Design of Motorized Moving Stage with Submicron Precision

Tatag Lindu Bhakti[1], Adhi Susanto[2],
Paulus Insap Santosa[3], Diah Tri Widayati[4]
[1, 2, 3]Department of Electrical Engineering and Information Technology,
Faculty of Engineering, Gadjah Mada University.
Grafika Street No. 2, Yogyakarta, 55281. INDONESIA
[4]Faculty of Animal Sience, Gadjah Mada University
Fauna Street No. 3, Bulaksumur, Yogyakarta, 55281. INDONESIA

Abstract

A motorized moving stage with submicron precision is needed to support cellular manipulation e.g. in vitro fertilization in cattle breeding industry. This study aims to build an automatic moving stage prototype which has two degrees of freedom using hybrid stepper motor connected mechanically with rails of the microscope moving stage. Microscope stage movement is fully controlled using main software which connected logically to ATMEGA 8 through serial communication chip proxy FT232RL. Movement testing using OptiLab® Advanced image processing software show if motorized moving stage has smallest horizontal step resolution 0.198 ± 0.001 μm/step with hysteresis 5.99 ± 1.09 μm and smallest vertical step resolution 0.197 ± 0.004 μm/step with hysteresis 2.36 ± 1.28 μm in 16 sub-division microstep driver setting. Motorized moving stage has also linear response with R = 0.999 at various testing signal frequencies.

Keywords - Hybrid Linear Actuators, Stepper Motor, Motorized Stage, Microscope Moving Stage, Microstep Driver.

1. INTRODUCTION

Cellular manipulation in assisted reproduction requires supporting equipment to help livestock industry researcher and practitioner performs gamete cells micromanipulation with less error. The presence of submicron precision automatic moving stage in livestock breeding industry which can be fully controlled automatically using software is expected to reduce gamete fusion failure probability in assisted fertilization.

2. THEORETICAL BASIS

2.1. Stepper Motors

Stepper motors are type of motors which designed to be installed on open loop control system. Stepper motors generate discrete rotational movement which relevant to their loop resolution and can be operated accurately as predictions when worked below their holding torque limit.

There are three types of stepper motors: permanent magnet (PM), variable reluctance (VR) and hybrid [1][2][3]. Fig. 1 shows internal structure of three type's stepper motors. As its name implies, permanent magnet stepper motor has a permanent magnet drum on rotor core. Variable reluctance stepper motor utilizes stator magnetic induction to move soft iron materials contained on its rotator, whereas hybrid stepper motor combines working principles of PM and VR stepper motors with jagged-magnetic surface design profile to create high-resolution rotary step through caliper (vernier) principle.

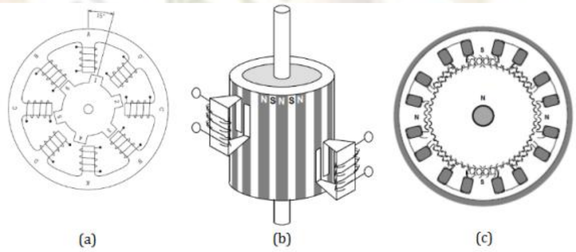

Fig. 1 Motor Structures (a)VR, (b)PM and (c)*Hybrid* [2][3]

2.2. Microstep Control

Stepper motor can be controlled using four methods; wave step control, full step control, half step control and microstep control. In wave step control method, rotor movement is fully controlled using single solenoid excitation while in full step control; rotor movement is controlled using a pair of opposite solenoid excitation. In half step control, two pairs of stator solenoid excitation result a certain angle of attack according to its rotating center and in microstep control method, stepper motor is controlled similarly with half step, but with advanced phase-current control on each active solenoid to make more precision step movement.

