# Development of Limited Angle Brushless Torque Motor Control Drive for Scan Mirror Mechanism

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***Abstract*— This paper illustrate the design and realization of control drive electronics of Limited Angle brushless torque motor for position control of Scan mirror mechanism. The scan mirror mechanism is controlled for the intended limited mechanical angle within +/- 20deg. The control drive is designed for six selectable positions within +/- 20deg with an accuracy of 0.75 degree. These six selectable positions are achieved with rates of 1 deg/sec, 2 deg/sec and 3 deg/sec according to the requirement. The control input to the drive electronics is given through PC interface for the required position and rate. The input/output is presented in GUI front end. The instantaneous data of present position and rate of the scan mechanism is logged in PC for reference.**

**Keyword- Control drive, PC interface, Permanent magnet motor, Digital control, scan mechanism.**

## I. INTRODUCTION

Permanent Magnet(PM) Brushless motors have gained its popularity due to many contributing factors like advancement of power electronics, invention of the high power density type PM [1], advancement in microelectronics field which offers abundant functionality[1],[2] and cost effective solutions. If modern control techniques are implemented these high field PM machines have good servo performance. They are suitable as direct drives in robotics, optical scanning automation for speed and position control. Moreover Brushless motor is preferred than DC commutator motor, due to the advantages like high torque to weight ratio, high reliability, precise positioning, and maintenance free operations. Applications such as optical scanning, thermal imaging, servo valves, scan mirror mechanism, direct laser mirrors, position missile-guidance radar antennas, open shutters for heat-seeking sensors requires a small electrical signal to be converted into limited mechanical rotation. In scan mirror mechanism the mirror has to scan E/W and N/S directions with intended angle resolution, accurate slope, pointing accuracy, low jitter and controllability. In such mechanisms Brushless Limited Angle Torque motor is widely used [3] and hence a simple and compact drive is attempted for such motor.

## II. BRUSHLESS LIMITED ANGLE TORQUE MOTOR

Limited angle Brushless Torque (LABLT) motor is a rotary electromagnetic actuator. The rotor in a LABLT carries field magnets, and the stator supports armature windings (similar to the construction of conventional brushless motors). LABLTs, however, are wound single phase, unlike conventional brushless types, which are typically wound for two or three-phase operation. Single-phase construction eliminates the need for commutation circuitry [4] thus reducing the cost of the motor.

Dawson et.al developed torque motor based on the polarized reluctance principle[5] while Zhang constructed the Limited angle motor based on laws of relay principle[3] and the motor designed by Murali Krishna and Kannan had a toroidal wound slotless configuration for accomplishing accurate tracking[6]. Hence in this paper the control drive is configured for toroidal wound slotless brushless configuration of Limited angle torque motor.

Armature windings in some limited-angle torquers are embedded in slots around the inside periphery of a laminated stator, a construction similar to that used with conventional brushless motors. The rotor in a limited-angle torquer carries field magnets, and the stator supports armature windings (similar to the construction of conventional brushless motors) as shown in Fig.1. Slot-wound LATs exhibit higher motor constant than corresponding toroidally wound types. The primary reason is that a larger number of conductors can be exposed to the magnetic field. In slot-wound LATs, heat is more easily conducted from the armature core to the outer housing than in toroidal versions, which can rely only on the mounting tabs for heat conduction. Thus, slot-wound types generally can carry heavier loads than corresponding toroidally wound motors. Slot-wound LATs, however, exhibit more torque ripple (cogging) and generate greater friction and hysteresis losses [5].

