Advanced Camera Support on Allwinner SoCs with Mainline Linux

Paul Kocialkowski
paul@bootlin.com

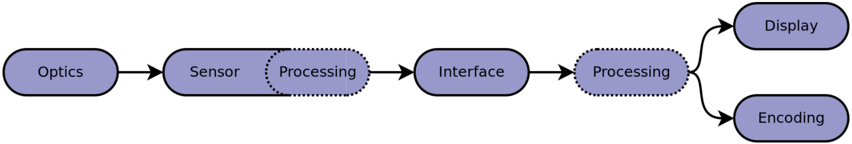
bootlin
embedded Linux and kernel engineering

Paul Kocialkowski

- Embedded Linux engineer at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Open-source contributor
  - Initial author of the **cedrus** VPU driver in V4L2
  - Contributor to the **sun4i-drm** DRM driver
  - Contributing the **logicvc-drm** DRM driver
  - Developed the **displaying and rendering graphics with Linux** training
- Living in **Toulouse**, south-west of France

An Introduction to Image Capture Technology

Overview of the Digital Image Capture Chain



An image capture chain

- **Optics**: shape light rays
- **Sensor**: convert light to digital values
- **Interface**: transport values
- **Processing**: produce good-looking pictures
- **Display/encoding**: show/store pictures *(out of the scope of this talk)*

Processing RAW Images

Data coming from a sensor ADC needs processing:

- Data corresponds to a **bayer pattern**, not pixels
- Brightness is linear, not adapted for display
- Sensors have a non-zero **dark-level current**
- Noise is present, color is off, image looks bad

Enhancement takes place in **Image Signal Processors (ISPs)**

Three distinct domains are involved:

1. **Bayer domain**, ends with debayering step
2. **RGB domain**, ends with YUV conversion
3. **YUV domain**, ends with final picture

Image Enhancements in ISPs

Various enhancements are usually applied to the image:

- **Dead pixel correction**: discard invalid values
- **Black level correction**: remove dark level current
- **White balance**: adjust R-G-B balance with coefficients/offsets
- **Noise filtering**: remove electronic noise
- **Color matrix**: adjust colors for fidelity
- **Gamma**: adjust brightness curve for non-linearity
- **Saturation**: adjust colorfulness
- **Brightness**: adjust global luminosity
- **Contrast**: adjust bright/dark difference

Image Enhancements in ISPs

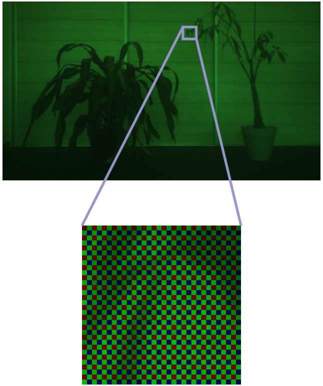
More advanced enhancements may also be applied:

- **Lens shading**: correct lens irregular brightness
- **Lens dewarp**: correct lens geometry distortion effect
- **Stabilization**: crop to remove shaking
- **Color LUT**: Translate colors with a specific style

Hardware implementations:

- ISPs embedded in sensors tend to be **simple**
  - Provide YUV data to the camera interface
- Multimedia Systems on a Chip often have an **advanced ISP**
  - Require raw bayer data on the camera interface
  - Require specific calibration data for the sensor/lens

Processing RAW Images: Illustration



Bayer step

RGB step

YUV step

Parameters to Adjust

Some parameters depend on the situation:

- **Focus** depends on the area of interest
- **White balance** depends on the light source(s)
- **Exposure** depends on the amount of light

Exposure depends on a few parameters:

- Diaphragm **aperture** (f-number)
- **Exposure time** (shutter speed)
- **Amplifier gain** (ISO number equivalent)

Advanced users will set parameters manually, with artistic implications

Automatic Parameters Control with 3A

In other cases, automatic parameters control is desirable:

- **Automatic exposition**: manage exposure time and gain (optionally diaphragm)
- **Auto-focus**: detect blurry and sharp areas, adjust with focus coil
- **Auto white balance**: detect dominant lighting and adjust

Implemented using 3A algorithms:

- General algorithms described in **academic literature**
- Involve a **feedback loop** system, using statistics
- Implementations are usually **hardware specific** (ISP and sensor), often considered to be the secret sauce!