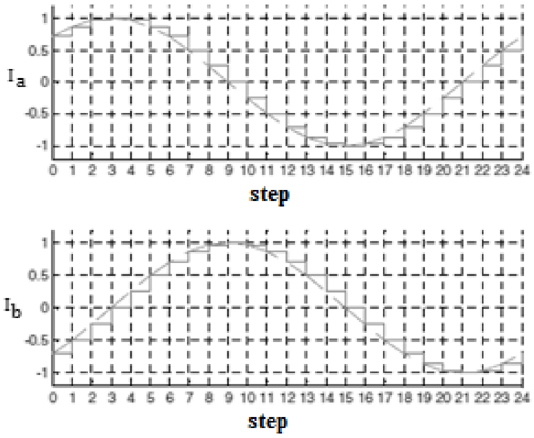

Fig. 2 Current Control in Each Phase to Create Microstep movement [4][5]

There are three type's microstep control techniques; square line path, circle line path and random line path. In square line path control, final torque magnitude which generated through interaction of two pairs solenoids is always greater than or equal to maximum torque generated from single solenoid element. In circular line path control, final torque magnitude is always equal to maximum torque generated from single solenoid element. While in random line path control, final torque magnitude has arbitrary value depends on interaction between each active solenoid. Fig. 3 shows illustration of each microstep control techniques.

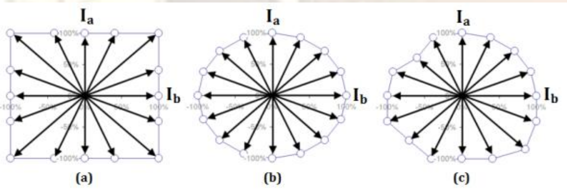

Fig. 3 Three Types of Microstep Control Techniques. (a)Square Line path, (b) Circular Line path and (c) Random Line path[5]

If I_a represents amount of electrical current passing through first phase of solenoid series, I_b represents amount of electrical current passing through second phase of solenoid series and R is total resistive barriers at each phase, then power dissipation of microstep control (P) can be formulated as follows (1)

$$P = \left(I_a^{\,2} + I_b^{\,2}\right) R \qquad (1)$$

with angle of attack (θ_R) (2)

$$\theta_R = tan^{-1}\left(\frac{I_a}{I_b}\right) \qquad (2)$$

2.3. Hybrid Linear Actuator (HLA)

HLA is a linear actuator consisting of hybrid stepper motor with extended rotator shaft paired with screw cap to convert rotational movement into linear movement. Fig. 4 shows the physical appearance of HLA external type.

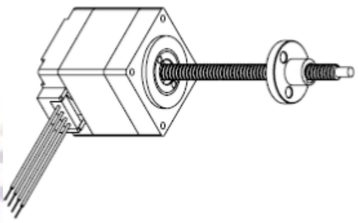

Fig. 4 HLA External Type [6]

Fig. 5 shows converting mechanism from rotational movement into translational movement in HLA threaded shaft. Assuming all of rotational steps can be perfectly transformed into linear steps, amount of the linear displacement can be calculated using (3)

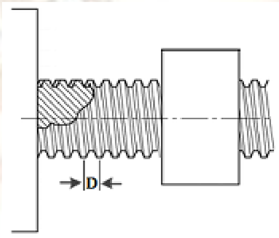

Fig. 5 Converting Mechanism of Rotary Movement into Translation Movement in HLA

$$l = \left(\frac{D}{N}\right) n_r \qquad (3)$$

l is amount of linear displacement came from rotational movement, D is distance between corresponding screw "teeth" (see Fig. 5), N is number of full turning steps are needed by system to make one full rotation (360°) and n_r is number of steps generated from stepper motor. Amount of N can be calculated using (4)

$$N = \frac{360^{o}}{u} \qquad (4)$$

Equation (4) shows that N depends on u value which represents smallest full step resolution which can be generated by stepper motor without has a slip and without microstep driving emulation.

2.4. ATMEGA 8 Microcontroller

Microcontroller is electronic devices which can be programmed to execute specific application routine. Physically, microcontroller is an integrated circuit consisting of main processor, Random

Access Memory (RAM), permanent memory (ROM) and input/output pin which can be utilized to make communication with external devices.