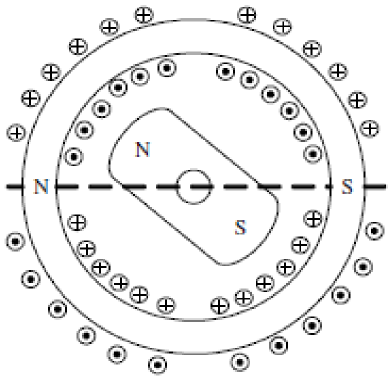


Fig. 1. Configuration of LABLT

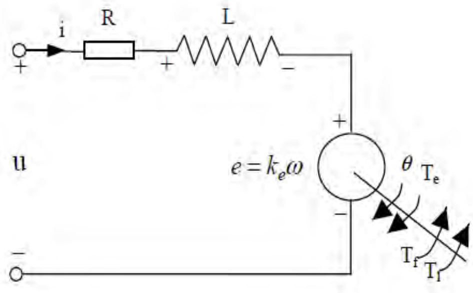


Fig. 2. Equivalent circuit of LABLT

With reference to the equivalent circuit shown in Fig.2 of LABLT the dynamic equation can be written as

$$u = iR + L\frac{di}{dt} + k_e\omega \tag{1}$$

$$T_e = J\frac{d\omega}{dt} + T_f + T_l \tag{2}$$

Where u,i are winding voltage and current. R,L are the winding resistance and inductance, $K_e$ is the back-EMF constant, θ, ω, j are the rotor position, speed and rotor inertia. $T_l$,$T_e$,$T_f$ are load torque, electromagnetic torque and friction torque respectively.

With $\frac{d\theta}{dt}$ = ω and assuming friction torque as negligible. State-space approach to equation (1), (2) yields,

$$\begin{bmatrix} \frac{di}{dt} \\ \frac{d\omega}{dt} \\ \frac{d\theta}{dt} \end{bmatrix} = \begin{pmatrix} \frac{-R}{L} & \frac{-k_e}{L} & 0 \\ \frac{k_t}{J} & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} i \\ \omega \\ \theta \end{bmatrix} + \begin{bmatrix} L^{-1} \\ 0 \\ 0 \end{bmatrix} u \tag{3}$$

where $k_t$ is torque coefficient. Equation 3 gives the relation between electrical and mechanical variables. Since the magnetic field is constant, the developed torque in LABLT is proportional to the current applied across the coil.

*A. Limited Angle motor control range*

The torque characteristics of LABLT motor under test is shown in the Fig.3. It has a constant torque region of over ±20 degree. LABLT armature design is a single phase toroidal winding around the armature core, divided into four segments for four poles and each winding spread over 85deg mechanical on the stator lamination stack. The permanent magnet rotor assembly has four magnets mounted on the magnetic stainless steel ring in order to provide uniform torque for ±20 deg.

*B. Requirement Specifications*

The requirement of drive electronics for LABLT is as follows,

1. Sweep angle required **:** +/- 20 deg
2. Position accuracy **:** 0.75 deg
3. Input voltage **:** +/-12V and +5V
4. Rate selection **:** 1 deg/sec, 2deg/sec , 3 deg/sec
5. PC Interface **:** RS 232
6. Position sensor **:** 10bit absolute encoder

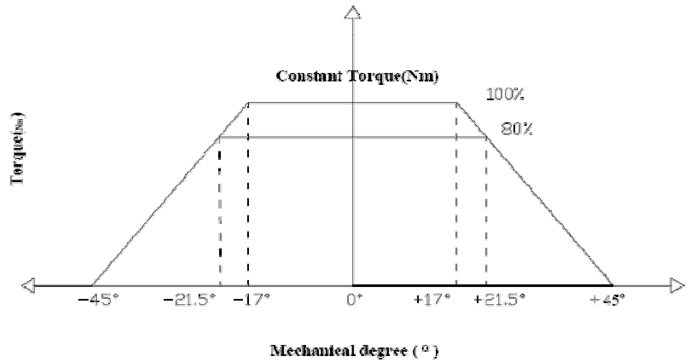


Fig. 3. LABLT Characteristics

## III. CONTROL DRIVE ELECTRONICS

### *A. Functional Block Diagram*

A simple and cost effective control drive electronics for LABLT motor is designed for meeting the above requirements using digital implementation of Proportional Integral and Derivative (PID) controller with PIC18F4455 Microcontroller. The functional block diagram is shown in Fig 4. At every sampling interval (10ms), the set input rate as well as absolute LABLT position is read in the PIC Microcontroller. Measured LABLT rate is expressed as

