Tiger Tunable Lens Card (TGTLC)

Description

The TGTLC is a Tiger card that can power 2 Electrically Tunable Lenses (ETL) such asOptoTune's EL-10-30.

ETLs are polymer lenses whose curvature and thus focal length can be changed by applying current. They are available with diverse cover glass coating and optional offset lens.

Features

- TGTLC card can control up to 2 Electrically Tunable Lens (ETL) (such as C60-Tunable 4F assemblies)
- Control with serial commands, manual input devices (knob or joystick), or a 0-5V analog signal
- Open loop control
- Very fast, 15ms transient response. Resonant frequency at 150Hz and 600Hz.

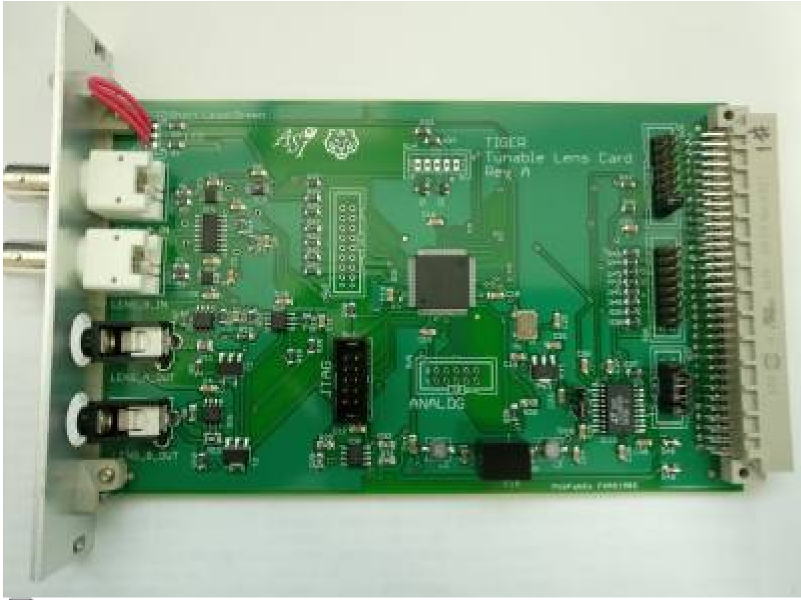
Applications

- Potential substitute for piezo-based focus devices depending on specifics (especially low-mag, low NA), e.g. can acquire Z series without moving the objective
- Performs like a continuous focus device when used with the ASI XYZ Tracker Plugin in Micro-Manager.
- Axial sweeping of beam focus in light sheet microscopy (e.g. be added to FIBER-COUPLED LASER SCANNER)

Electrical Characteristics

- Maximum output Voltage, 6 Volts
- Maximum output current, up to 290 mA per channel. (On RevA and A2 cards max current was only 200 mA)
- Current resolution, 4.4 µA. (On RevA and A2 cards current resolution is only 50 uA)

Tiger Card



TGTLC: Tiger Tuneable Lens Card

Front Panel

Rev A2 (Click to Enlarge)

On RevA2 and above cards, the BNC connectors are dual purpose. By arranging jumpers in certain way, the BNC can be used for TTL IN and OUT triggering, or used to control the Tunable lens with a external analog input control (0-5 V).

Rev A (Click to Enlarge)

On RevA cards, the BNC connectors are hardwired for External input control

WARNING!! DO NOT connect Tunable Lens to TGLED cards, it has same 3.5mm mono connectors. The TGLED card will fry it. The TGLED card outputs currents at 900 mA, while the Tunable lens can only handle currents up to 400 mA. This issue has been resolved in newer version of TGTLC cards where a 6pin Circular connector is used instead of 3.5mm mono connector.

Operation

Control

TGTLC lets the user control a Electrically Tunable Lens(ETL) either in **Internal** mode or **External** mode. TGTLC card mode can be set with the PM command.

In **Internal** mode, the user can adjust the ETL's focal length with serial commands like MOVE MOVREL or with manual input devices like Joystick and Knob. Refer to JOYSTICK command for more info.

In **External** mode, the user can adjust the ETL's focal length with a 0-5V analog signal.

The TGTLC card is a constant current driver, it converts the user input into a currents (up to 290ma) that is applied to the ETL to produce a change in its curvature which results in the focal length change.

