Time Domain Continuous Imaging using LED Sensels

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Abstract

Time domain continuous imaging (TDCI) centers on the capture and representation of time-varying image data not as a series of frames, but as a compressed continuous waveform per pixel. A high-dynamic-range (HDR) image can be computationally synthesized from TDCI data to represent any virtual exposure interval covered by the waveforms, thus allowing both exposure start time and shutter speed to be selected arbitrarily after capture, which also enables extraction of video with arbitrary framerate and shutter angle. Unfortunately, conventional sensors cannot directly implement TDCI capture, so earlier work focused on postprocessing conventional sensor output to approximate TDCI streams.

The current work describes the first direct implementation of TDCI sensing. The sensors discussed here are not image sensor chips, but prototype equivalent circuitry and control logic as low pixel count board-level sensor modules constructed using commodity components. An LED is used to implement each sensel, and each is sampled asynchronously independent of all other sensels by reverse biasing the LED to charge its inherent capacitance and then timing how long the photocurrent takes to reach a fixed threshold voltage. These open source LED-based TDCI sensor modules are used to construct stand-alone TDCI cameras, allowing performance measurements, tweaking of the control logic, and empirically verifying that true TDCI sensing is practical.

Time Domain Continuous Imaging (TDCI)

- **TDCI** is a type of **IMEV** (IMage EVolution) capture and frameless image processing that can
  - **Capture high dynamic range with low noise**
  - **Render a virtual exposure for any time interval**
  - **Render video at any frame rate and shutter angle**
- Records **each time a pixel changes its expected value**, compressing by skipping unchanged pixel value predictions

Time Domain Continuous Imaging (TDCI)

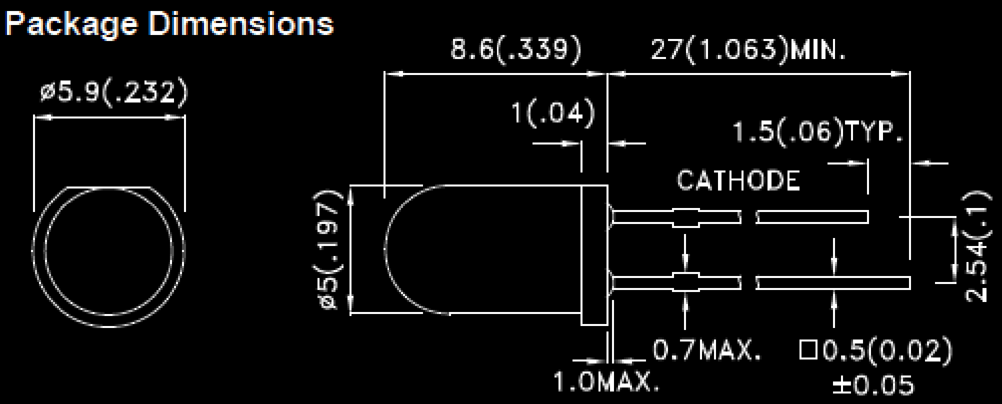
LED Sensels?

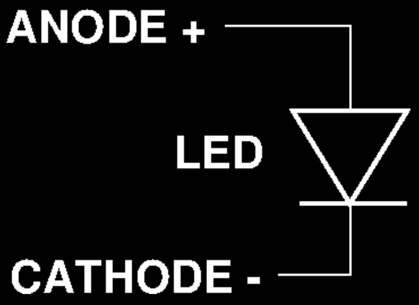
- A **Light Emitting Diode** (**LED**) can be used
  - To **emit** light in a narrow (< 50nm) wavelength range
  - To **sense** light of comparable or shorter wavelength

  `https://github.com/paulhdietz/LEDSensors`

- Light sensing can work in either of two basic modes
  - **Photovoltaic**: typically generating ≤ 2V @ μA (small signals requiring *analog* measurement)
  - **Photoconductive**: reverse-biased, light increases leakage (can *digitally* **measure charge decay time**)

