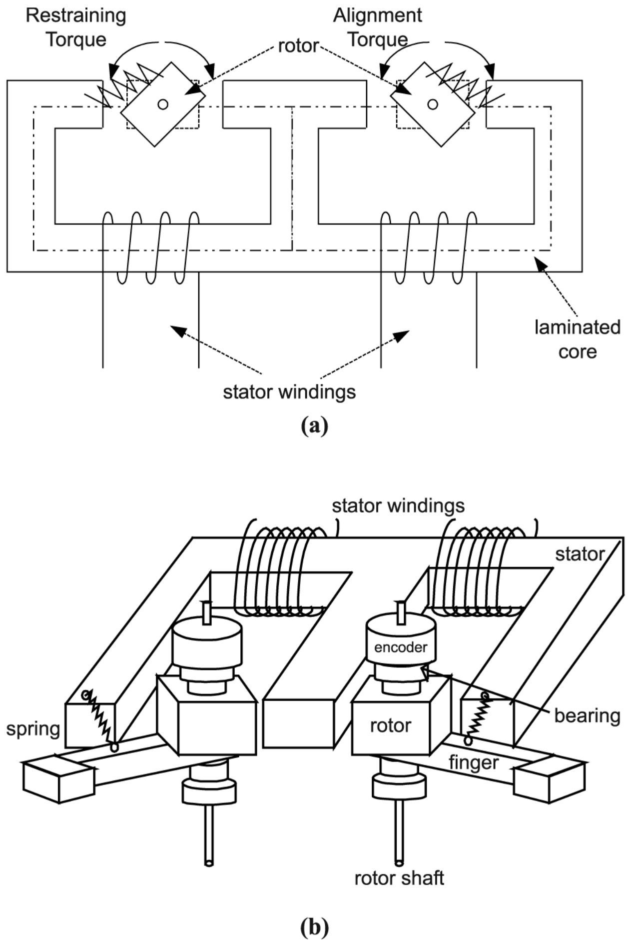
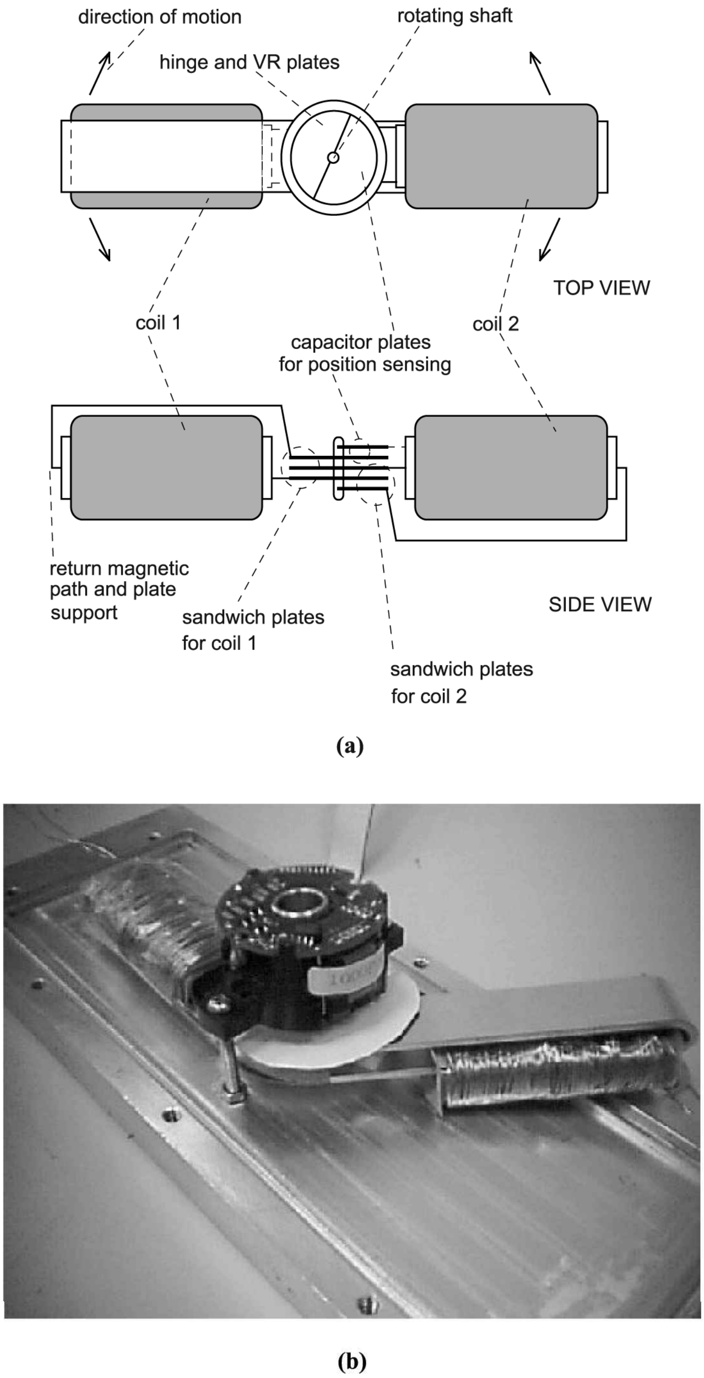


