Embedded Video Systems With Zephyr

Josuah Demangeon, Panoramix Labs, tinyVision.ai

Background

A contractor working essentially with tinyVision.ai


Helion
ENGINEERING VISION
tinyvision.ai

Autoportrait: I am curious about a lot of topics, but only scratch the surface.

You are welcome and invited to dive in depth!

Video Systems

Famous example: home cinema

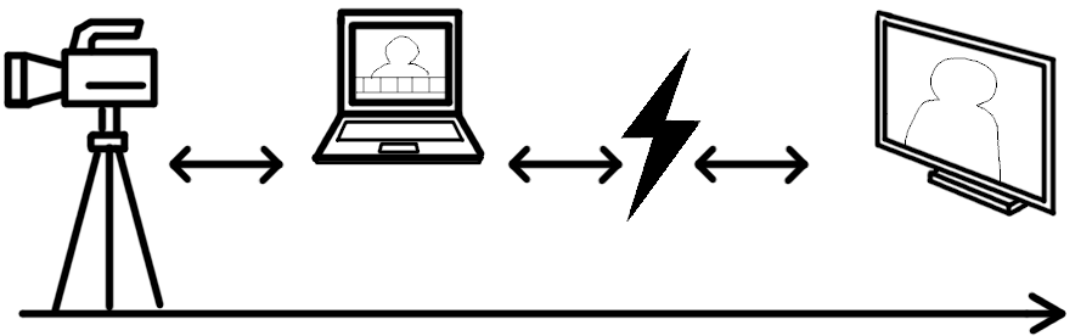

BRAVIA
DONOR
CURRENT WORK UNIT
SONY

Pro Video Camera

Video editing software

Distribution network

Final destination: human eyes

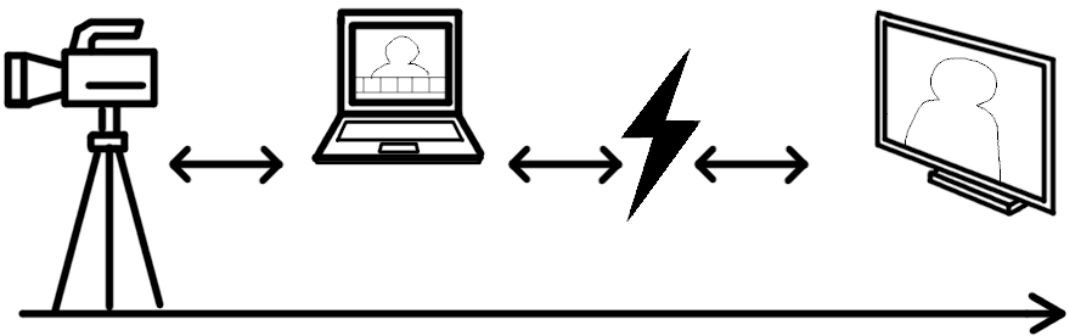


Pro Video Camera

Video editing software

Distribution network

Final destination: human eyes

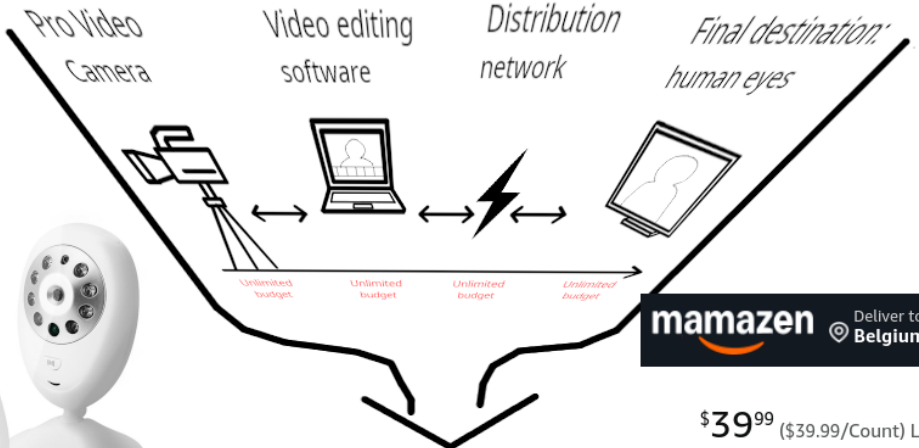


Unlimited budget

Unlimited budget

Unlimited budget

Unlimited budget



Babyphone

Embedded Video Systems

Constraints:

→ Cost budget

→ Processing budget

→ Time budget (low-latency, real-time)

Can only work at low-resolution...

Embedded Video Systems

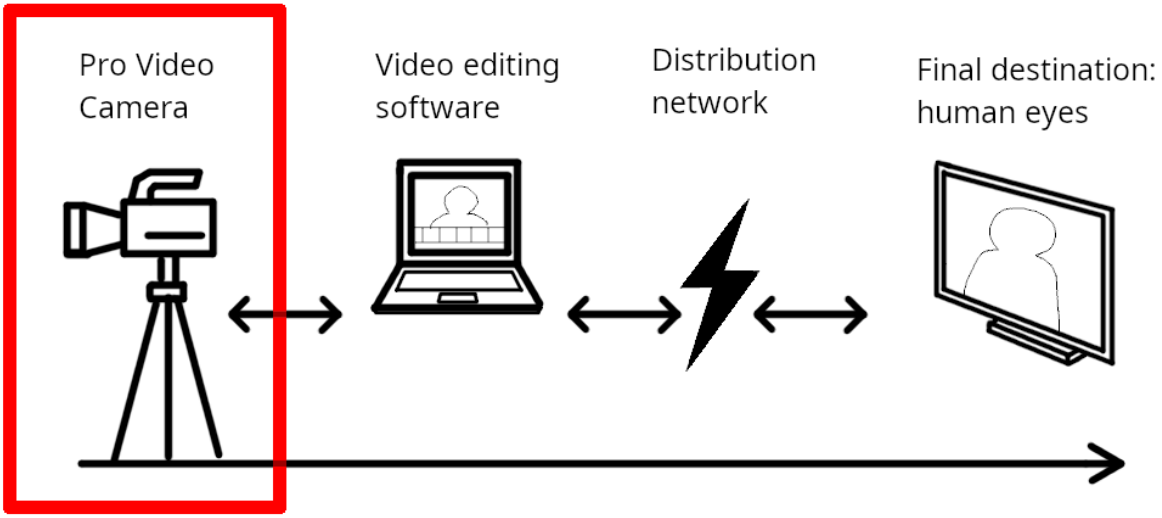
Constraints:

→ Cost budget

→ Processing budget

→ Time budget (low-latency, real-time)

Can only work at low-resolution... <- FALSE!



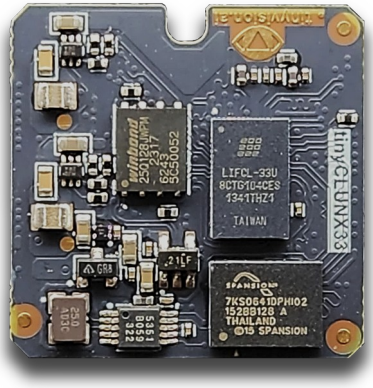
Needs an operating system too!

Embedded is not always low-end.

Embedded Video Systems

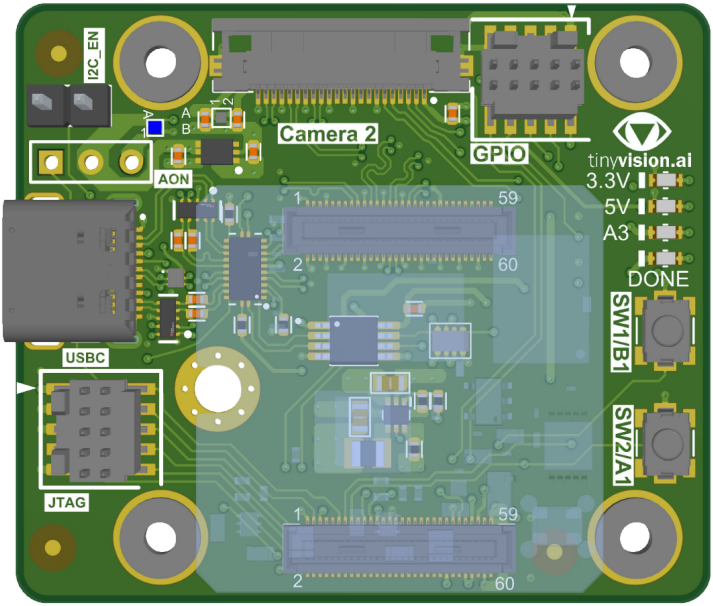
"Why not use an USB camera?"