$$\text{Measured LAT Rate} = (\text{LABLT}_{\text{present position}} - \text{LABLT}_{\text{previous position}}) * k \quad (4)$$

where k is constant

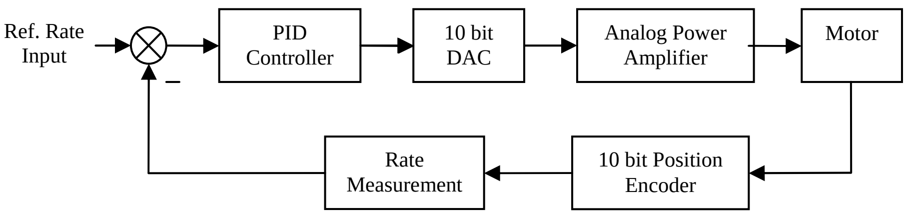


Fig. 4. Control electronics block diagram

The Error rate is computed by subtracting the measured LAT rate from the set input rate. This error rate will be input to the PID controller. The controller computes the output for the given error rate. The controller output is transferred to 10-bit Digital to Analog Converter (DAC) to regulate the LABLT coil current. The DAC output is amplified by an analog power amplifier, which feeds the actual current to the LABLT coil. The LABLT torque thus produced is proportional to the current supplied to the LABLT coil.

### *B. Digital PID Implementation*

The analysis for designing a digital implementation of a PID controller in a Microcontroller (MCU) or FPGA device requires the standard form of the PID controller to be discretised [7-9]. Defining $u(t)$ as the controller output, the final form of the PID algorithm is obtained as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (5)$$

Where

$K_p$ **:** Proportional gain, a tuning parameter

$K_i$ **:** Integral gain, a tuning parameter

$K_d$ **:** Derivative gain, a tuning parameter

$e$ **:** Error

$t$ **:** Instantaneous time (the present)

Approximations for first-order derivatives are made by backward finite differences. The integral term is S discretised, with a sampling time Δt as follows,

$$\int_0^{t_k} e(\tau)\,d\tau = \sum_{i=1}^{k} e(t_i)\,\Delta t \qquad (6)$$

The derivative term is approximated as,

$$\frac{de(t_k)}{dt} = \frac{e(t_k) - e(t_k - 1)}{\Delta t} \qquad (7)$$

Thus, a velocity algorithm for implementation of the discretised PID controller in a microcontroller is obtained by differentiating $u(t)$, using the numerical definitions of the first and second derivative and solving for $u(t_k)$ and finally obtaining

$$u(t_k) = u(t_{k-1}) + k_p \left[ \left( 1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t} \right) e(t_k) + \left( -1 - \frac{2T_d}{\Delta t} \right) e(t_{k-1}) + \frac{T_d}{\Delta t} e(t_{k-2}) \right] \qquad (8)$$

For every sampling interval, the error value $e(t_k)$ will be computed and substituted in the above equation thereby to compute the controller output. The controller output is scaled to suitable gain and transferred to DAC to adjust the LABLT current based on the required torque output.