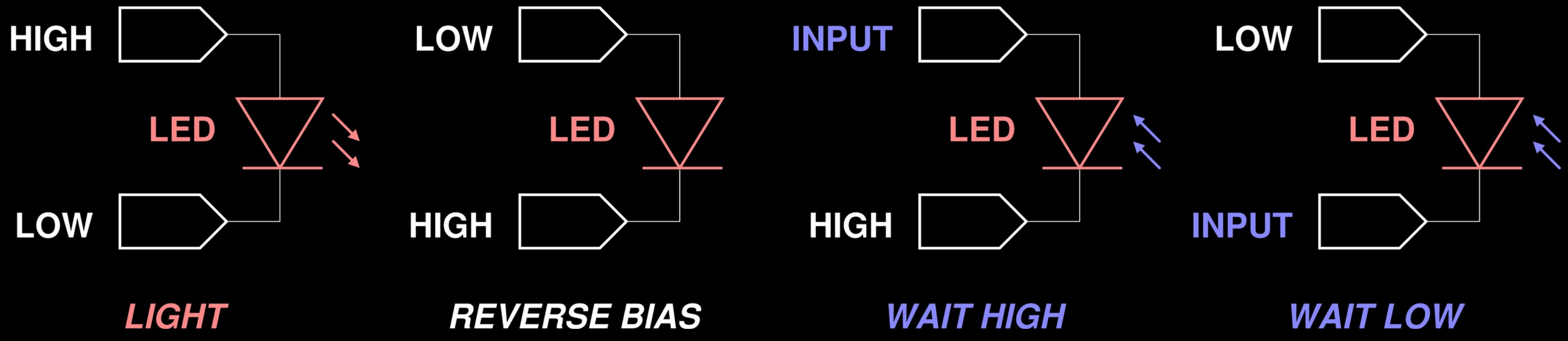
Standard Discrete LED Packaging





- Standard **3mm** or **5mm** diameter, can get much smaller
- Top can be **rounded**, **flat**, or **concave**
- Some LEDs have diffusers; “white” LEDs have phosphor

LED as a digital input

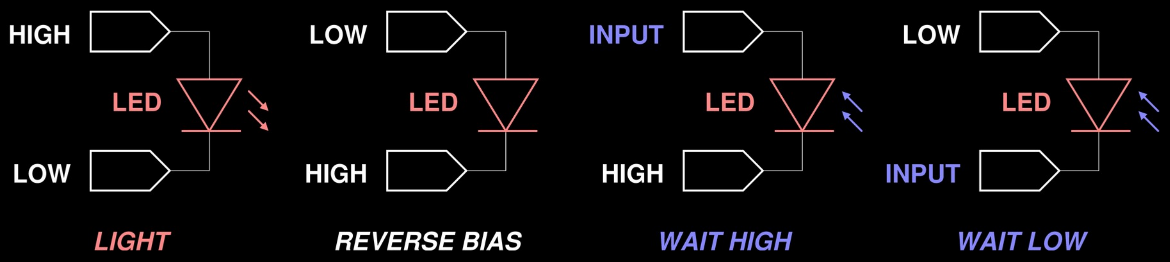


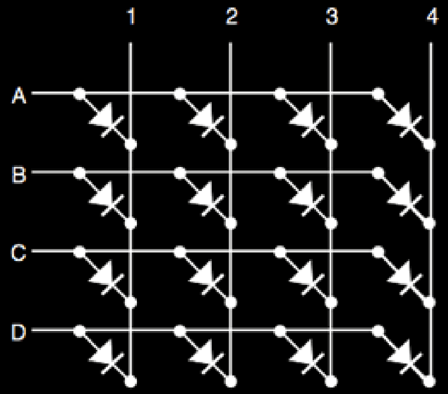
- Explained in *Very Low-Cost Sensing and Communication Using Bidirectional LEDs*, `https://doi.org/10.1007/978-3-540-39653-6_14`
- Best sensitivity cycling ***REVERSE BIAS***, ***WAIT HIGH***

Control Logic

- Independently time LED reaching a threshold
  - **Wait high anode**: cathode held high; set anode low to reset
  - **Wait low cathode**: anode held low; set cathode high to reset
- Various timing options, including:
  - Continuously sample all and reset each as it triggers
  - Sample in order using history-based time prediction
  - Encode and send trigger position, locally reset
  - Time locally, and only signal when time prediction changes

Partially Decoded LED Matrix as a digital input





- Still viable using fact that ABCD1234 can be `H`, `L`, `Z`, `?`(input):
  - `LLLLHHHH`: all reverse bias
  - `????HHHH`: A=A1|A2|A3|A4, B=B1|B2|B3|B4, …
  - `LLLLHLLL` → `????HZZZ`: A=A1, B=B1, C=C1, D=D1

TDCI IMEV (IMage EVolution) Data Stream

- Every event updates a map of current pixel values, supporting
  - **Live view**
  - **Incrementally-updated histogram**
  - Output of a record **only when expected value changes**
- Various TDCI IMEV streaming options for X*Y array, e.g.:
  - Output a record with pixel x,y coordinates and new value
  - Output a record with **spatiotemporal distance to last change** computed as $((t - t_{last}) * (X * Y)) + (x - x_{last}) + ((y - y_{last}) * X)$

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Experimental Evaluation of LEDs as Sensors

- Built test rig for comparing effectiveness of LEDs as sensors
  - Sensitivity varies widely with details of LED
  - Lens matters: **rounded**, **flat**, or **concave**
  - LEDs don't detect photons of longer wavelength than emitted
- Built various ultra-low-pixel-count LED cameras including
  - **CILKY** (**Continuous Imaging LEDs from KentuckY**) **M42**
  - **Ciro-flex CILKY** TLR (Twin Lens Reflex)
- High pixel count is coming (e.g., yesterday's plenary), also tried **ISS-286**: **Single-sensel image capture using an LCD panel**