We are now implementing the USB camera *itself*.



tinyCLUNX33: the heart of an USB 3 webcam.

3.4 Gbit/s under 80 mW


I2C_EN
A
B
1
2
Camera 2
GPIO
tinyvision.ai
3.3V
5V
A3
DONE
AON
1
59
2
60
USBC
SW1/B1
SW2/A1
JTAG
1
59
2
60

Embedded Video Systems

"Why not just a Raspberry Pi?"

→ Power budget

→ Performance

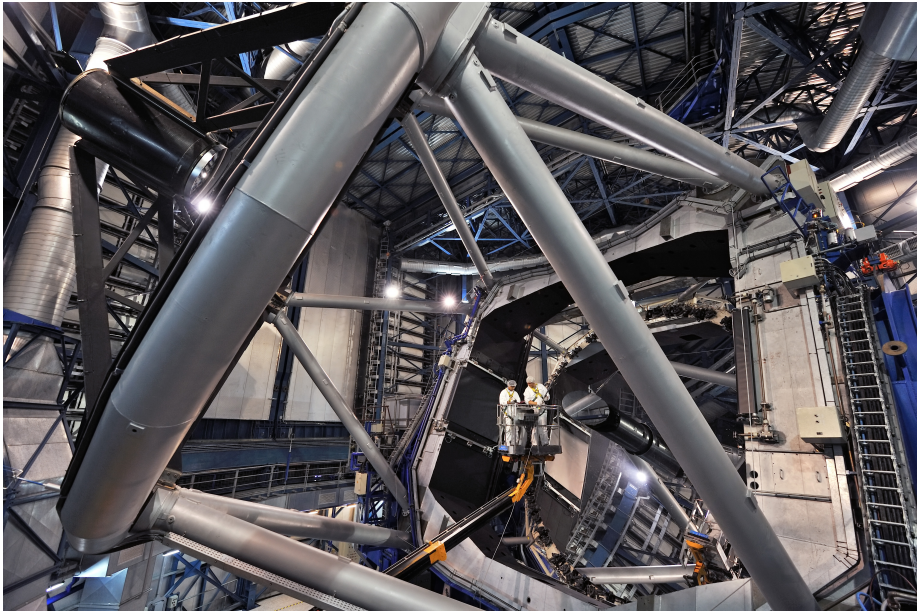
→ Cost

→ Latency

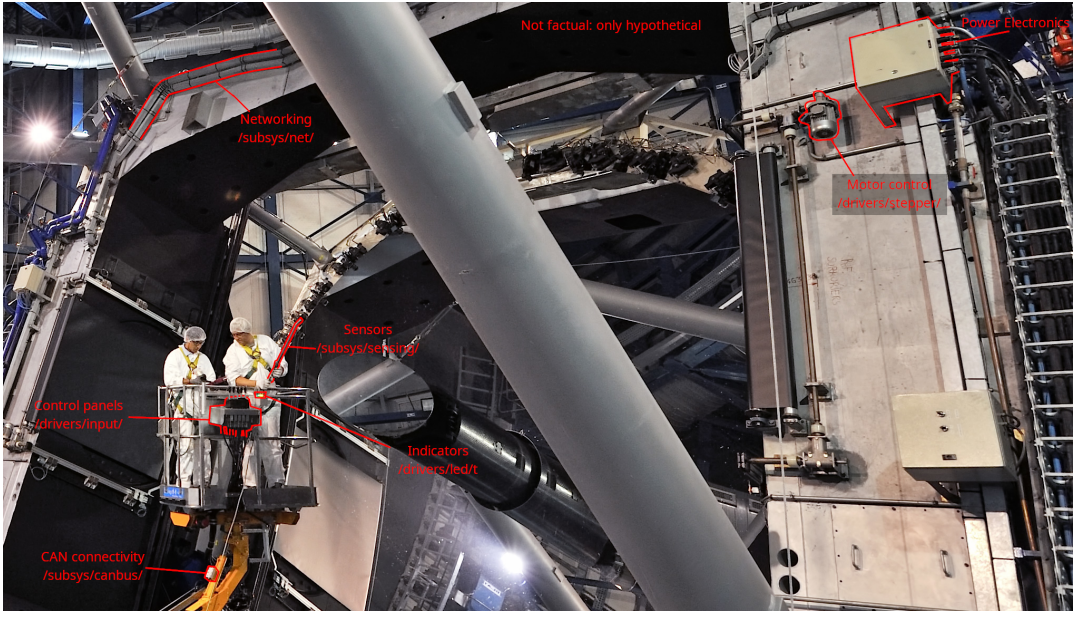

ArduCam

Embedded Video Systems

Can be very large:



We can imagine a lot involved to assist the video function:


Not factual: only hypothetical
Power Electronics
Networking
/subsys/net/
Motor control
/drivers/stepper/
Sensors
/subsys/sensing/
Control panels
/drivers/input/
Indicators
/drivers/led/t
CAN connectivity
/subsys/canbus/

Still there on small embedded systems:

→ Motor for auto-focus ("VCM" motor `#include <zephyr/drivers/video-controls.h>`)

→ I2C communication with other chips (`#include <zephyr/drivers/i2c.h>`)

→ Turning on/off the chip power (Power Management)

Embedded Video Systems

But usually the smaller the better: how to shrink?

Switch from Linux OS → RTOS like Zephyr

Which board running it can do video?

Video-capable boards running Zephyr

Video-capable means DVP (a.k.a. parallel port) or MIPI support.

Different software ecosystem

FFmpeg → ???

Gstreamer → ???

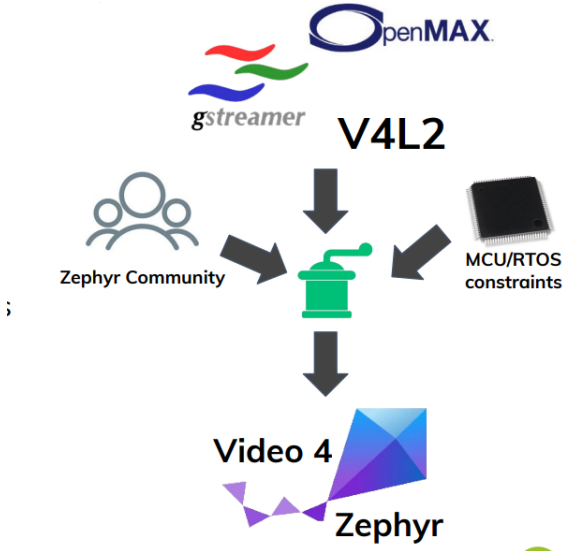
OpenCV → ???

PyTorch → ???

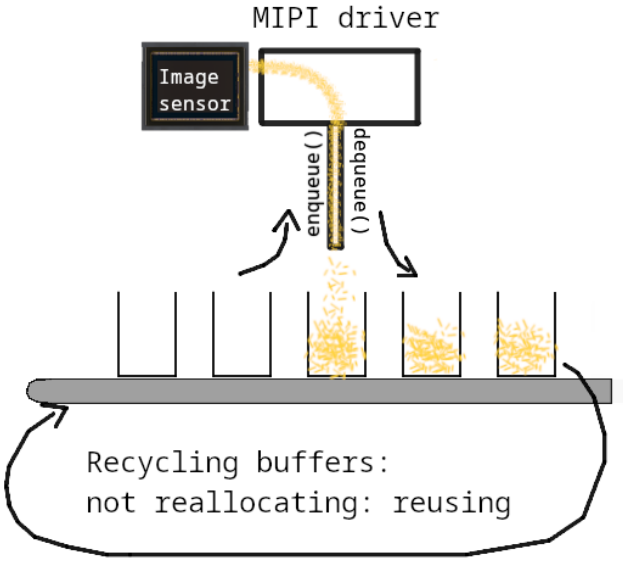
`/dev/video0` → ???

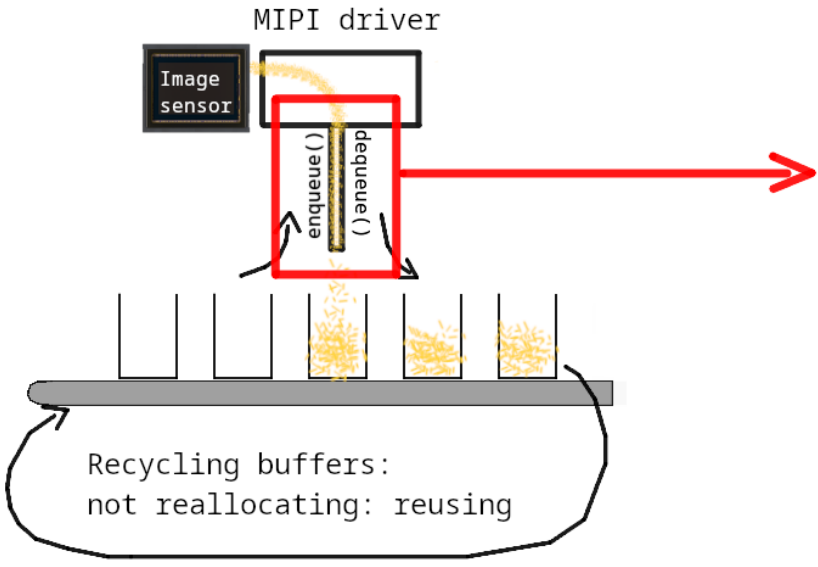
These software assumes a lot of resources. Everything to reinvent!