Hardware Interfaces for Capture

Sensors need to transmit data:

- Analog interfaces (CVBS, etc) are mostly deprecated
- **Parallel** digital interfaces: basic, BT.656
  typically used with old and low-end sensors
- **Serial** digital interfaces: MIPI CSI-2, LVDS, SDI, HiSPi
  typically used with high-end sensors

Basic parallel interface:

- One TTL signal per bit, usually 8/10/12/16/24 bits width
- Pixel clock and sync signals (hsync, vsync)

MIPI CSI-2 serial interface:

- Differential pairs, using double data rate (DDR)
- One clock lane (high rates) and 1-4 data lanes

Scope and Use Case

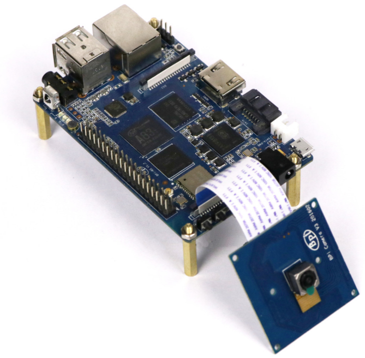
Scope and Use Case: Allwinner + MIPI CSI-2 + ISP

Allwinner platforms (V3 and A83T):

- Systems on a Chip with ARM CPUs
- MIPI CSI-2 receiver
- Camera interface (CSI)
- Image Signal Processor (ISP)

Image sensors (OV8865, OV5648):

- I2C control interface
- MIPI CSI-2 transmitter
- Bayer RAW formats (10/12 bits)
- Minimal to inexistent onboard ISP



The BananaPi-M3 with OV8865 connected

Status of Allwiner Camera Support in Mainline Linux

Allwinner platform support in mainline Linux:

- Long-time effort from the **sunxi community**, very active
  `https://linux-sunxi.org/Linux_mainlining_effort`
- Multimedia areas are often the last missing parts
- Allwinner started contributing (more or less) very recently

Camera support in mainline Linux:

- `sun4i-csi` driver for first generation CSI
- `sun6i-csi` driver for second generation CSI
- Third generation CSI support is missing
- MIPI CSI-2 and ISP support was entirely missing
  non-free blobs for ISP support and A80 MIPI CSI-2 in SDK

Video4Linux2 (V4L2) is the subsystem/API for media support in Linux

- Supports various types of **pixel-related devices**
  basically anything that is not a display or gpu
- Provides userspace with **video devices** (e.g. `/dev/video0`)
- Implements a generic **userspace API** including:
  - Format negotiation, implemented in `struct v4l2_ioctl_ops`
  - Memory management (alloc, free, mmap), implemented in `struct vb2_mem_ops`
  - A queue interface for buffers of a given type (output, capture...), implemented in `struct vb2_ops`
  - A control interface for configuration
- Good fit for **all-in-one devices** (e.g. USB UVC cameras)
  assumes that a memory (DMA) interface is available

V4L2 Support for Complex Camera Systems : Subdevs

Complex systems bring the need for **more refinement**:

- Internal blocks with FIFOs
- External devices with interfaces (e.g. sensors)
- Possibility to configure each block and the topology

Hence the notion of **subdevs** was introduced to V4L2:

- Represent a single block (usually not DMA-capable)
- Exposed to userspace via dedicated nodes `/dev/v4l-subdev0`
- Dedicated format configuration, implemented in `struct v4l2_subdev_pad_ops`
- Dedicated stream management, implemented in `struct v4l2_subdev_video_ops`
- Called by video devices with `v4l2_subdev_call`

Subdevs need to be **parented to a v4l2 device** (controlling entity)

Simple case: the **all-in-one driver**

- A single driver may register a parent v4l2 device, a video device and subdev(s)
- The subdev can be registered directly:
  `v4l2_device_register_subdev(v4l2_dev, subdev);`

Complex case: **multiple drivers** involved

- The video device driver will typically register a v4l2 device
- Each subdev driver will register its subdev asynchronously:
  `v4l2_async_register_subdev(subdev);`
- A driver that needs a subdev needs to identify and wait for it