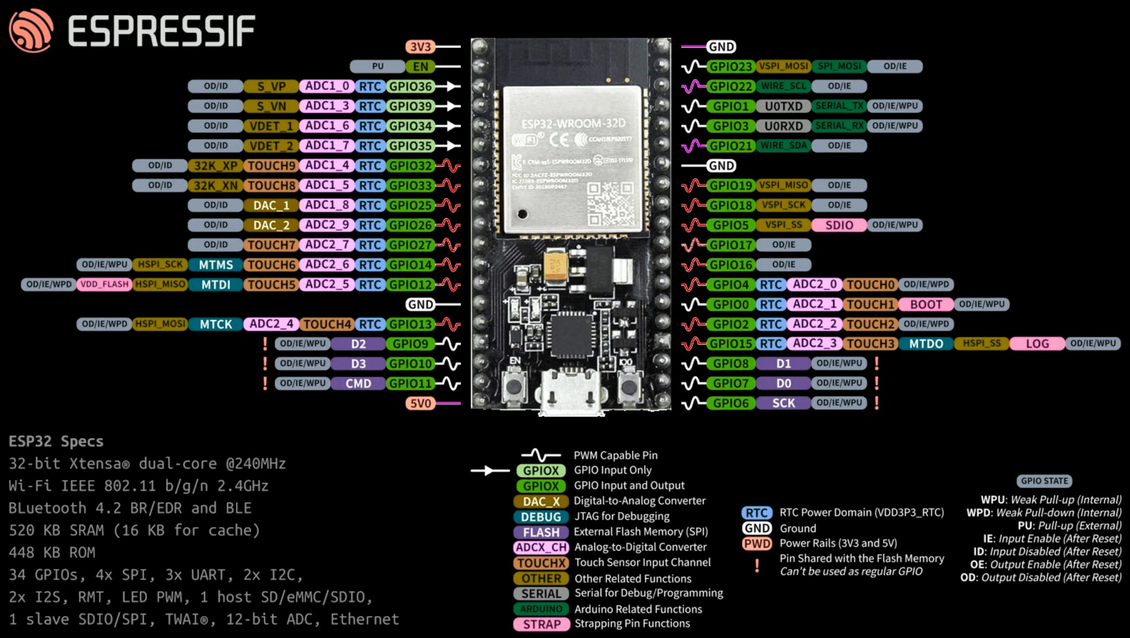
Ciro-flex CILKY 260221 Concept

- Replace back of a 1940s TLR with LED sensor & electronics
- 6x6cm medium format fits a decent number of LEDs
- Metal chassis needs grounding… LED sensing sees capacitance changes

Ciro-flex CILKY 260221 Construction

- 3D-printed custom back and sockets for components
- Wire-wrap
- 5V common cathode for 16 LEDs

CILKY Processing



- LED control/sensing uses 16 GIOP, OLED live view uses I2C

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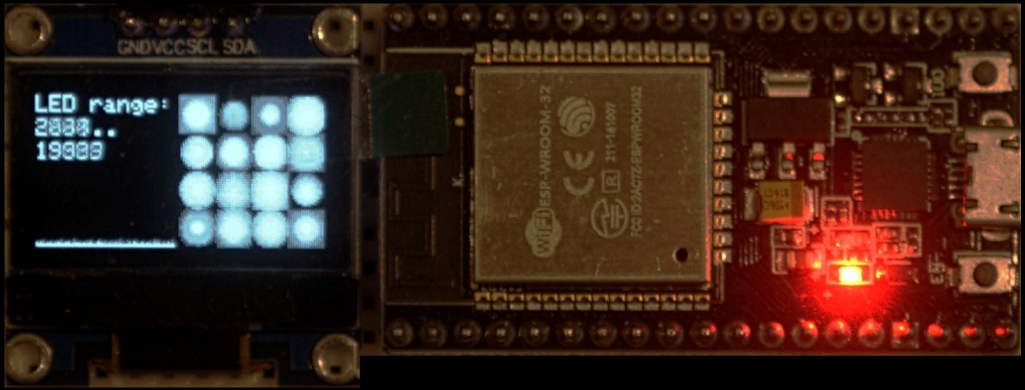
CILKY Processing



- ESP32 independently times threshold events from all 16 LEDs, directly implementing TDCI IMEV capture and compression
- Recent behavior is summarized on an OLED display

Ciro-flex CILKY 260221 Results

- Rear-mounted OLED display and ESP32 controller
- **Only 16 pixels**…
  5mm red flat-top LED sensels
- Counts range from tens to over 3 million: up to **over 18 EV DR**

Conclusion – LEDs do work!

- Timing threshold events is a viable alternative to ADC
  - We used LEDs, but it's just a light-controlled RC circuit (which does make it very sensitive to capactive coupling)
  - **Time measurements give high DR TDCI IMEV streams**
  - **Flexible sampling**: each sensel can be independently reset
  - **Output is digital**, easily multiplexed and/or compressed
- Note: **a LED camera can also be a LED projector!**
- What can TDCI IMEV do? **COIMG-163**: **NUTIK: A Testbed for Functional Post-Capture Munipulation of Time and Gain**