Zephyr Video APIs


OpenMAX
gstreamer
V4L2
Zephyr Community
MCU/RTOS
constraints
Video 4
Zephyr

;


MIPI driver
Image sensor
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing

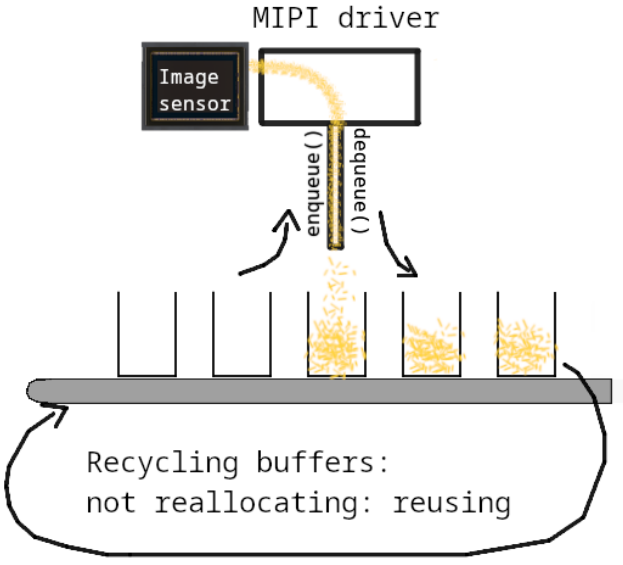


Data API

not implemented
by all drivers

```
/* Error handling ommitted */

video_stream_start(mipi_dev);
vbuf = video_buffer_alloc(1280 * 720 * 3, K_FOREVER);
while (true) {
    video_enqueue(mipi_dev, VIDEO_EP_OUT, vbuf);
    video_dequeue(mipi_dev, VIDEO_EP_OUT, &vbuf, K_FOREVER);
    /* do something with vbuf→data */
}
```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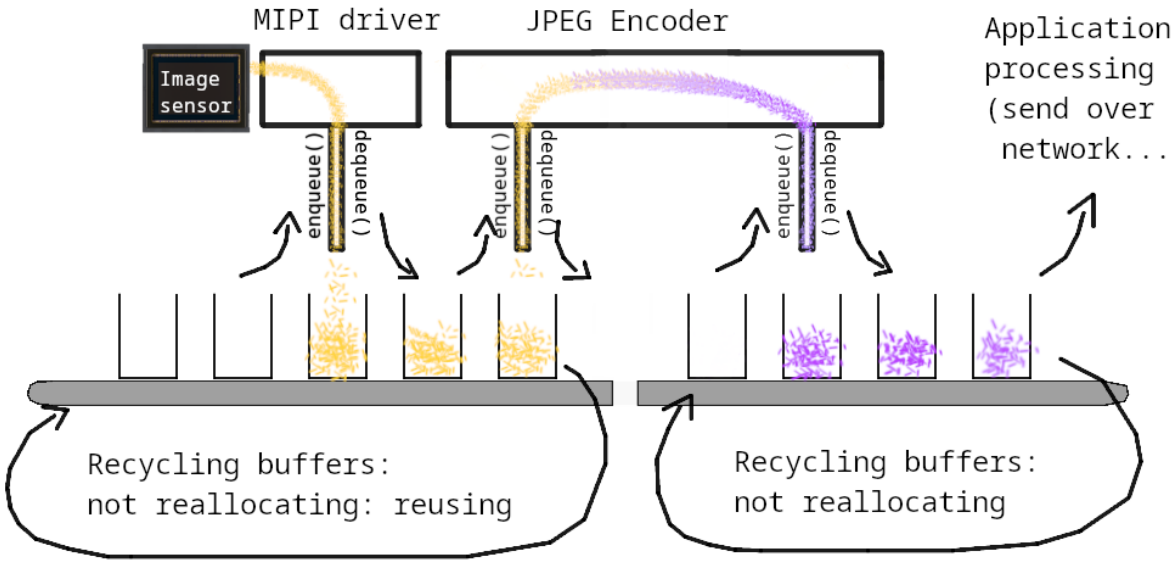
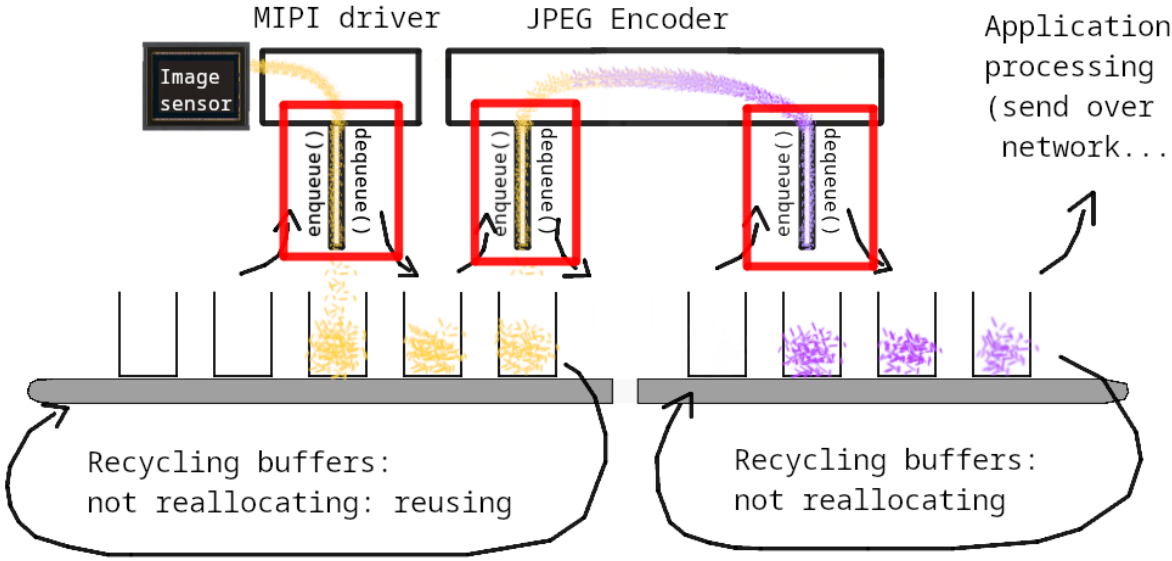

MIPI driver
JPEG Encoder
Application processing (send over network...)
Image sensor
enqueue()
dequeue()
enqueue()
dequeue()
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing
Recycling buffers:
not reallocating


MIPI driver
JPEG Encoder
Application processing (send over network...)
Image sensor
enqueue()
dequeue()
enqueue()
dequeue()
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing
Recycling buffers:
not reallocating

```
/* Only one buffer of each */
vbuf_raw = video_buffer_alloc(1280 * 720 * 3, K_FOREVER);
vbuf_jpeg = video_buffer_alloc(JPEG_BUF_SIZE, K_FOREVER);
while (true) {
    video_enqueue(mipi_dev, VIDEO_EP_OUT, vbuf_raw);
    video_dequeue(mipi_dev, VIDEO_EP_OUT, &vbuf_raw, K_FOREVER);
    video_enqueue(jpeg_dev, VIDEO_EP_IN, vbuf_raw);
    video_dequeue(jpeg_dev, VIDEO_EP_IN, &vbuf_raw, K_FOREVER);
    video_enqueue(jpeg_dev, VIDEO_EP_OUT, vbuf_jpeg);
    video_dequeue(jpeg_dev, VIDEO_EP_OUT, &vbuf_jpeg, K_FOREVER);
    /* Do something with the JPEG data */
}
```

Nice and simple, but no concurrency: a lot of time spent waiting.