Units/Resolution

Post firmware version 3.19

User has two options for unit ie user input when commanding their ETLs. First is a 16-bit abstract integer, another is diopters. User can pick their preferred units with Command:PR.

- The abstract units, its a 16 bit integer. This replaces the previously 4000 count default axis profile B1.
- Upper limit is **32768** with 290 ma of current, lower limit is **-32768** with 0 ma of current, and default starting position is **0**.
- **1** is the smallest step change possible, which causes 4.4µA change in current applied to ETL.

- The second option is in 1/1000 of diopter(dpt). ETL's manufacture calibrated the ETL in factory and stored the diopter vs current curves on the ETL's EEPROM. TGTLC RevB and above cards are able to read this data, parse it and calculate the slope and intercept from this data. Its then able to accept user input in 1/1000 of a diopter and calculate the current it needs to apply to the ETL to get the desired diopter.
- This option is also available on older RevA and A2 cards, which can't read the eeprom data, instead they go by default values.

Pre firmware version 3.19

- With the default axis profile (B1), ETL's upper limit is **2000**, lower limit is **-2000**, and default starting position is **0**.
- Total travel is **4000** counts
- **1**is the smallest step change possible, which causes 50µA change in current applied to ETL.

Note: An ETL has no feedback sensor. The TGTLC card is operating the ETLs in an open loop. The current applied is regulated. Between aging, temperature effects, there may be error in the user input and actual diopter observed.

Example

Let's say the Electrically Tunable Lens (ETL) axis letter is **V**.

```
M V=-32768
:A
```

The above command would move the ETL to lower limit, where 0 amps of current would be applied ETL

```
M V=-32767
:A
```

The above command would move the ETL to slightly above lower limit, where 4.4µA of current would be applied ETL

```
M V=0
:A
```

The above command will move the ETL to middle of the travel range by applying 145mA of current.

```
M V=32768
:A
```

The above command will move the ETL to upper limit of the travel range by applying 290mA of current.

Anti-Aliasing Filter

This option has been removed in TGTLC RevC cards and above.

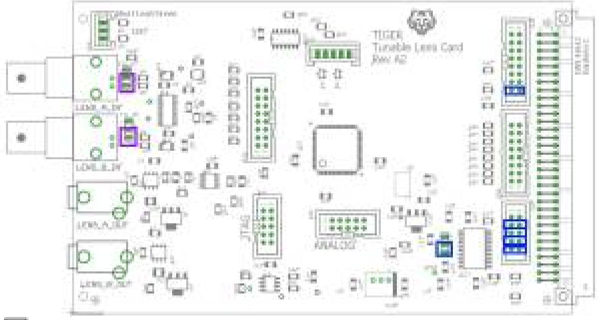
The TGTLC card has a low pass 5th order Bessel filter onboard. The filter's cut-off frequency can be adjusted between 100Hz and 650KHz with the BACKLASH command. This is the anti-aliasing filter on the signal which smooths out the jagged edges generated with a DAC. Setting the cutoff frequency with a high value will cause the filter to not interfere with user input.

The default cut-off frequency is 300Hz.

Serial Commands

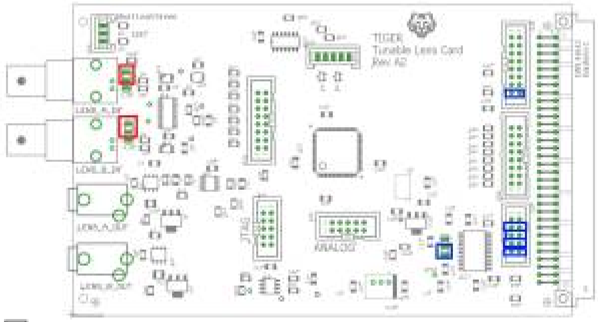
Apart from core serial commands like MOVE, MOVREL, JOYSTICK command etc. Below is a list of serial commands that have specific function on the TGTLC card.