Fig. 6 ATMEGA 8 Microcontroller [7]

Fig. 6 shows physical appearance of ATMEGA 8 microcontroller. In accordance to [7], ATMEGA 8 is an 8-bit microcontroller produced by ATMEL Corp. and come with 8 Kbyte Flash PEROM (Programmable and Erasable Read Only Memory) used to store main code. ATMEGA 8 processor can work up to 16 MHz clock frequencies and designed using RISC (Reduced Instruction-Set of Computing) processor architecture named ATMEL AVR®.

3. CONSTRUCTION OF MICROSTEP DRIVING MECHANISM

The single axis model of microstep driver consists of four main parts: displacement-to-pulse accumulation converter to translate set point displacement into its associative pulse amount, pulse generator, microstep movement controller and hybrid linear actuator which driven by hybrid stepper motor to handle microstep's movement on each stage axis. Movement control mechanism is designed without feedbacks assuming HLA is loaded under its holding torque limit to avoid any slips step. Fig. 7 shows microstep movement control algorithm.

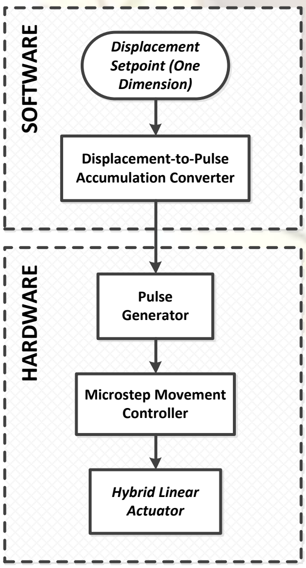

Fig. 7 Control Algorithm of Single Axis Motorized Moving Stage

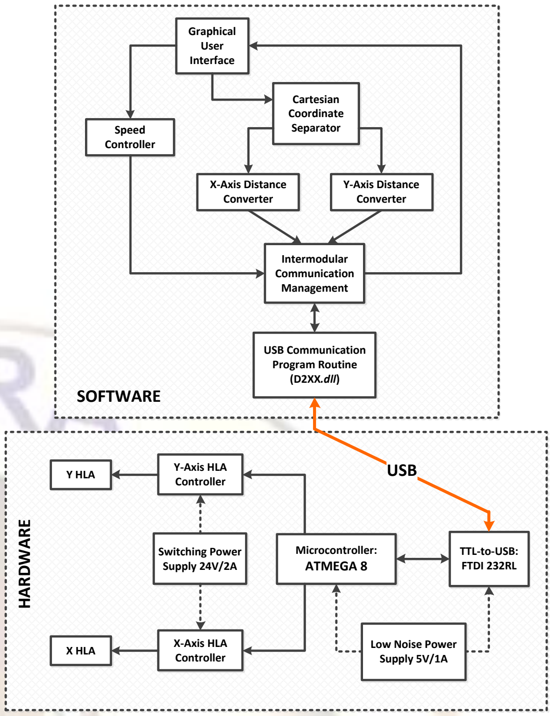

Fig. 8 Block Diagram of Motorized Moving Stage Control

Motorized moving stage consists of software and hardware parts which can be communicated each other through USB (Universal Serial Bus) as shown in Fig. 8. Main software is used to make set point input for control system, set HLA's motion speed and calculate associative amount of pulse needed to make precision movement using constants calibration which has been recorded in software code. Hardware is used to generate real pulse signal as ordered from software and realize it into physical movement steps with submicron precision. An anti-backlash mechanism is attached on HLA to minimize translational hysteresis emerging at movement conversion process as shown in Fig. 9.

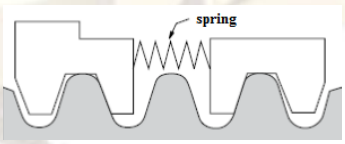

Fig. 9 Anti-Backlash Principle

Anti-backlash mechanism using spring elasticity properties to give initial force on a pair of linear actuator nut to reduce spatial clearances area which occurs in mechanical contact area between threaded shaft's surface and nut inner surface. This anti-backlash mechanism has been built to increase HLA's precision movement.