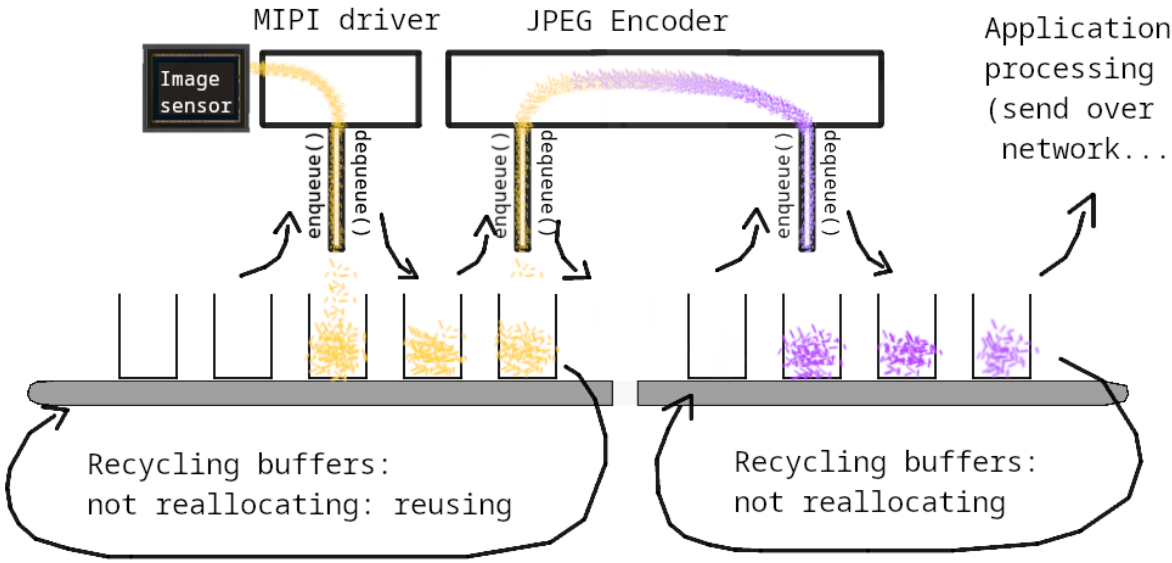
```
for (int i = 0; i < 3; i++) {
    vbuf_raw = video_buffer_alloc(1280 * 720 * 3, K_FOREVER);
    video_enqueue(mipi_dev, VIDEO_EP_OUT, vbuf_raw);
}

for (int i = 0; i < 3; i++) {
    vbuf_jpeg = video_buffer_alloc(JPEG_BUF_SIZE, K_FOREVER);
    video_enqueue(jpeg_dev, VIDEO_EP_OUT, vbuf_jpeg);
}

/* Thread 1: Handle the filled buffers */
while (true) {
    video_dequeue(mipi_dev, VIDEO_EP_OUT, &vbuf_raw, K_FOREVER);
    video_enqueue(jpeg_dev, VIDEO_EP_IN, vbuf_raw);
}

/* Thread 2: Handle the emptied buffers */
```

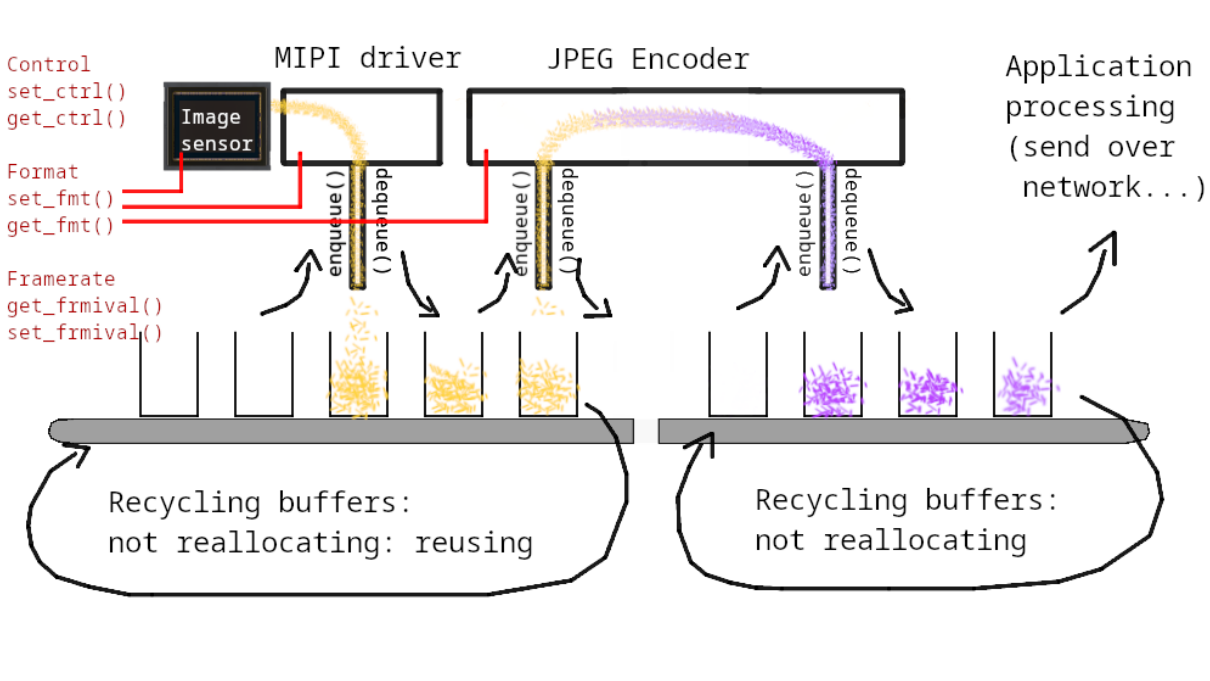
```
while (true) {
    video_dequeue(jpeg_dev, VIDEO_EP_IN, &vbuf_raw, K_FOREVER);
    video_enqueue(mipi_dev, VIDEO_EP_OUT, vbuf_raw);
}

/* Thread 3: Handle the JPEG buffers */
while (true) {
    video_dequeue(jpeg_dev, VIDEO_EP_IN, &vbuf_jpeg, K_FOREVER);
    app_use_jpeg_buffer(vbuf_jpeg);
    video_enqueue(jpeg_dev, VIDEO_EP_OUT, &vbuf_jpeg, K_FOREVER);
}
```

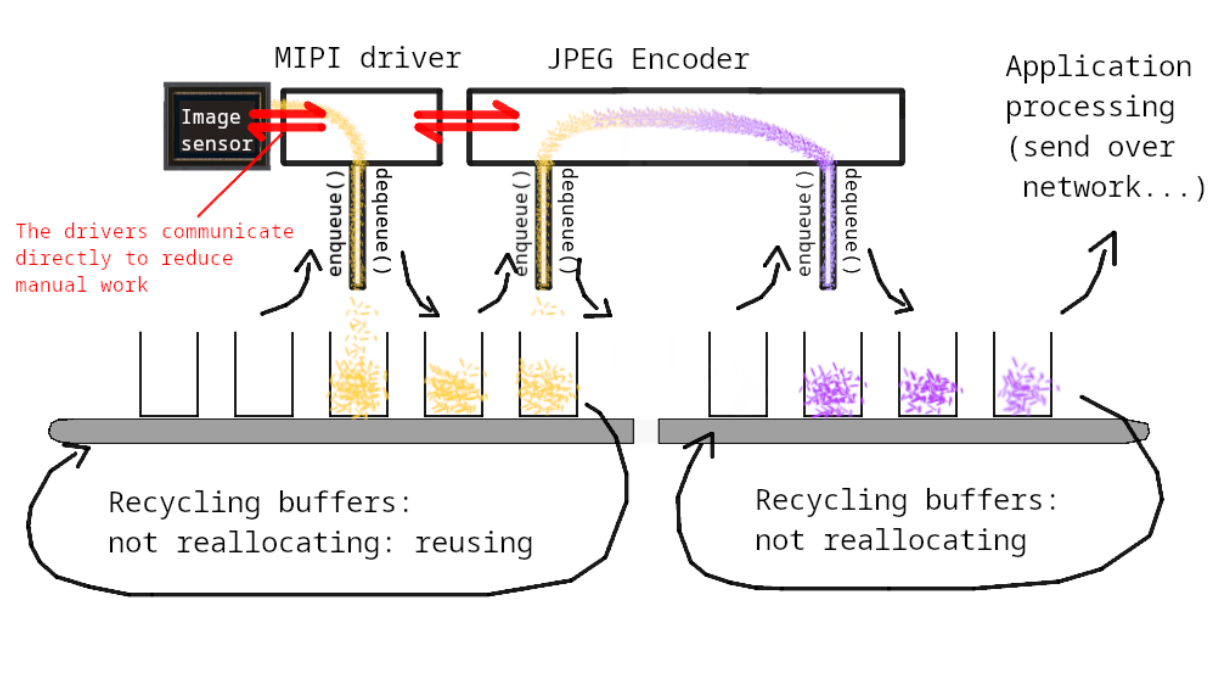
Fully parallel, but consumes a lot of threads: more memory overhead and context switching.

```c
/* First prepare a few buffers */

/* Subscribe to the events */
video_set_signal(mipi_dev, &signal);
video_set_signal(jpeg_dev, &signal);

/* React to the events */
while (k_poll(&events, 1, K_FOREVER) == 0) {
    if (video_dequeue(mipi_dev, VIDEO_EP_OUT, &vbuf_raw, K_NO_WAIT) == 0) {
        video_enqueue(jpeg_dev, VIDEO_EP_IN, vbuf_raw);
    }
    if (video_dequeue(jpeg_dev, VIDEO_EP_IN, &vbuf_raw, K_NO_WAIT) == 0) {
        video_enqueue(mipi_dev, VIDEO_EP_OUT, vbuf_raw);
    }
    if (video_dequeue(jpeg_dev, VIDEO_EP_OUT, &vbuf_jpeg, K_NO_WAIT) == 0) {
        video_enqueue(jpeg_dev, VIDEO_EP_OUT, vbuf_jpeg);
        app_use_jpeg_buffer();
    }
}
```

Good parallelism, single thread (more scalable). Maybe this can be automated for easier pipelines.