Hardware Jumper Configuration



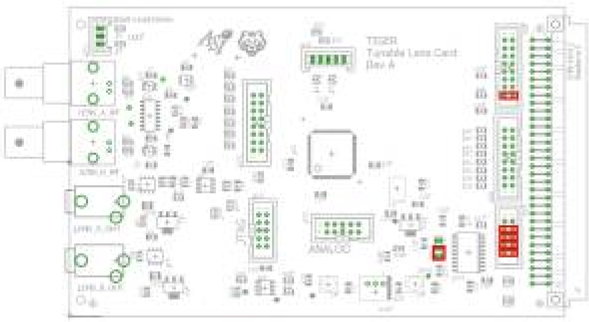
Jumper in External Input config for Rev A2 ; Click to Enlarge

When the jumpers are arranged in above configuration (JP2 and JP3 have jumpers on pins 3 and 2). The BNC connectors can be used to control the Tunable Lens with an analog voltage of 0-5V. Use the Command:PM to set axis to external input or internal input mode.



Jumpers in TTL config for RevA2;Click to Enlarge

When the jumpers are arranged in above configuration (JP2 and JP3 have jumpers on pins 1 and 2). The BNC connectors can be used to TTL. More info Command:TTL. If you'd like the Tunable Lens card to trigger a camera, set it up in above configuration.



Jumper config for Rev A ; Click to Enlarge

Tunable Lens Optics

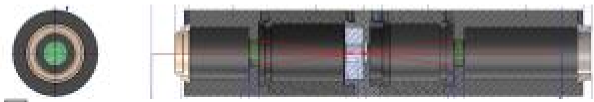
Although the Tunable Lens Card can be (and has been) used with other tunable lenes, ASI normally uses it with the Optotune EL-10-30-TC series which have convenient mechanical mounting in ASI's C60 system. Besides the default EL-10-30-TC-VIS with tuning range from +8.3 to +20 diopter, ASI has a handful of similar lenses with a stiffer membrane that operates from +5 to +10 diopters which is more resistant to gravity-induced sag.

The tunable lens power is specified in diopters which has units of 1/meters. To determine the focal length simply take the reciprocal; e.g. 12 diopter = 1/12 m = 83.3 mm. +8.3 diopters to +20 diopters is focal length 120 mm to 50 mm.

Because the tunable lens has strictly positive focusing power it is often useful to combine it with a negative lens to create a combined effect where a collimated input beam can be made to either converge or diverge via the ETL. With the 8-20 diopter ETL a -70 mm f.l. lens is commonly used, and a -150 mm f.l. lens for the 5-10 diopter stiff version. Order the combined ETL, C60 housing, and offset lens as C60-TUNELENS-70 and C60-TUNELENS-150 respectively (the latter make sure to specify the stiff lens version). The offset lens is mounted very near the tunable lens so to a very good approximation the combined focal length can be calculated as $f_{eff} = 1/(1/f_{ETL} + 1/f_{offset})$, or equivalently expressed in diopters $D_{eff} = D_{ETL} + D_{offset}$. Note that no deflection = infinite focal length = zero diopters.

Be aware that the tunable lens is less ideal optically than achromatic lenses, so for imaging applications make sure any aberrations are acceptable. Zemax models of the tunable lens can be found on Optotune's website.

4f Tunable Lens Assembly



ASIs Tunable Lens 4F Assembly

ASI's tunable Lens 4F assembly leverages the tunable lens to remotely focus an microscope image (i.e. adjust objective's focal plane without moving the objective itself). It goes between the microscope and the camera, similar to an image splitter. Optically it comprises a pair of 60 mm f.l. relay lenses with a tunable lens between them. It is possible to construct similar relays with different relay lenses from ASI's modular system.

Here are the main features:

- Easy assembly; it screws into the C-mount (see photo) port of most microscopes.
- Only active component is the tunable lens, driven by the the Tunable Lens Card.
- The focal length of the standard tunable lens spans between 8 to 20 diopter. The resulting focus change will depend on your optics as described below.

The displacement of the objective's focal plane is given by

\begin{equation}\delta_{focus} = \frac{-1}{M_{det}^2}*\frac{n*f_r^2}{f_{ETL}}\end{equation}

where M_{det} is total magnification from sample to camera (most often the objective's nameplate magnification); n is refractive index of immersion medium; f_r is focal length of the two lenses in 4F assembly; F_{ETL} is effective focal length of the ETL in combination with any offset lens.