4. RESULTS OF MOTORIZED MOVING STAGE DESIGN

HLA is driven by two phases-hybrid stepper motor with dimension code: NEMA (National Electrical Manufacturers Association) 11 as shown in Fig. 10. Stepper motor has working voltage 4.0V/0.95A per phase and has full turning step resolution (u) 1.8°±5%. Movement converter attached on HLA's shaft with theoretical value $\frac{\partial l}{\partial n_r}$ 3.175 µm per full step (1.8°).

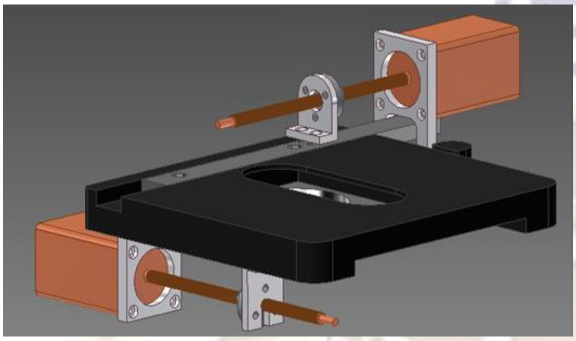

Fig. 10 HLA Installation on Microscope Moving Stage (X-Axis and Y-Axis)

Each step movement of HLA's motor is controlled using microstep driver which pre-programmed using denumerator constant value as listed in Table I. Theoretically, microstep driver can handle stepper motor current up to 1.5 A per phase at maximum working frequencies (20 KHz). Fig. 11 shows HLA installation in XZS HLA-107BN biological light-microscope.

Table I. Implications of Denumerator Constant Setting upon Linear Resolution Movement

Denumerator Constant (Sub-Division)	**Theoretical Value: $\frac{\partial l}{\partial n_r}$ (µm/ pulse)**
1	3.1750
2	1.5875
4	0.7938
8	0.3969
16	0.1984
32	0.0992
64	0.0496

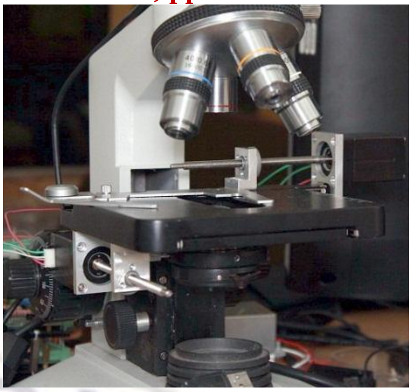

Fig. 11 HLA Assembled in XZS-107BN Stage

Red circle in Fig. 12 shows a limit switch providing emergency stop for XY movement. It used to make emergency stop and set zero point reference for each axis. Movement restriction procedure is necessary to protect HLA from overdriving which potentially damaging mechanical structures.

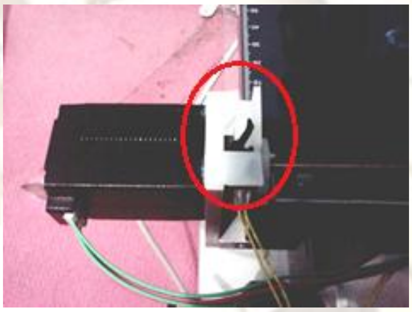

Fig. 12 HLA's Limit Switch

To get near-integer value of step movement but still provides sufficient torque, stepper motor driver is programmed at 16 sub-division setting value with maximum operating frequency 18,519 KHz (pulse period 54 µs). According to Table I, 16 sub-division setting value will produce 3,675 µm/sec with 0.198 µm/step resolution on each axis. Its driver setting allows HLA to make 1 µm (approx.) displacement using 5 pulses.

5. TESTING RESULT

5.1. Linearity Testing

Linearity testing of motorized moving stage prototype is performed by actuating microscope's stage independently in one axis direction then stage position is measured using 10 µm objective micrometer which interpolated using OptiLab® Advanced image processing software. Fig. 13 shows linear movement testing result.