MIPI driver
JPEG Encoder
Application processing (send over network...)
Image sensor
enqueue()
dequeue()
enqueue()
dequeue()
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing
Recycling buffers:
not reallocating


Control
set_ctrl()
get_ctrl()
Format
set_fmt()
get_fmt()
Framerate
get_frmival()
set_frmival()
Image sensor
MIPI driver
JPEG Encoder
Application processing (send over network...)
enqueue()
dequeue()
enqueue()
dequeue()
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing
Recycling buffers:
not reallocating


MIPI driver
JPEG Encoder
Application processing (send over network...)
Image sensor
The drivers communicate directly to reduce manual work
enqueue()
dequeue()
enqueue()
dequeue()
enqueue()
dequeue()
Recycling buffers:
not reallocating: reusing
Recycling buffers:
not reallocating

```
imx219: imx219@10 {
        compatible = "sony,imx219";
        port {
                imx219_ep_out: endpoint {
                        remote-endpoint-label = "mipi0_ep_in";
                };
        };
};
```

```
mipi0: mipi@b1000010 {
        compatible = "tinyvision,mipi";
        port {
                mipi0_ep_in: endpoint {
                        remote-endpoint-label = "imx219_ep_out";
                };
```

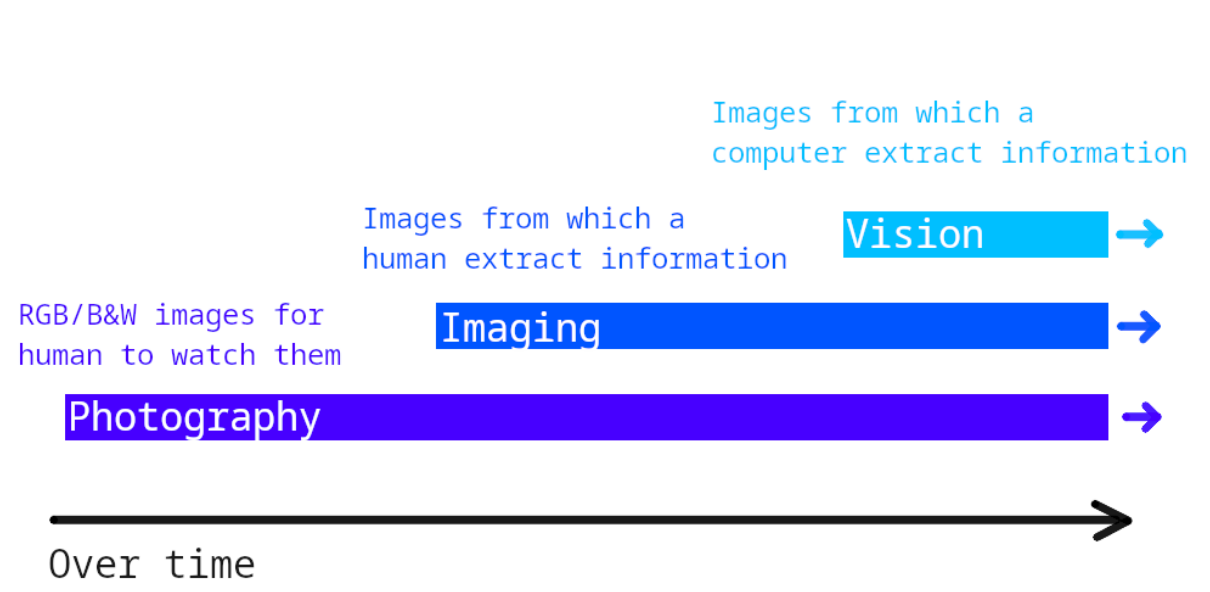
```
                mipi0_ep_out: endpoint {
                        remote-endpoint-label = "jpegenc_ep_in";
                };
        };
};
```

```
jpegenc0: jpegenc@b1000010 {
        compatible = "tinyvision,jpegenc";
        port {
                jpegenc0_ep_in: endpoint {
                        remote-endpoint-label = "mipi0_ep_in";
                };
                /* jpegenc0_ep_out: to the application */
        };
};
```

Next steps: automating more of the pipeline? What would make it more convenient?

Systems doing what?

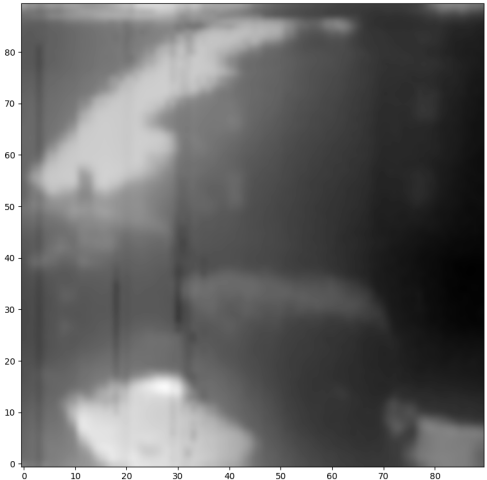
On a journey from Phontons to Video, and how that is used

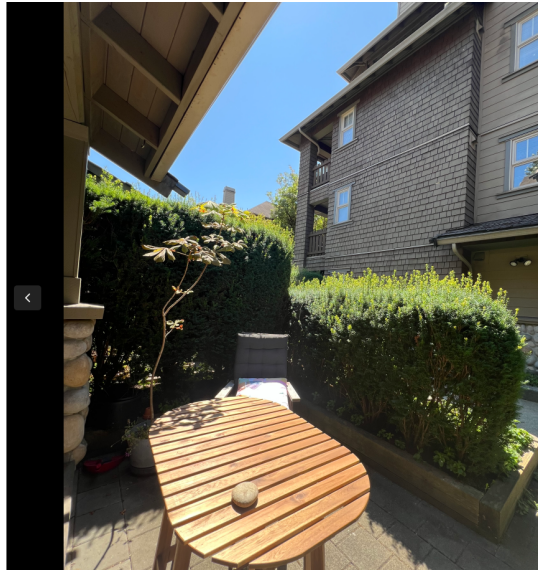


Inspired from a MIPI alliance presentation (2018)

Photodiode

Phenomenon of semiconductors producing voltage when exposed to the light.


0
10
20
30
40
50
60
70
80



Note: photoresistor instead of photodiode here

```
#include <zephyr/drivers/pwm.h> // if using servomotors
#include <zephyr/drivers/stepper.h> // if using stepper motors
#include <zephyr/drivers/adc.h> // measure the light intensity
```

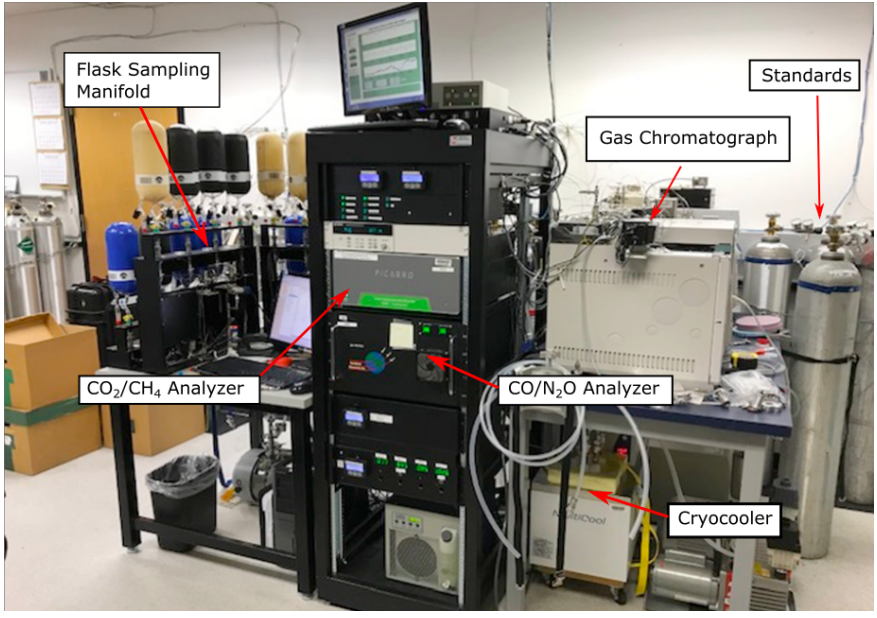
Photons → Photonics

Much more than just video:

→ Gas detection/characterization, i.e. NDIR CO2 sensors

Industrial, safety, medical use-cases.

