A Novel 2D Variable Reluctance Planar Actuator for Industrial Automation

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Abstract

The manufacturing of advanced electronic products and components requires precise two-dimensional (2D) planar motion for surface positioning, parts assembly and component insertion. To achieve precise 2D planar motion, most of these high-performance manufacturing machines use cascaded X-Y tables with rotary motors and rotary-to-linear mechanical couplings. Though this is the most widely-used method, it has disadvantages of complex mechanical structure, frequent mechanical adjustments, high manufacturing/maintenance cost, and low reliability. This paper proposes a novel 2D Variable Reluctance (VR) planar actuator to replace conventional X-Y tables. Unlike existing planar motors based on permanent magnet synchronous drive, inductive drive, and open loop stepper drive, this paper proposes a 2D actuator based on variable reluctance driving method. The proposed actuator has a very simple and robust structure. It has very few mechanical parts, and it can be manufactured easily. A prototype actuator was fabricated. Preliminary characteristics measurements confirmed that the proposed structure is very suitable for high-performance planar drive in industrial automation.

I. Introduction

This paper describes the development of a novel, high performance, 2D, direct drive motion system for industrial manufacturing applications. The 2D actuator is based on VR principle, and it aims to replace the traditional X-Y table as a higher performance and lower cost alternative.

Presently, the Sawyer motor [1, 2] is the only form of 2D planar actuator available in industry. However, this kind of actuator is based on open-loop stepping motor principal, and (i) it cannot achieve very high speed and acceleration, (ii) it is susceptible to loss of steps, and (iii) it is unable to provide high stiffness. There have been attempts to add feedback control [3] or use composite magnetic material [4] for the Sawyer motor, but the improvement in performance (esp. on acceleration/deceleration) is not substantial, due the inherent stepping motor structure of the Sawyer motor. There have also been attempts to build a 2D planar motor using the induction motor principle [5], 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 VR driving principle. Even publication on high performance one-dimensional linear VR drive is very rare. Nearly all publications regarding VR drives are on rotary device only. During the past few years, there have been some examples of constructing a 2D planar motor based on the permanent magnet synchronous motor principle. All of these proposals either involve (i) very complicated checker-board arrangement of permanent magnet surface [6], or (ii) complex multi-coil matrix windings [7]. Up till now, a practical and low-cost solution of manufacturing permanent magnet 2D planar motor is still unavailable.

Variable reluctance motor has never been a popular choice for high-precision and high-speed motion applications, because it is difficult to control and its output has high-force 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. It was only until recent years which we see a general resurge of interest in the variable reluctance motor [8]. This was mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through complex control strategy". It must be stressed that most of these developments are directed towards general speed/torque control of rotary VR motors only.