*C. Circuit simulation and realisation of control circuit*

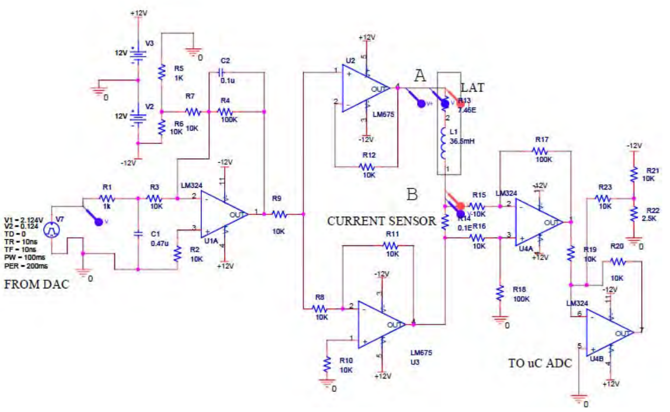


Fig. 5 Schematic for control voltage range verification

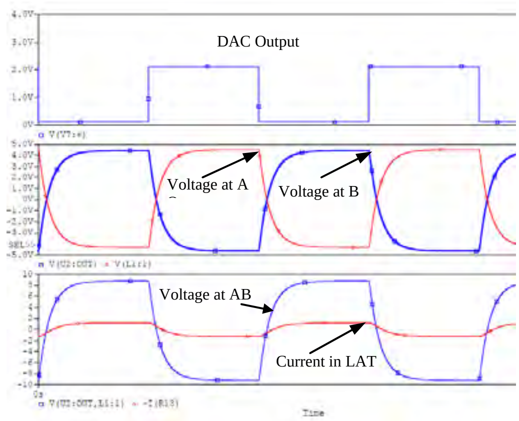


Fig. 6 Controller Output waveform

The LABLT drive control circuit is planned with PIC18F4455 Microcontroller for controlling the gain, a Serial 10-bit DAC, DAC signal conditioning circuit and analog power amplifier. In addition, it has the provision to read the user input as well as 10 bit parallel Encoder interface to read LABLT absolute position. Schematic is shown in Fig.5 is simulated for validation of control range, response and accuracy. The results of simulation assures that a position accuracy of 0.5 degree achievement as shown in the Fig.6.

An RC circuit to MCLR pin will serve as reset for the microcontroller. PIC microcontroller has the limitation of DAC hence an external serial DAC is interfaced with PIC. The DAC is of 10-bit resolution and can be operated with +5V supply. The DAC has internal voltage reference of 2.048V with a thermal stability of 50ppm/°C. The DAC output is configured as 0V to 4.196V by using the internal amplifier, which amplifies the reference to a gain of 2. The DAC output update is step change in nature. In order to minimize this stepping noise, a single pole RC filter is designed for the DAC output.

The LABLT requires positive and negative currents for rotation in forward and reverse direction respectively. Since the DAC polarity is positive (0V to 4.196V), a level shifter and gain stage is used to convert the positive DAC output voltage to bidirectional output (-7.42V to +8.57V).

Analog power operational amplifier which will deliver up to 3amp current to the load is chosen. Further the amplifier is checked for internal compensation to support high bandwidth operations. In addition to power opamp to control the LABLT more effectively, a push-pull power configuration is selected. This will provide additional amplification factor of two [10],[11]. In this configuration, one end of LABLT is connected to buffer power amplifier output, whereas the other end of LABLT is connected to inverted power amplifier. If the buffer amplifier is sourcing, the inverting amplifier is sinking the current from the LABLT coil. In this way, the additional amplification factor 2 is achieved.

Peak torque demand 2.5 Nm is achieved within limits with the help of current controller circuit. Current to the LABLT coils is sensed by two numbers of parallel connected 0.2E /2W resistor with the coil. The control signals are manipulated by carrying the obtained equivalent voltages in proportion to the conditioned load current to PIC Microcontroller. A 10-bit absolute encoder of Autonics make is selected for LABLT rotor position measurement and to achieve the position accuracy requirement. The outputs are parallel 10-bit with PNP open collector [12]. The output is 10-bit binary format with a resolution of 0.35 degrees. The encoder outputs are of PNP open collectors and are terminated with 10KΩ resistors. The PIC digital I/O ports (PORT D and PORT B) are configured as input port to read the encoder data. Thus with the data of the simulation the design of control circuit is finalised and the layout is realised for PCB fabrication and subsequent soldering. Finished PCB with components is compact as shown in Fig.7