Since 1958: measuring Earth atmospheric CO2 with "1-pixel image sensors"

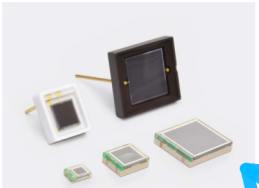

Flask Sampling Manifold
Standards
Gas Chromatograph
CO_2/CH_4 Analyzer
CO/N_2O Analyzer
Cryocooler

→ Biology/medical research, i.e. DNA sequencing

HAMAMATSU
PHOTON IS OUR BUSINESS

MPPC® (multi-pixel photon counter)

S13360 series



MPPCs for precision measurement

MPPC is a type of device called SiPM (silicon photomultipliers). It is a new type of photon counting device that consists of multiple Geiger mode APD (avalanche photodiode) pixels. It is an opto-semiconductor with outstanding photon counting capability and low operating voltage and is immune to the effects of magnetic fields.
The S13360 series are MPPCs for precision measurement. The MPPCs inherits the superb low afterpulse characteristics of previous products and further provide lower crosstalk and lower dark count. They are suitable for precision measurement, such as flow cytometry, DNA sequencer, laser microscope, and fluorescence measurement, that requires low noise characteristics.

Features

- **Reduced crosstalk and dark count (compared to previous products)**
- **Outstanding photon counting capability (outstanding photon detection efficiency versus numbers of incident photons)**
- **Compact**
- **Operates at room temperature**
- **Low voltage (V_{BR}=53 V typ.) operation**

Applications

- **Fluorescence measurement**
- **Laser microscopes**
- **Flow cytometry**
- **DNA sequencers**
- **Environmental analysis**
- **Various academic research**

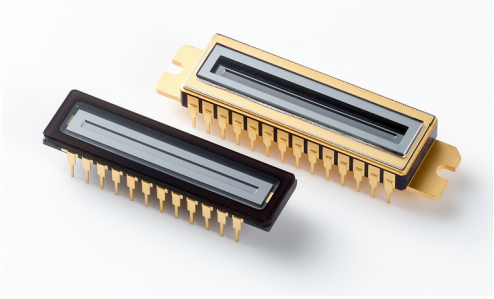
Sensing voltage: not a very Linux thing to do...

A single line of pixels

Line sensors: a single line at a time.

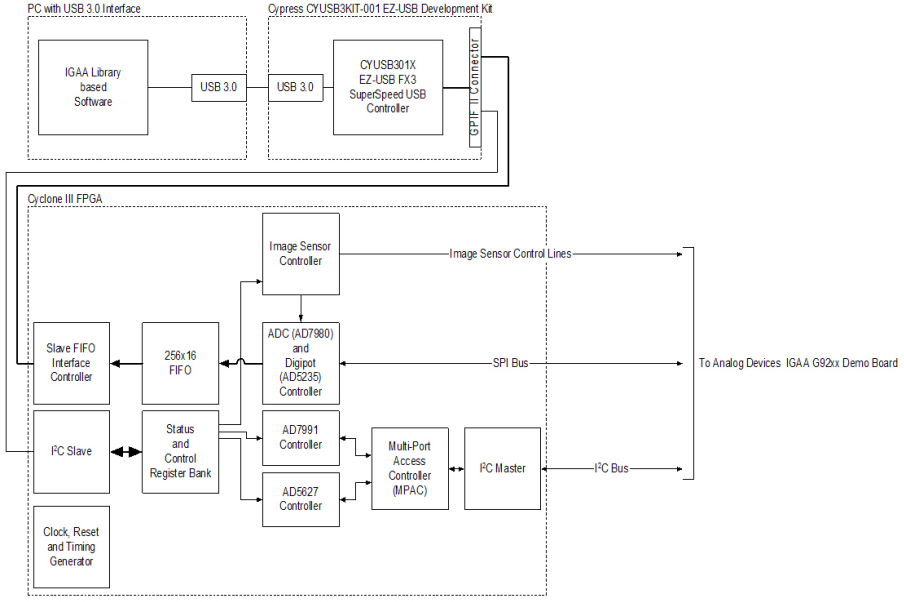
Not digital interface but analog interface: need an ADC to get digital readout.

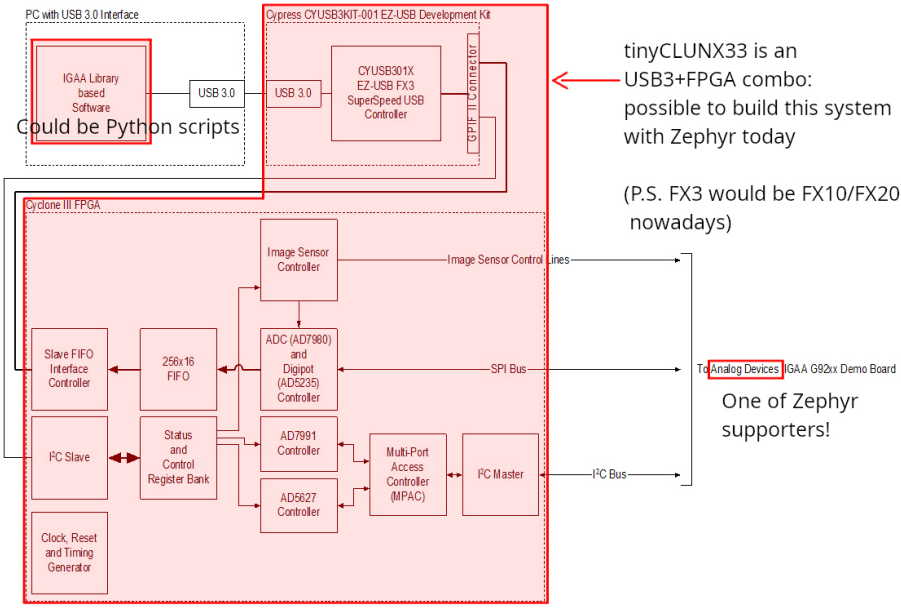
Sensing one pixel at a time, need to go fast!



Requires a fast ADC to handle the input.

Hamamatsu recommends an FPGA (customizable chip) + Analog Devices Analog-Digital-Converter (ADC).


PC with USB 3.0 Interface
IGAA Library based Software
USB 3.0
Cypress CYUSB3KIT-001 EZ-USB Development Kit
USB 3.0
CYUSB301X EZ-USB FX3 SuperSpeed USB Controller
GPIF II Connector
Cyclone III FPGA
Image Sensor Controller
Image Sensor Control Lines
Slave FIFO Interface Controller
256x16 FIFO
ADC (AD7980) and Digipot (AD5235) Controller
SPI Bus
To Analog Devices IGAA G92xx Demo Board
I²C Slave
Status and Control Register Bank
AD7991 Controller
AD5627 Controller
Multi-Port Access Controller (MPAC)
I²C Master
I²C Bus
Clock, Reset and Timing Generator


PC with USB 3.0 Interface
IGAA Library based Software
Could be Python scripts
USB 3.0
Cypress CYUSB3KIT-001 EZ-USB Development Kit
USB 3.0
CYUSB301X EZ-USB FX3 SuperSpeed USB Controller
GPIF II Connector
tinyCLUNX33 is an USB3+FPGA combo: possible to build this system with Zephyr today
(P.S. FX3 would be FX10/FX20 nowadays)
Cyclone III FPGA
Image Sensor Controller
Image Sensor Control Lines
Slave FIFO Interface Controller
256x16 FIFO
ADC (AD7980) and Digipot (AD5235) Controller
SPI Bus
To Analog Devices IGAA G92xx Demo Board
One of Zephyr supporters!
I²C Slave
Status and Control Register Bank
AD7991 Controller
AD5627 Controller
Multi-Port Access Controller (MPAC)
I²C Master
I²C Bus
Clock, Reset and Timing Generator

Multiple lines

Tools that can be used for building video systems: hardware to access the sensors implement all of that chain

→ Difficulty of embedded video: accessing parallel port or MIPI

→ Can use adapter chips like Himax HX6538 (not yet supported) or small FPGAs

What comes out of an image sensor

Dark (no auto-exposure) Green (no color correction)

Steps of an ISP.