V4L2 Support for Complex Camera Systems : Fwnode Graph

The fwnode graph represents the connection between different blocks:

- Typically described in device-tree with port/endpoint
- The meaning of each port is described in the device-tree bindings
- Endpoints are retrieved by the driver and parsed with a helper:
  `fwnode_graph_get_endpoint_by_id()`
  `v4l2_fwnode_endpoint_parse()`
- May contain an indication of the bus type:
  `enum v4l2_mbus_type`, e.g. `V4L2_MBUS_CSI2_DPHY`
- As well as bus-specific information:
  e.g. `struct v4l2_fwnode_bus_mipi_csi2`

Device-tree example for camera to MIPI CSI-2 bridge:

```
imx219: camera@10 {
  compatible = "sony,imx219";
  ...
  port {
    camera_to_bridge: endpoint {
      data-lanes = <1 2>;
      link-frequencies = /bits/ 64 <456000000>;
      remote-endpoint = <&bridge_from_camera>;
    };
  };
};
```

```
mipi_csi2: csi@1cb1000 {
  compatible = "allwinner,sun8i-v3s-mipi-csi2";
  ...
  ports {
    ...
    port@0 {
      reg = <0>;
      bridge_from_camera: endpoint {
        data-lanes = <1 2>;
        remote-endpoint = <&camera_to_bridge>;
      };
    };
    ...
  };
};
```

Async registration allows other drivers to use the subdev:

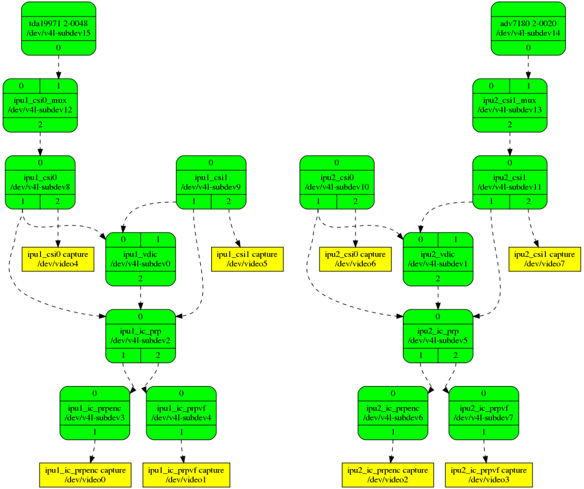
- A link between devices is described with **fwnode graph**
- An **async notifier** will match and notify when the subdev is available: `v4l2_async_notifier_add_fwnode_remote_subdev`
- The async notifier can be used by the driver with a v4l2 device: `v4l2_async_notifier_register(v4l2_dev, notifier);`
- Or by a subdev that needs another subdev (e.g. a bridge): `v4l2_async_subdev_notifier_register(subdev, notifier);`
- A callback gives the requesting driver a `struct v4l2_subdev`

V4L2 Support for Complex Camera Systems : Media Controller

The **media controller** API provides coordination between blocks:

- Each block is an **entity** with sink/source **pads** derivated from a video device or a subdev
- Entities declare a particular function e.g. `MEDIA_ENT_F_PROC_VIDEO_PIXEL_FORMATTER`
- **Links** between pads of entities are created by drivers, may allow userspace to enable/disable them
- Grouped in a media device (tied to a v4l2 device)
- Performs **runtime validation** for links, implemented in `struct media_entity_operations`'s `link_validate`
- Topology is **exposed to userspace**, usually controlled with `media-ctl`:

```
media-ctl -l '"sun6i-csi-bridge":1 -> "sun6i-csi-capture":0[1]'
```



The i.MX capture driver's media topology

V4L2 Support for Image Signal Processors (ISPs)

Specific aspects related to ISPs:

- Usually have an internal pipeline with **multiple blocks**
- Parameters are **highly specific** (not a good fit for V4L2 controls)
- Provide stats **information buffers** (3A, histogram)
- Exposes one or multiple **capture interfaces**