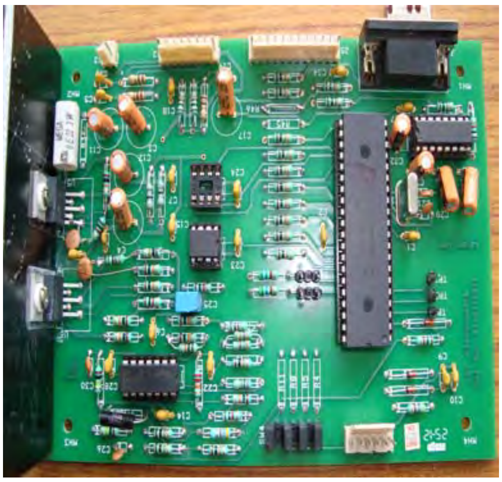

Fig.7. LABLT drive control board

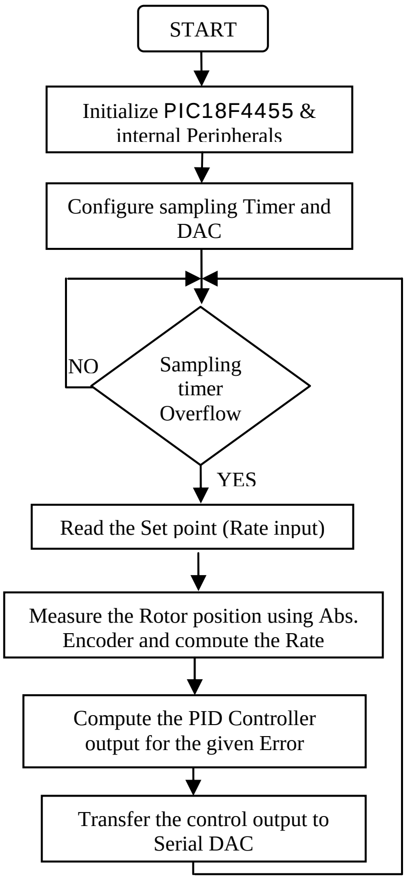


Fig 8. PIC Control program flow chart

*D. Control Software*

The software is designed using PIC cross compiler, which is a C compiler for PIC18 series devices. The software is single monolithic code started execution after the reset exception occurred. With reference to the program control flow shown in Fig.8 at any instance the set rate will be read first and followed by reading the encoder angle. The encoder rate is computed by subtracting the present angle position with the previous sample interval encoder position[13]. The controller error is computed by subtracting the measured rate from the set rate. The computed error will serve as input to the PID controller.

Once an error rate computation is completed, the discretised PID equations are obtained to compute the correction required. The controller output is scaled to suit 10-bit DAC and transferred to the serial DAC, which in turn controls the current flowing to the LABLT coils. The same control program is repeated for every sample interval .

*E. PC Interface and Data Logger*

PC interface is accomplished through RS232 communication interface. Although the traditional methods are intelligent and failsafe the interface is complex[14] in addition to interface, modern control needs data to be collected and stored. The 5 pin D connector is provided for connecting PC with drive electronics and 9 pin D connector is provided for connecting the drive electronics with encoder. The power connector is used to interface the LABLT motor armature terminals and power supply with the module.

From the GUI interface front end snap as shown in Fig.9 reveals the following data can be had which is logged for future reference in a .txt file.

- Port address represents the port of PC to which the LABLT electronics is connected.
- 9 preset selectable position input are designed between +20deg and -20deg at three selectable rates.
- Three rate input selection command for 1deg/sec, 2 deg/sec and 3 deg/sec
- Hex value of +30deg and -30deg input can be given to the program by clicking the XSend and YSend buttons.
- Present position of LABLT rotor is given in degrees.