(For more details see Fahrbach, Florian O., et al. “Rapid 3D Light-Sheet Microscopy with a Tunable Lens.” Optics Express, vol. 21, no. 18, 2013.)

Using the above equation it can be shown that the range of tuning of the objective's focal plane can be expressed as

$$Range_{focus}= \frac{n*f_r^2*D_{ETL}}{M_{det}^2}$$

where D_{ETL} is the range of the tunable lens expressed in diopters and $Range_{focus}$ is expressed in micrometers (um). Conveniently the range is independent of the offset lens chosen, but the offset lens changes the center point of the focus range. [1]

Using a 12 diopter range of the standard ETL and 60 mm as f_r, we can use the above equation to compute the following table of attainable focus shift with the C60-TUNELENS-4F assembly using air objectives. Note that the range is small for high magnification and significant for low magnification.

Magnification	focus range (60mm f_r)	focus range (100mm f_r)
5x	1.7 mm	4.8 mm
10x	432 um	1.2 mm
20x	108 um	300 um
40x	27 um	75 um
60x	12 um	33 um
100x	4 um	12 um

Caveats

Telecentric or “4f” spacing is required between the microscope tube lens and the objective so that the tunable lens will only change the focal plane. To the extent that the microscope body is not telecentric, actuating the tunable lens will change the magnification in addition to refocusing. Most commercial microscopes are not telecentric but it is easy to achieve telecentricity using ASI modular microscope components.

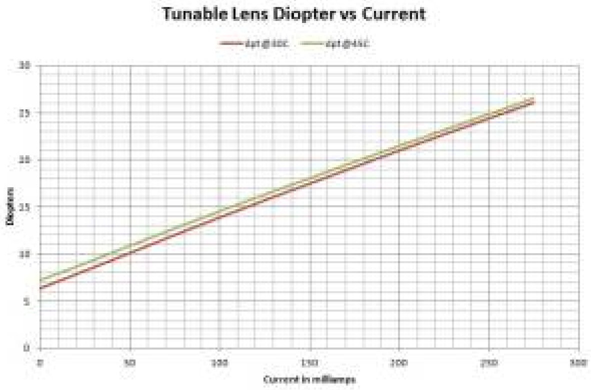
The relay uses a 60 mm f.l. achromat lens which is a very short focal length which can potentially add aberrations. However it keeps the total length of the assembly reasonable and sidesteps the potential problem of insufficient clear aperture of the ETL. [2]

More problematic for scientific imaging, the clear aperture of the relay lens can limit the allowable camera FOV. Vignetting will occur if the relay lens clear aperture is smaller than the sensor-side FOV plus the size of the objective back aperture demagnified by the ratio f_r/f_{TL}. the The default lens in C60-TUNELENS-4F has 15 mm diameter, so clearly it cannot work with a full-size sCMOS camera (18.8 mm diagonal) even if the back aperture size is negligible. Using the C60-100-D as f_r is preferred for large-format camera sensors. However, the C60-TUNELENS-4F is sufficient for e.g. a 9 mm diagonal camera with the Nikon 10x/0.45 air objective with Nikon tube lens ((2*0.45*200/10)*60/200 = 5.4 mm diameter demagnified back aperture).

The tunable lens can introduce optical aberrations which may be important for imaging applications but are negligible in tracking applications. These aberrations can be simulated in ray tracing software using models provided by Optotune. One unique aberration is gravity-induced sag of the tunable lens; for applications with stringent optical requirements it is recommended to mount the ETL with optic axis along gravity and/or use the stiffer variant.

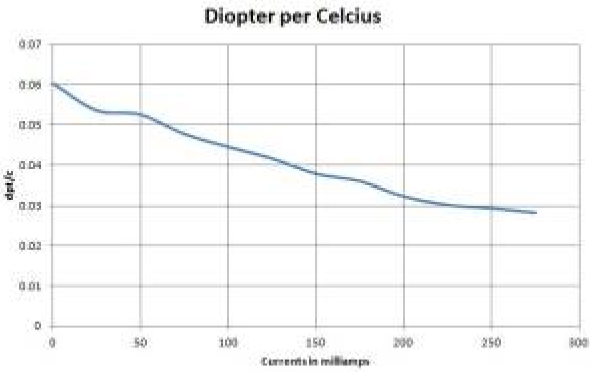
Temperature Compensation

Tunable Lens are susceptible to temperature change, their diopter decrease as temperature increases.Below is a graph of diopter vs current at two different temperatures