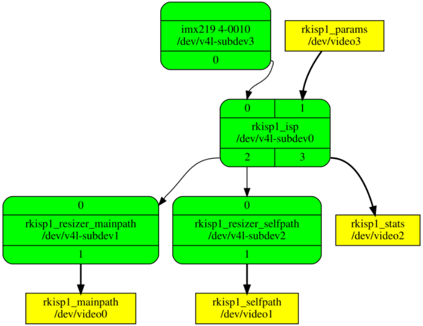
ISPs integration in V4L2:

- Processor represented by a subdev/media entity: `MEDIA_ENT_F_PROC_VIDEO_ISP`
- **Capture video devices** for pixels: queues with type `V4L2_BUF_TYPE_VIDEO_CAPTURE`
- **Meta output video devices** for parameters: queue with type `V4L2_BUF_TYPE_META_OUTPUT` with dedicated (struct) buffer type
- **Meta capture video devices** for stats: queue with type `V4L2_BUF_TYPE_META_CAPTURE` with dedicated (struct) buffer type

V4L2 Support for Image Signal Processors (ISPs): rkisp1

Example driver: **rkisp1**

- `rkisp1_isp` subdev device to coordinate
- `rkisp1_mainpath`, `rkisp1_selfpath` giving pixels, with resizers
- `rkisp1_params` taking `struct rkisp1_params_cfg`
- `rkisp1_stats` giving `struct rkisp1_stat_buffer`



The rkisp1 media topology

Accomplished Work for Advanced Camera support on Allwinner

A31/V3 and A83T MIPI CSI-2 Support

- MIPI CSI-2 controllers feed (raw) data to the **CSI controller**
- Represented as bridges (subdevs) between CSI and the sensor
- Requires **adaptation to the CSI code** to select interface
- Needs to get sensor **pixel rate** from dedicated control: `V4L2_CID_PIXEL_RATE`
- Using a D-PHY block with the **generic Linux PHY API**
  - `phy_mipi_dphy_get_default_config` helper not accounting for DDR

A83T Support:

- **Reference source code** in Allwinner SDK: `drivers/media/video/sunxi-vfe/mipi_csi/bsp_mipi_csi.c`
- Some **magic values** in registers (undocumented)
- D-PHY is mixed with controller registers
  - In-driver PHY provider and consumer

A31/V3 and A83T MIPI CSI-2 Support

A31/V3 Support:

- **Reference source code** in Allwinner SDK:
  `drivers/media/video/sunxi-vfe/mipi_csi/{protocol,dphy}`
- **Documentation** available in A31 user manual
- Same D-PHY block used for MIPI DSI, in Rx mode instead of Tx
- Driver already exists for Tx, needs direction selection:
  - Describe with submode? Not a run-time decision...
  - Describe with different compatible? Same hardware block...
  - Describe with optional device-tree property

V3 and A83T MIPI CSI-2 Support: Patch Series

- First iteration sent out in October 2020
- Merged in v6.0 in June 2022

```
arch/arm/boot/dts/sun8i-a83t.dtsi                                          |  26 ++
arch/arm/boot/dts/sun8i-v3s.dtsi                                           |  68 ++++
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi.c                         | 218 +++++++----
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi.h                         |  65 ++--
drivers/media/platform/sunxi/sun6i-csi/sun6i_video.c                       |  57 +--
drivers/media/platform/sunxi/sun6i-csi/sun6i_video.h                       |   7 +-
drivers/media/platform/sunxi/sun6i-mipi-csi2/sun6i_mipi_csi2.c             | 600 ++++++++++++++++++
drivers/media/platform/sunxi/sun6i-mipi-csi2/sun6i_mipi_csi2.h             | 117 ++++++
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/Kconfig                  |  11 +
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/Makefile                 |   4 +
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/sun8i_a83t_dphy.c        |  92 +++++
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/sun8i_a83t_dphy.h        |  39 ++
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/sun8i_a83t_mipi_csi2.c   | 666 ++++++++++++++++++
drivers/media/platform/sunxi/sun8i-a83t-mipi-csi2/sun8i_a83t_mipi_csi2.h   | 197 +++++++++++
drivers/phy/allwinner/phy-sun6i-mipi-dphy.c                                | 164 +++++++++-
25 files changed, 2633 insertions(+), 141 deletions(-)
```