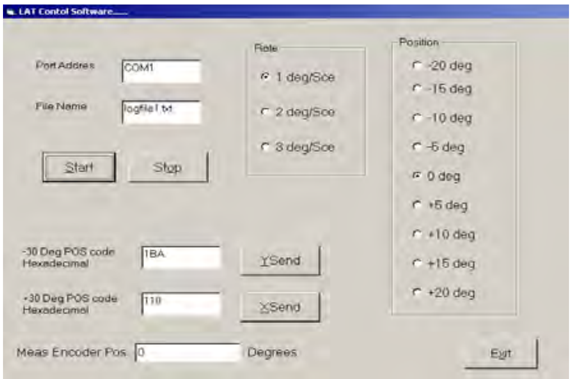


Fig 9. LABLT software GUI

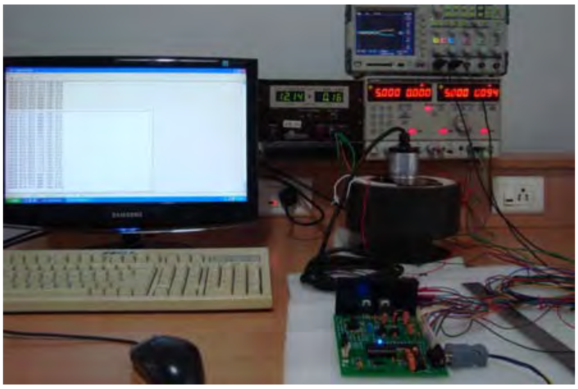

Fig 10. LABLT test setup

*F. Test setup, Results and Discussion*

The snap shot shown in Fig.10 is the test setup conducted at Sona SPEED lab for validation of position and rate requirements. To validate the requirement of 6 selectable positions between +/- 20deg with a position accuracy of 0.75deg the following inputs were chosen between +/- 20 deg and its corresponding observed LABLT position is noted from LABLT Control software GUI and tabulated below.

TABLE I
TEST RESULTS

| S.No | Rate = 1deg/sec | | Rate = 2deg/sec | | Rate = 3deg/sec | |
|---|---|---|---|---|---|---|
| | **Position Input in deg.** | **Position Observed in deg** | **Position Input in deg** | **Position Observed in deg** | **Position Input in deg** | **Position Observed in deg** |
| 1 | -20 | -20.03 | -20 | -20.03 | -20 | -20.03 |
| 2 | -15 | -15.11 | -15 | -15.11 | -15 | -15.11 |
| 3 | -10 | -9.84 | -10 | -9.84 | -10 | -9.84 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 5 | 4.92 | 5 | 4.92 | 5 | 4.92 |
| 6 | 10 | 9.84 | 10 | 9.84 | 10 | 9.84 |
| 7 | 15 | 15.11 | 15 | 15.11 | 15 | 15.11 |

For the tested toroidal wound LABLT motor (Refer annex for specifications) at SonaSPEED lab and from the tabulated results it is found that a position accuracy of 0.2 deg is achieved which is well above the required specification of 0.75 deg position accuracy.

## IV. CONCLUSION

The drive electronics thus designed is developed and demonstrated for six selectable angles within +/- 20deg with a position accuracy of 0.2degree and to drive the LABLT motor for selected command rate of 1 deg/sec,

2 deg/sec and 3 deg/sec thus meeting the requirement specifications.

The control software and PC interface GUI gives the operator to command the motor easily from the front panel for the required position and rate without any special skill sets. The data is logged automatically in .txt file which can then be used for reference.

ACKNOWLEDGMENT

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Appendix
LABLT motor Specifications

| | | | |
|---|---|---|---|
| 1. | Peak torque | : | ±2.5 Nm |
| 2. | Peak power | : | 50 watts(max) |
| 3. | Constant torque region | : | ± 20º |
| 4. | $K_t$, $K_b$ | : | 1.25 ± 7 % |
| 5. | Electrical time constant | : | 4.0 ms ± 30 % |
| 6. | Operating voltage | : | 28 V |

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