Graph showing diopter vs Current at two different temperatures

This diopter per celcius change isn't constant and varies too. Below is a graph of the change diopter change per celsius vs current.



diopter per Celsius change at various current

Fortunately this effect is predictable and the manufacturer has built a temperature sensor into the Tunable lens and provided characterization data. At the factory , we analyze this data and build a model. The parameters for this model are saved on the Tunable Lens EEPROM itself. The Tunable Lens card reads the EEPROM on starup. These parameters can be read and altered through serial commands ERROR(E), PCROS(PC), PG and PSG

When Temperature compensation is enabled (through the PM [Axis]=2) command, firmware periodically reads the temperature sensor on the Tunable Lens and adjust the DAC. This change won't be reflected in the position of the Tunable Lens read with WHERE(W) or set with MOVE (M). The correction is happening on a internal layer, right before the DAC and current amplifier.

Calculation

Below is how the temperature compensation is calculated and applied.

- First for a given current, Diopter per Celsius (*D/T*) at that current is calculated

$$\frac{D}{T} = I_{user}*K_1+C_1$$

- Then current temperature is measured by reading the temperature onboard the Tunable lens , and subtracting that from the set point temperature. This set point temperature is where the Tunable lens was characterized at factory, and coefficients like K_1 and C_1 were calculated.
- This temperature change is multiplied with Diopter per Celsius (*D/T*) to get Diopter change

$$D = \frac{D}{T}*(T_{current}-T_{setpoint})$$

- The Diopters are converted back to current by multiplying it with Diopter to current coefficient K_{D2I}. Then subtracted from the user input current before being applied to the Tunable Lens

$$I_{applied} = I_{user}- D*K_{D2I}$$

The coefficients K_1 , K_{D2I} and constants C_1 and $T_{setpoint}$ are calculated from two Diopter vs Current curves the Tunable lens manufactured provides with each Tunable lens. They are calculated by ASI technicians and stored onboard the tunable lens itself. If a user would like to alter any of these settings, they may do it through the following commands.

- C_1 is set through PC [AXIS]=#
- $T_{setpoint}$ is set through PSG [AXIS]= #
- K_{D2I} is set through E [AXIS]=#
- K_1 is set through PG [AXIS]=X. Where X is

$$X=\frac{K_1*-1}{10000000}$$

Applications

One of the main applications of Tunable Lens system is with ASI XYZ Tracker plugin as a continuous focus device. For more info refer to the ASI XYZ Tracker Micro-Manager plugin page.

Serial Command Cheatsheet

The commands shown here are assumed to be issued to the V axis.

Note: when setting the value of K_1, use the formula provided for X.

TGTLC Serial Commands			
Property	**Set**	**Get**	**Notes**
Where	-	`W V`	Returns the current position
Mode	`PM V=#`	`PM V?`	Internal or external mode
C_1	`PC V=#`	`PC V?`	Temperature compensation
$T_{setpoint}$	`PSG V=#`	`PSG V?`	Temperature compensation
K_{D2I}	`E V=#`	`E V?`	Temperature compensation
K_1	`PG V=X`	`PG V?`	X = (K_1 * -1)/10,000,000

Absolute Move	M V=#	-	Internal mode only
Relative Move	R V=#	-	Internal mode only

The BACKLASH command is deprecated, it used to change the Bessel filter prior to hardware revision C.

Additional Reading

- Optotune EL-10-30 datasheet
- App Note: Optical focusing in microscopy with Optotune’s focus tunable lens EL-10-30

tiger, manual, tlens, TGTLC, temperature

1) Mathematically that is because diopters is $1/f_{ETL}$ and any offset lens simply adds to the optical power as measured in diopters.

2) To maintain the full NA of the detection lens requires that the image of its back aperture fit within the aperture of the tunable lens. For the usual 10 mm ETL aperture and the 60 mm f.l. lens in C60-TUNELENS-4F this requirement can be stated as M_{det} > $12*{NA}_{obj}$, which is nearly always true. For 100 mm f.l. f_r the constant factor in the equation is 20 instead of 12.