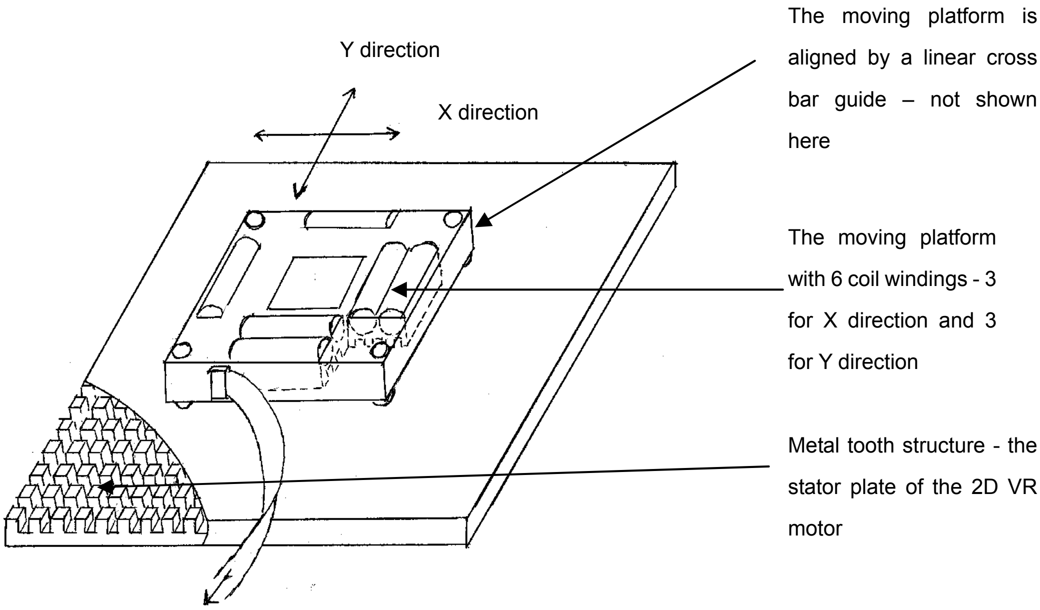


Fig. 1 The 2D VR planar actuator

The 2D VR planar actuator described in this paper has a simple and robust structure. Since there is no need to cascade two linear slides, the overall inertia becomes lower and more balanced. Due to the employment of VR drive principle, manufacturing of the actuator is simple, the base can be made from a single piece of ferrite metal, and the moving part is made from simple coil windings and ferrite metal pieces. Unlike DC brushless drive, no expensive and hard-to-handle magnets are required. The 2D VR actuator is a direct-drive actuator Mechanical coupling, lead screws, magnets, and brushes are not required. The degree of precision is inherent into the structure, and special mechanical adjustments are not necessary. The actuator is particularly suitable for high-speed and high-precision operations. Comparing to traditional DC motors-driven X-Y tables, the proposed actuator has a much simpler structure and is less expensive. It is more robust and fault tolerant, and has less overheating problem. The proposed direct drive 2D VR planar actuator has very low maintenance cost.

II. The overall motor structure

Fig. 1 shows the construction of the 2D VR planar motor. It 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 3-phase coil windings with wide magnetic teeth are employed on the moving platform. The wide magnetic teeth ensure that there is 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 resulting design is very similar to the Linear VR motor designed earlier [9, 10] by the same laboratory. The design of the "toothed structure" 2D planar motor is shown in Fig. 2.

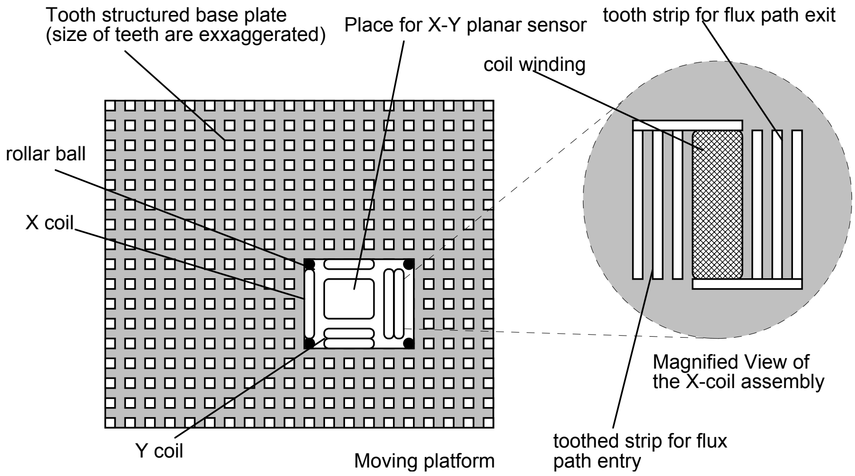


Fig. 2 Layout of the toothed structure base and the coil arrangement.