ISP Support and Integration

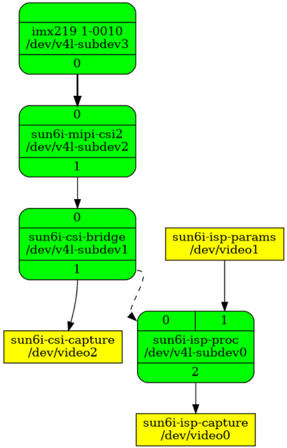
Input/output aspects:

- ISP takes (raw) data from one of the **CSI controller(s)**
- DRAM input exists in theory but unable to make it work
- Input/interface part of CSI controller needs to be configured
- **Internal mux** routes data to ISP instead of CSI DMA
  - Impossible to switch back to CSI DMA without reboot
- **Two outputs** available: main-channel and sub-channel

Major CSI rework required:

- Separate bridge from DMA engine (subdev and video device)
- Register with ISP's v4l2/media devices for common topology
- Allow standalone use (both with and without ISP enabled): `sun6i_csi_isp_detect` helper

ISP Support and Integration: Topology



The sun6i-isp/sun6i-csi media topology

CSI components:

- sun6i-csi-bridge
- sun6i-csi-capture

ISP components:

- sun6i-isp-proc
- sun6i-isp-params
- sun6i-isp-capture

MIPI CSI-2 interface:

- sun6i-mipi-csi2
- sun8i-a83t-mipi-csi2

ISP Support and Integration: Features and API

Parameters configure **modules of the ISP**:

- Passed via `sun6i-isp-params` video device
- uAPI structure: `struct sun6i_isp_params_config`
- Applied to next load buffer update

Supported features:

- **Bayer coefficients**, with R/GR/GB/B gain/offset: `struct sun6i_isp_params_config_bayer`
- **2D noise filtering** (BDNF) coefficients for G and R/B: `struct sun6i_isp_params_config_bdnf`
- Submitted to **staging** since a stable uAPI needs all features covered

ISP Driver and Integration: Patch Series

- First iteration sent out in September 2021
- Merged in v6.2 in November 2022

```
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi.c                   | 1051 ++++++++---------
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi.h                   |  155 ++---
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi_bridge.c            |  895 ++++++++++++++++
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi_bridge.h            |   64 ++
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi_capture.c           | 1094 ++++++++++++++++
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi_capture.h           |   73 +++
drivers/media/platform/sunxi/sun6i-csi/sun6i_csi_reg.h               |  364 ++++++-----
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp.c                    |  577 ++++++++++++++++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp.h                    |   86 +++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_capture.c            |  759 ++++++++++++++++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_capture.h            |   79 +++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_params.c             |  571 ++++++++++++++++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_params.h             |   53 ++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_proc.c               |  598 ++++++++++++++++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_proc.h               |   61 ++
drivers/staging/media/sunxi/sun6i-isp/sun6i_isp_reg.h                |  275 +++++++++
drivers/staging/media/sunxi/sun6i-isp/uapi/sun6i-isp-config.h        |   43 ++
51 files changed, 8702 insertions(+), 1808 deletions(-)
```

Future Work and Improvements

Remaining Features to Implement

Roadmap for ISP driver completeness:

- Support **more platforms** (at least A83T)
- Declare **hardware revisions** (modules availability):
  `media_dev->hw_revision`
- Support for **stats** (hist/ae/awb/af/afs)
- Support for **sub-channel, scaling and rotation**
- **Complete uAPI** that describes all modules
- Support for **all available modules**
  - Start with black level correction, color matrix and gamma
- Userspace **3A algorithms** support

Integration with libcamera

- Community-driven project for advanced camera support: **libcamera**
- Provides **abstraction** for applications, GStreamer, Android
- Implements **complex pipeline support**
- Implements **hardware-specific 3A algorithms**
- Good fit for Allwinner A31 ISP userspace support

We're hiring!

- Embedded Linux / Linux kernel engineers
  - Linux BSPs, Linux kernel drivers, U-Boot, Buildroot, Yocto
  - Open-source contributions
  - Conferences
  - Offices in Lyon, Toulouse, or full remote
  - 2+ years of experience
- Internships for computer science engineering students
- `https://bootlin.com/company/careers/`

Questions? Suggestions? Comments?