Why an ISP is useful for robotics?

→ Get always values withing same range

→ Poor exposure: no data at all

→ De-fisheye

→ Avoid artefacts to trigger a detection on the NPU or other vision algorithm

Conclusion: A lot to handle to get a reasonable image out of a sensor!

Hardware that can help accessing this image.

What it takes...

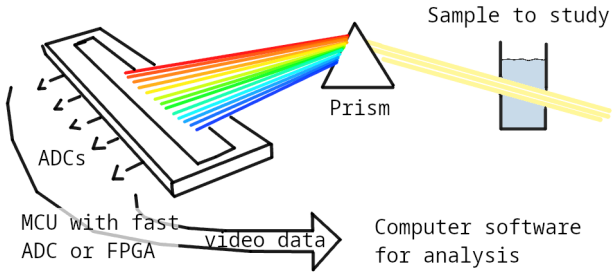
What would it take to build various devices on Zephyr

!! disclaimer: hardware is hard !!

!! disclaimer: not everything shown has drivers !!

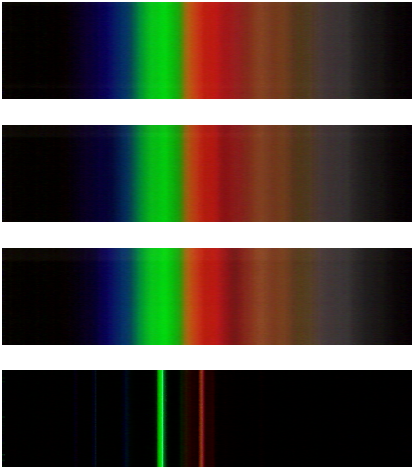
Also works without Zephyr, just putting things in perspective.

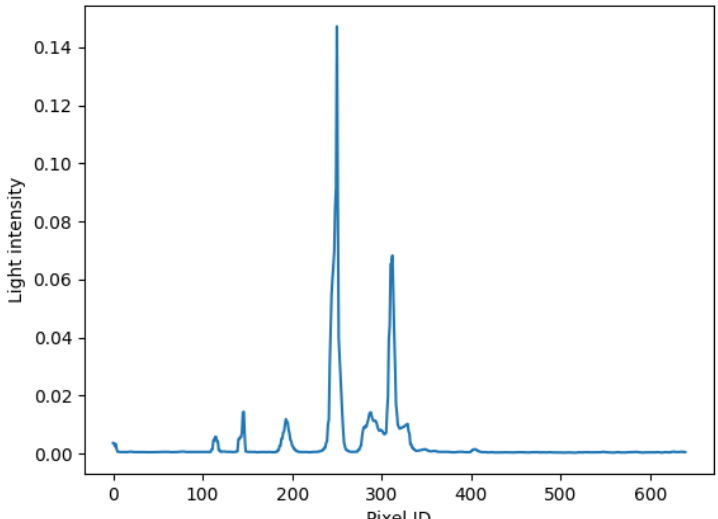
What it takes... Spectrophotometer



Need a very fast ADC! Not many board will have one...

→ Good to have a lot of options.




0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Light intensity
0
100
200
300
400
500
600
Pixel ID

What it takes... Drones

VMU RT1170

Overview

The VMU RT1170 features an i.MX RT1176 dual core MCU with the Cortex-M7 core at 1 GHz and a Cortex-M4 at 400 MHz. The i.MX RT1176 MCU offers support over a wide temperature range and is qualified for consumer, industrial and automotive markets. The VMU RT1170 is the default VMU for CogniPilot's Cerebri, a Zephyr RTOS based Autopilot.

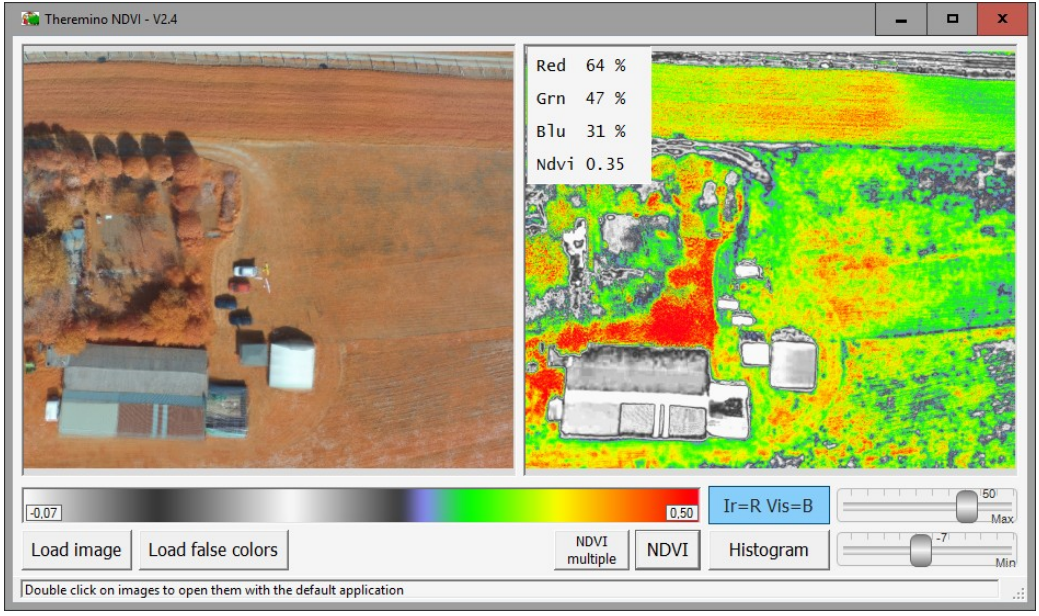
Hardware

- MIMXRT1176DVMAA MCU
  - 1GHz Cortex-M7 & 400Mhz Cortex-M4
  - 2MB SRAM with 512KB of TCM for Cortex-M7 and 256KB of TCM for Cortex-M4
- Memory
  - 512 Mbit Octal Flash
  - TF socket for SD card
- Ethernet
  - 2 wire 100BASE-T1
- USB
  - USB 2.0 connector
- Power
  - Redundant dual picoflex power ports
- Debug
  - 10 pin debug and shell adapter board to 20 Pin JTAG debugger and USB-C shell
- Sensor

Board Overview

VMU RT1170

Name:	`vmu_rt1170`
Vendor:	NXP Semiconductors
Architecture:	arm
SoC:	mimxrt1176


Theremino NDVI - V2.4
Red 64 %
Grn 47 %
Blu 31 %
Ndvi 0.35
-0,07
0,50
Ir=R Vis=B
50
Max
-7
Min
Load image
Load false colors
NDVI multiple
NDVI
Histogram
Double click on images to open them with the default application

What it takes... Yeast monitoring station

Monitoring process of beer, kombucha, lactic fermentation

Video but also...

CO2 polling for building charts.

LED API for illuminating when taking a capture.

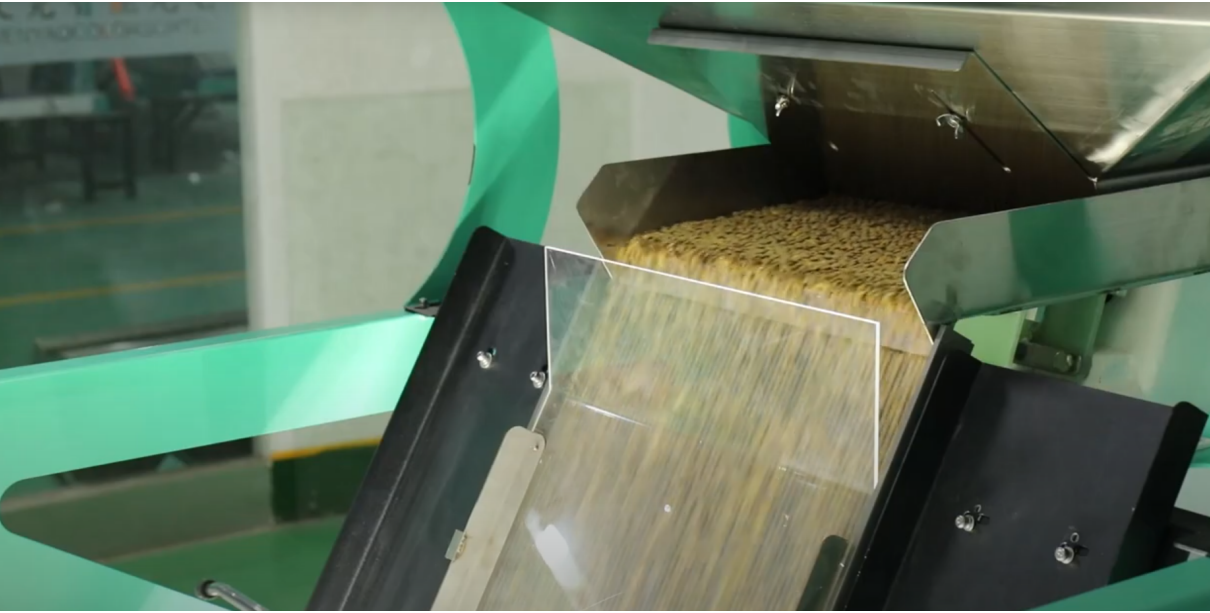
Video controls API for manual exposure tuning during "flash".