Figure 6 The cross-sectional diagram (a) and the actual appearance (b) of the VR artificial joint



the shape of a human finger. By energizing the two coils in different ways, the joint can be controlled to follow different motion trajectories, press on an object with different force levels, and remain stationary at a position with variable stiffness.

3.3 The LVRM

Figure 7 shows the schematic diagram and the actual appearance of the LVRM (Cheung, 2000). The motor is optimised for

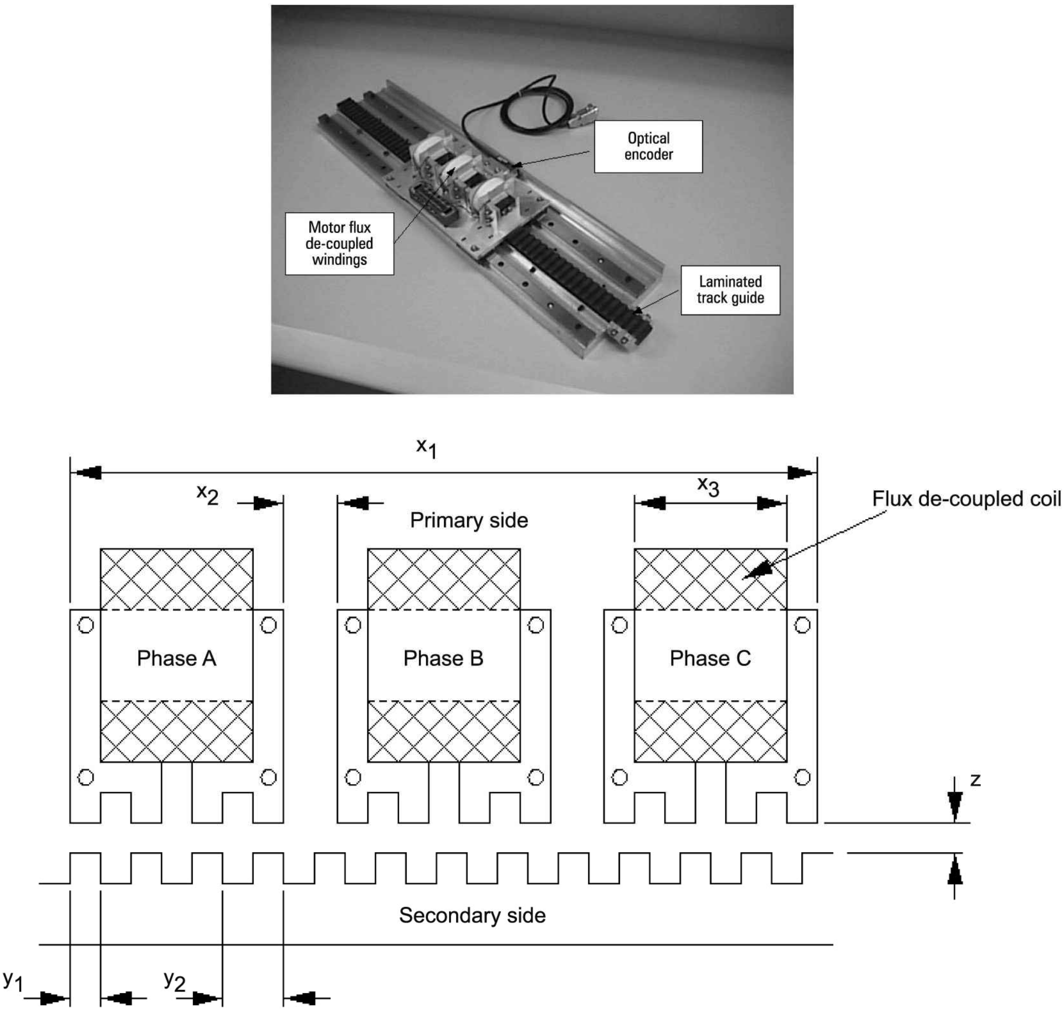
1. high power-to-size ratio,
2. low force ripple,
3. low leakage and eddy current loss, and
4. fast current dynamics.