Paul Kocialkowski

paul@bootlin.com

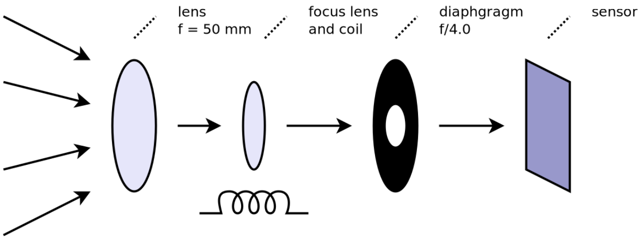
Extra Slides

Camera Optical Systems

Optical systems have multiple elements and purposes:

- **Lens** to make light converge towards sensor surface
  - **Focal length** (f) indicates the amount of convergence
  - Sets the angle of view, results in magnification/zoom effect
  - Optional moving elements to define focus plane
- Optional **focus coil** to electrically control focus adjustment
- Optional **diaphragm** to control aperture
  - **F-number** (e.g. `f/1.8`) indicates how open the diaphragm is
  - Aperture decreases with f-number (diaphragm closes)

Camera Optical Systems: Illustration



Camera optical system

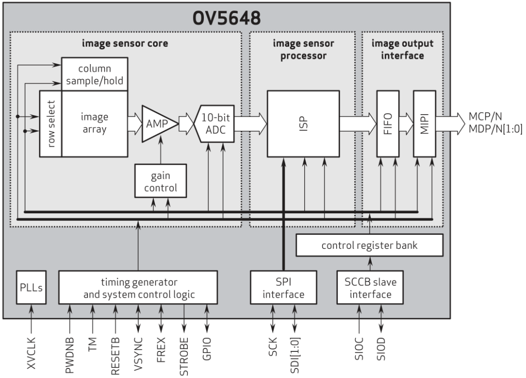
Diaphragm aperture variation *(CC BY-SA 3.0, KoeppiK, Wikimedia Commons)*

Image Sensors

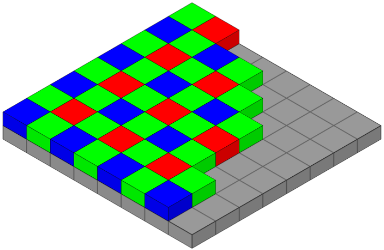
Components of an image sensor:

1. Color Filter Array (CFA) following a **Bayer pattern** (R/G/G/B)
2. Photo-sensitive cells (**photosites**) in CMOS or CCD technology
3. **Amplifier and ADC** to produce digital values
   - Generally 8, 10 or 12-bit data
4. Configurable **shutter speed** (exposure time)
5. **Clocks and timings** for frame rate
   - Capture cycle repeatedly following precise timings
   - External clock reference for internal PLLs
   - Limits exposure time
6. **Processing** (more or less advanced)
7. Control and **configuration** interface
   - Usually configured via I2C or SPI
8. Data **transmission** interface

Image Sensors: Illustration

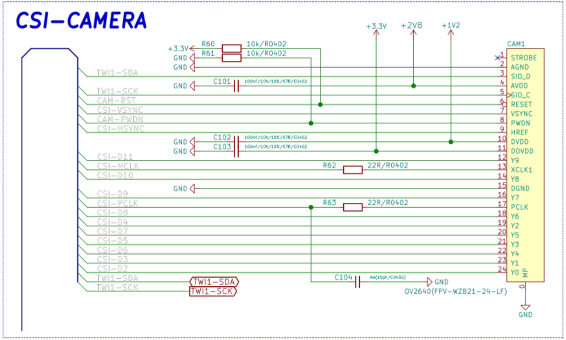


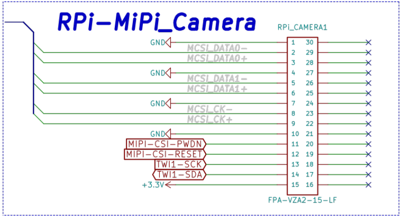
OV5648 block diagram *(Omnivision)*



Bayer pattern *(CC BY-SA 3.0, Cburnett, Wikimedia Commons)*

Hardware Interfaces for Capture: Schematics





Parallel and MIPI CSI-2 interfaces on the S3-OLinuXino