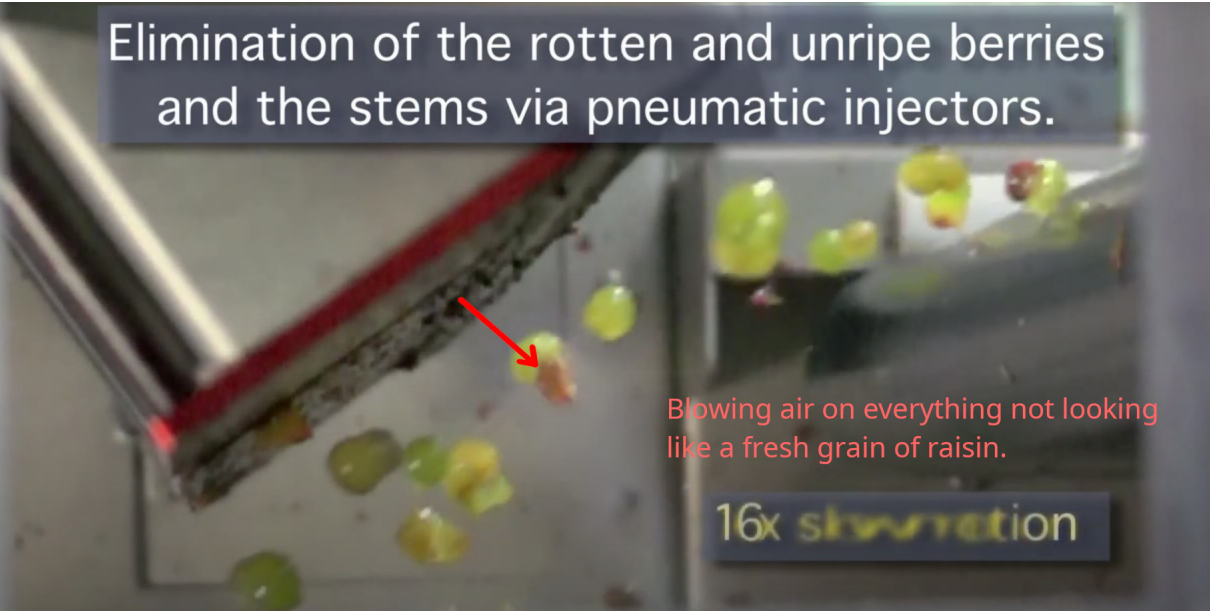
Wi-Fi to the home router.

HTTP client for sending the results.

What it takes... Sorting machine

Fastest board you can get! Most real-time you can get!




Elimination of the rotten and unripe berries and the stems via pneumatic injectors.
Blowing air on everything not looking like a fresh grain of raisin.
16x slowmotion

What it takes... Endoscopes/Borescope

Cameras usged by surgeons

Example of real endoscope camera module (CAMEMAKE):

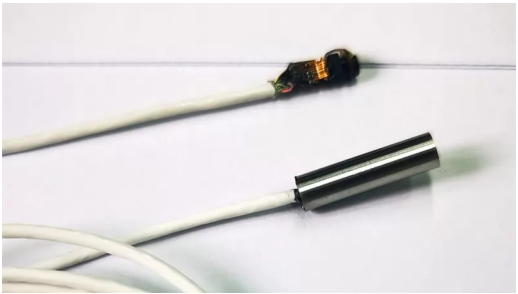
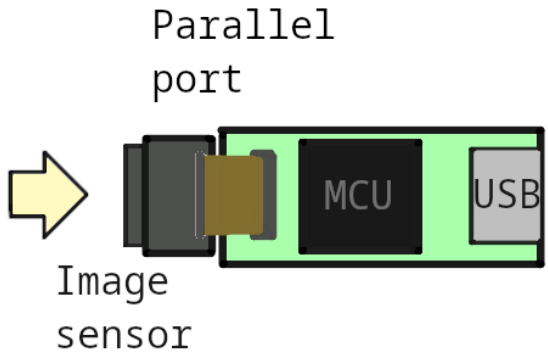
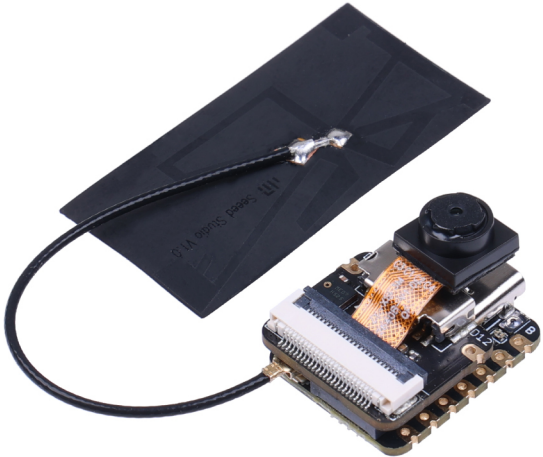


Image sensor driver
Video transfer driver <-> Video APIs <-> UVC

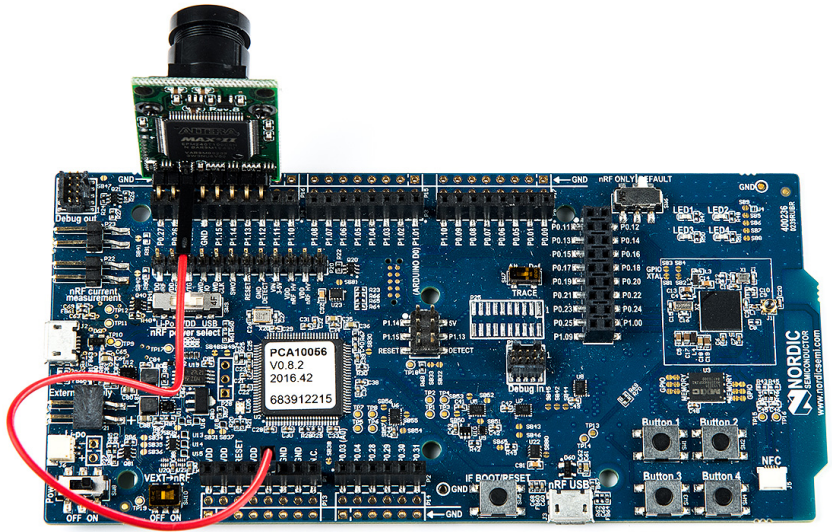


What it takes... Wi-Fi Smartglasses



What it takes... Bluetooth Smartglasses

Pre-Zephyr Nordic era: needs conversion.


PCA10056
V0.8.2
2016.42
683912215
Debug out
Debug in
nRF Current measurement
nRF Power select
VEXT-nRF
OFF ON
TRACE
RESET
DETECT
IF BOOT/RESET
nRF USB
Button 1
Button 2
Button 3
Button 4
NFC
LED1
LED2
LED3
LED4
nRF ONLY
DEFAULT
ARDUINO I/O HEADER
NORDIC SEMICONDUCTOR
www.nordicsemi.com

Any MCU with Bluetooth

SPI

Himax HM0360

(not yet supported)

640x480

Beyond Zephyr: ecosystem around it

What UVC adds to the table:

→ USB camera protocol supported on Linux, Windows, MaxOS, Android, iPad (not iOS yet), BSDs, 9front, QNX... (thanks to laptop lid cameras)

→ Linux interoperability: Standardize all the video controls with Linux

→ ROS2: integration of robotics (via USB cameras)

→ OpenCV (via USB cameras)

→ Want to suport a new sensor on any ecosystem? Bring Zephyr support, and now it's everywhere