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. The LVRM can operate in harsh environment with high performance. Presently, the LVRM can achieve a positional accuracy of 0.8 micron, and it has an acceleration/deceleration rate of 3.5 G. The present LVRM controller does not operate the motor into the saturation region. It is anticipated that the performance of the LVRM will increase much further when it is operated by the next version of the controller, which operates into the saturation region.

3.4 The PVRM

The PVRM has a 2D structure. The motor can generate force in the *X* direction as well as in the *Y* direction. Two-dimensional motions are in high demand for most manufacturing processes. By using a novel planar structure, the direct-drive PVRM can directly replace the traditional *X*-*Y* tables. The proposed actuator has a very simple structure with few mechanical parts, and it can be manufactured easily. The real challenge of this project lies not only on the 2D VR planar actuator design, but also on the 2D position sensing, the non-linear control methodology, and the PWM current drive. Figure 8(a) shows the cross-sectional layout of the PVRM. The 2D VR planar actuator is based on the "straightened-out" version of a 6/4 pole rotary switched reluctance motor, along the *X* and *Y* directions. Two sets of three-phase coil windings with wide magnetic teeth ware are employed on the moving platform. The wide magnetic teeth ensure that there is a little force coupling between the two motion axes. A finite element package was used to design the target motor with a high power-to-size ratio, low force ripple, fast current dynamics. The design of the "toothed structure" 2D planar motor is shown in Figure 8(b). The base was manufactured from the layers of

Figure 7 The LVRM



the laminated steel plates aligned in the X and Y directions, respectively. Two linear position encoders with resolutions of 1 μm are mounted onto the two ends of a moveable mechanical cross bar.

Presently, the motor is still under final development stage. However, the finite element analysis and the motion control simulation both indicate that the performance of the PVRM is similar to the LVRM. The motor is expected to have the performance as shown in Table I.

4. Controlling the direct-drive VR actuators

Since VR actuators exhibit the non-linear properties, it has a non-linear relation of torque/force output with position and current. To correct this non-linearity, the VR actuator controller must contain a force-current lookup table. Since most of the VR actuators mentioned in this paper are operated under the position and force regulation modes, a dual mode control strategy is preferred. Figure 9 is the overall block diagram of a typical VR actuator controller.

A cascade dual loop control strategy is proposed. The VR controller consists of a fast inner loop digital current controller and a slower outer loop position controller. For the outer loop, an adaptive PI controller is employed. Between the position controller and the current controller, a non-linear lookup table is required. The lookup table bridges the link between the two controllers. It receives force commands and position information, and outputs the desired current set points to the current controller. The dual loop cascade controller's operation is based on the assumption that the current controller has accurate tracking capability. As long as the inner current loop is accurate, the trajectory command issued by the outer loop will be followed from the outer loop to the inner loop,