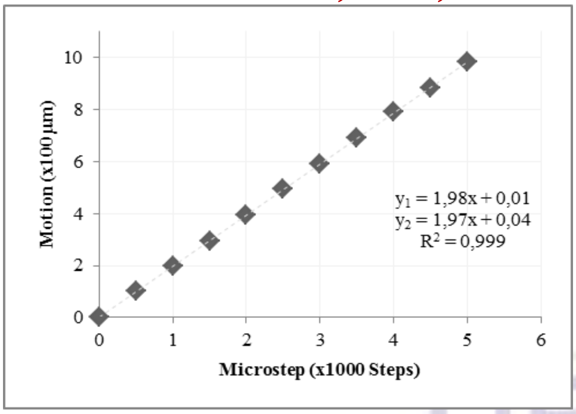

Fig. 13 Linear Response of Motorized Moving Stage Prototype

Fig. 13 show motorized moving stage has average horizontal microstep repeatability 0.198 ± 0.001 µm/step (y1) and vertical microstep repeatability 0.197 ± 0.004 µm/step (y2). Motorized moving stage has also linear response with R = 0.999 at various testing signal frequencies.

5.2. Hysteresis Testing

Hysteresis testing is performed by actuating microscope's stage backward and forward 20 times repeatedly to obtain hysteresis response of motorized stage. Fig. 14 shows results of hysteresis testing using 10 µm objective micrometer reference which interpolated using OptiLab® Advanced image processing software

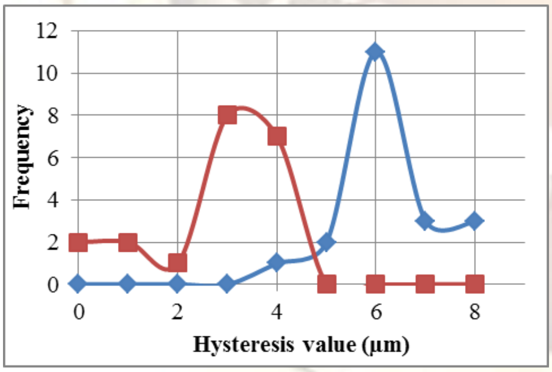

Fig. 14 Hysteresis Response of Motorized Moving Stage Prototype

Testing results in Fig. 14 shows motorized moving stage has average horizontal step hysteresis 5.99 ± 1.09 µm/step (diamond dots) and average vertical step hysteresis 2.36 ± 1.28 µm/step (square dots).

CONCLUSION

Testing results show motorized moving stage prototype has horizontal step resolution 0.198 ± 0.001 µm/step with hysteresis 5.99 ± 1.09 µm and vertical step resolution 0.197 ± 0.004 µm/step with hysteresis 2.36 ± 1.28 µm with maximum speed 3,675µm/sec in 16 sub-divisions microstep driver setting. Motorized moving stage has linear response with R = 0.999 at various testing signal frequencies.

ACKOWLEDGEMENTS

Authors would thank to all of Civitas Academica Electrical Engineering Department and Animal Science Department Gadjah Mada University and PT. Miconos Transdata Nusantara (www.miconos.co.id) which provided facility for motorized moving stage testing and calibration.

REFERENCES

[1] T. Kenjo, Stepping Motor and Their Microprocessor Controls, *Monographs in Electrical and Electronic Engineering*, (Oxford University Press New York, ISBN 0-19-859326-0, 1984).

[2] F. Eriksson, Stepper Motor Basics, *Industrial Circuits Application Note*, 1998.

[3] P. Yedamale and S. Chattopadhyay, Stepper Motor Microstepping with PIC18C452, *AN822 Article*, Microchip Technology Inc., 2002.

[4] X. Ma, G. An, and B. Li, Design and Implementation of an Automated Microscope Stage, *International Forum on Information Technology and Applications*, ISBN 978-0-7695-3600-2/09, DOI 10.1109/ IFITA.2009.268, 2009, 603-605.

[5] Tutorial Microstepping, Available [*Online*] at http://www.zaber.com/wiki/Tutorials/ Microstepping.htm, retrieved on 18 July 2012.

[6] Datasheet: Hybrid Linear Actuator 11E2045A4-095-001, Available [*Online*] at http://www.ms-motor.com/

[7] Datasheet: AT MEGA 8/L (Rev.2486Z–AVR–02/11), Available [*Online*] at http://www.atmel.com/