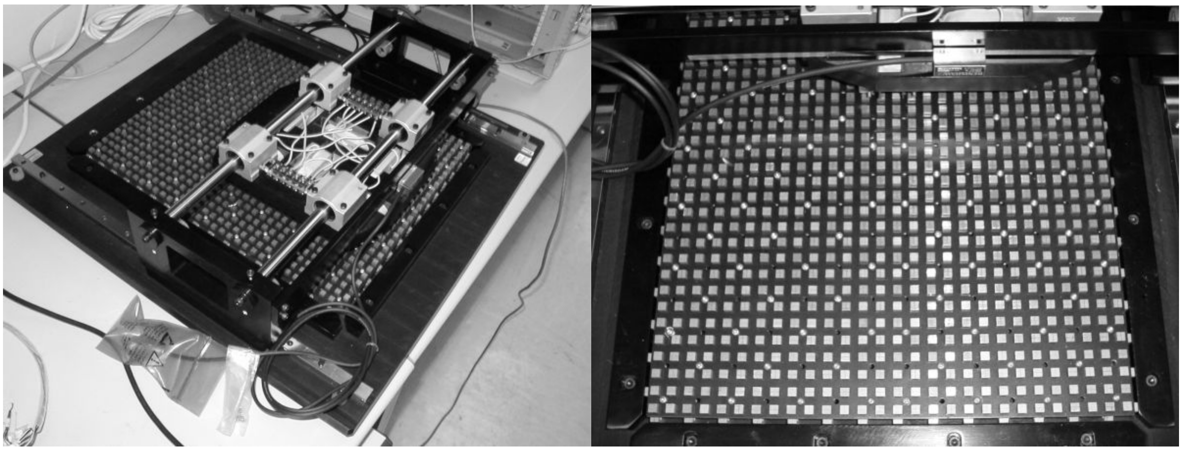
The base was manufactured from layers of laminated steel plates aligned in the X and Y directions. Two linear position encoders with resolutions of 1 μm are mounted onto the two ends of a moveable mechanical cross bar. The bar also acts as a restrictor to rotational movement on the moving platform. The final prototype has the following specifications:

Power output (X & Y axis)	80-100W	Travelling distance	300mm × 300mm
Resolution of planar encoder	1 micron	Acceleration/deceleration (expected)	>2G at 0.5kg load
Position Accuracy (expected)	±3 micron	Maximum Load	5kg
Tooth Pitch	5 mm	Size of base plate	450mm × 450mm

Table 1 Specifications of the 2D VR planar actuator

III. Fabrication of the motor

Fig. 3(a) and Fig. 3(b) show the actual appearance of the 2D VR planar motor. Two roller slides are employed to support the movement in the X direction, and another pair of linear guides are attached to the base to enable the motor to move in the Y direction.



(a) (b)

Fig. 3 Actual appearances of the 2D VR planar motor: (a) the overall motor structure, and (b) the laminated base plate

Fig.4 shows the arrangement of the magnetic circuit. A three phase flux de-coupled motor windings with longitudinal configuration is chosen because of the following advantages:

- The de-coupled flux windings lead to a simpler motor model due to zero mutual inductance.
- The individual phase windings reduce the manufacturing cost and complexity.
- Long travel distance can be accomplished easily by combining longitudinal track guides.

Altogether there are 6 coils, with 3 coils responsible for each direction. All six coils have same dimensions and ratings. By increasing the coil-teeth width, and make its dimension to be exactly the multiple of the teeth pitch, cross coupling of X-Y force can be minimised.

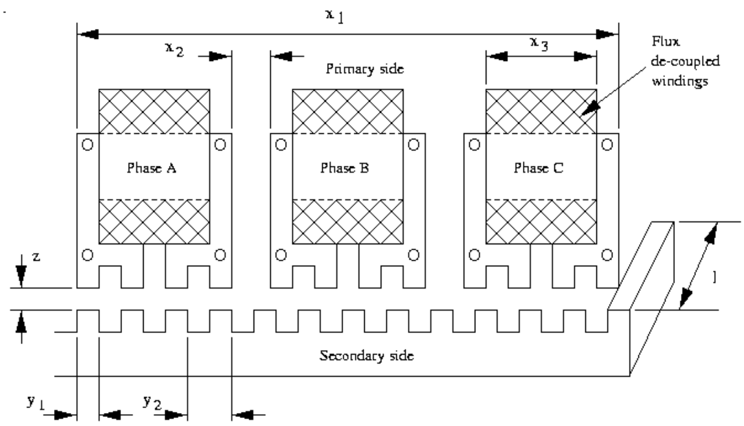
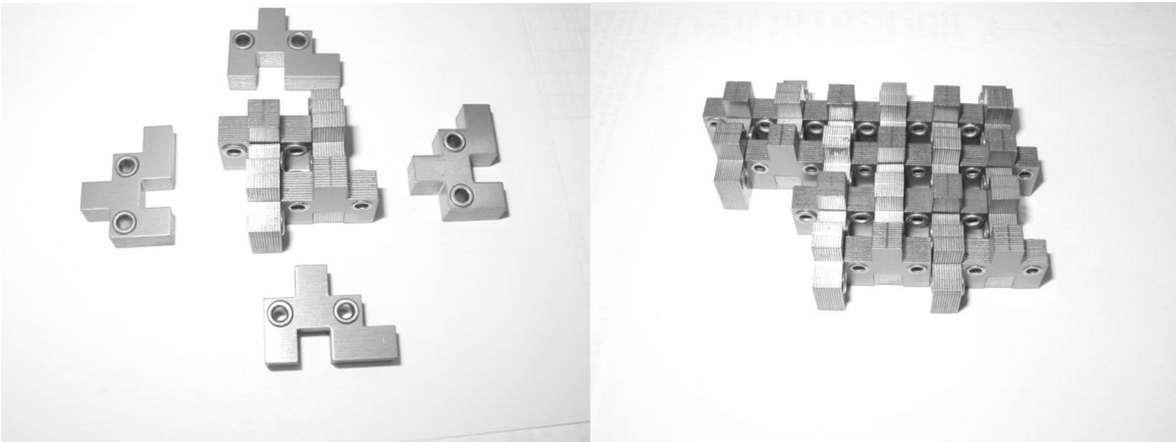