Figure 8 Overall structure of the PVRM: (a) side view, and (b) top view

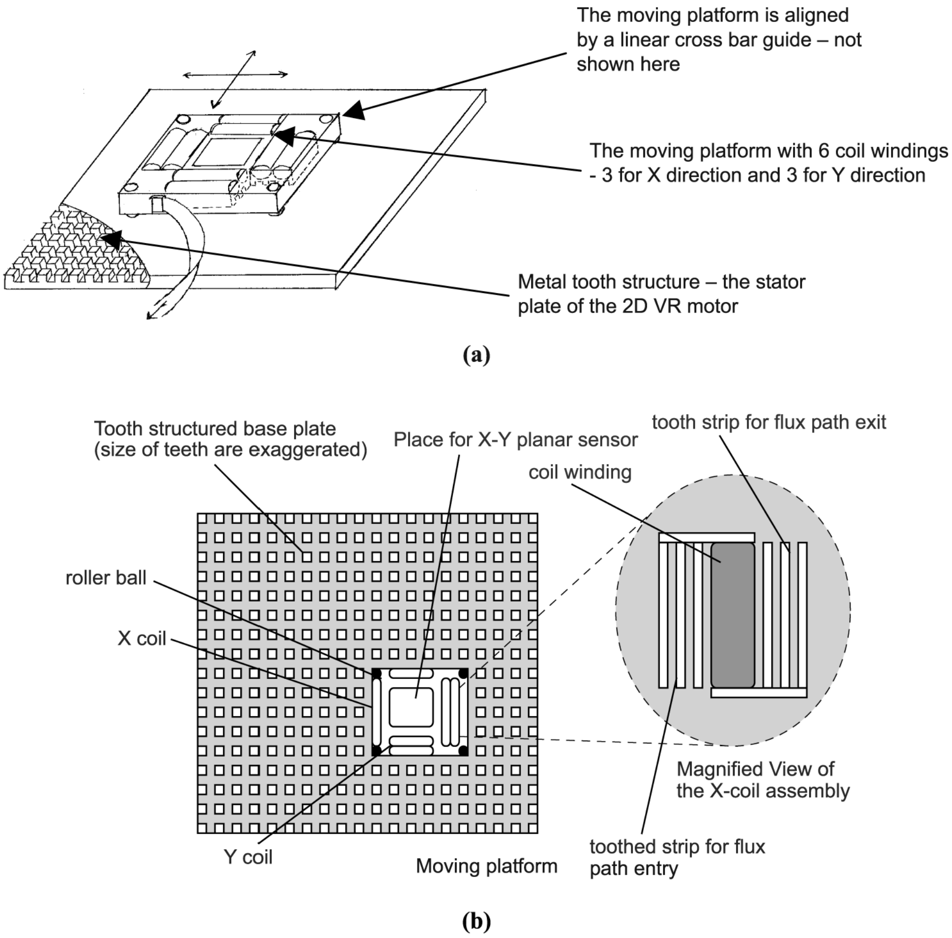
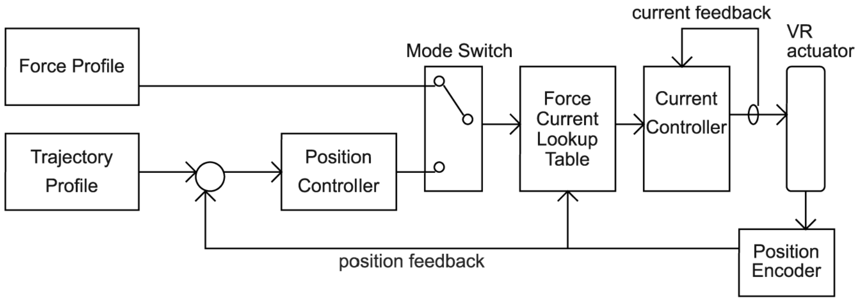


Table I

Power output (*X* and *Y* axis)	80-100 W	Travelling distance	300 × 300 mm
Resolution of planar encoder	2.5 micron	Acceleration/deceleration	>5 G at 0.5 kg load
Tooth pitch	6 mm	Maximum load	5 kg
Position accuracy	± 2 micron	Size of base plate	450 × 450 mm

Figure 9 The overall block diagram of a typical VR actuator controller



and onto the motor. If the VR actuator operates on position and force control modes, a mode switching mechanism is required. The switch selects the force command input between the trajectory controller and the force profile generator.

5. Conclusion

Higher performance and lower cost machines can be realised by using the VR direct-drive actuators, and by following the philosophy of "Simplifying the mechanics through specialized actuators and advanced control methodologies". The special VR actuators described in this paper are low-cost, robust, and reliable. They contain little mechanical adjustments, and can be easily manufactured. These advantages will enable direct-drive VR actuators to replace many traditional *X*-*Y* tables driven by the rotary motors and the 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 products mentioned earlier can be purchased and operated at a lower cost. The advantages of the VR direct-drive motion systems will also open up many new applications that are not feasible before (e.g. automatic crafting machineries). The proposed direct-drive VR actuators can be a valuable contributor to the automated manufacturing 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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