Fig.4 The coil structure and the magnetic circuit of the 2D planar motor

Fig. 5(a) and Fig. 5(b) show the construction of the toothed base plate. In order to simplify the construction, the base plate is constructed using the "LEGO" approach. The base plate is made up of small laminate blocks assembled together to form a large surface. This method of construction can reduce the manufacturing cost and simplify the overall construction complexity. Moreover, the same laminated blocks can be used to construct different sizes of base plate, according to different requirements and applications.



(a) (b)

Fig. 4 Construction of the laminated base plate: (a) the individual laminated blocks, and (b) forming the base with laminated blocks

IV. Flux and Force Measurement of the Prototype

Fig. 5 shows the actual measurement of force against position and current, and the 2D relationship of force and phase reluctance against distance, for one phase of the coil winding, along one direction of excitation. All indicators confirmed that the 2D VR planar motor is capable of delivering high-performance motions with appropriate control strategy. The actual measurement also reveals that there is very little force coupling between the X-axis and the Y-axis.

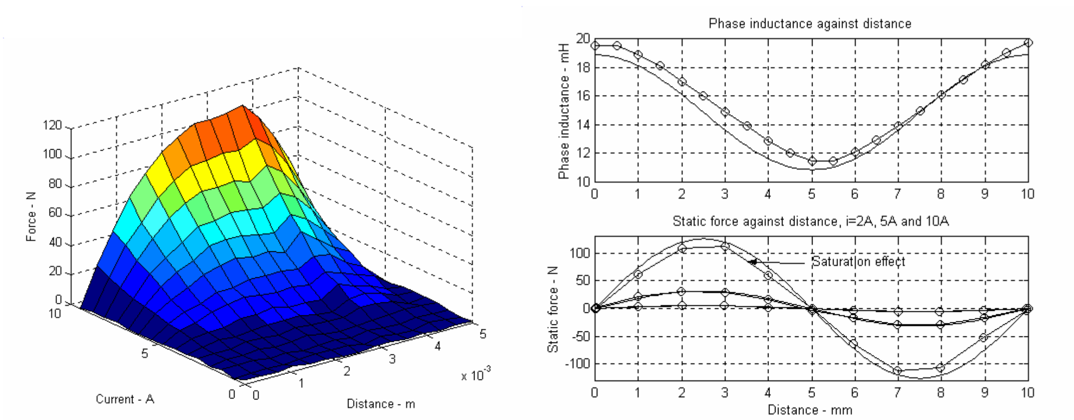


Fig. 5 Actual measurements of the 2D VR planar actuator

VI. Conclusion

This paper has described a novel planar motion actuator which has a simple and robust structure. The manufacturing procedure for the 2D VR planar motor is simple and straight forward: the moving platform houses 6 coils which can be made by coil winding machine individually. The base plate is constructed from small laminated blocks which can be manufactured separately. There is no need for the costly and complicated motor components of magnets, commutators, and complex windings. In this project, a 2D VR planar motor has been designed and fabricated. The measurements of the force and flux characteristics of the motor confirm that the proposed 2D VR planar motor is capable of delivering high performance motions. It is therefore an ideal replacement for traditional X-Y tables in industrial automation applications.

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