Advanced Camera Support on Allwinner SoCs with Mainline Linux

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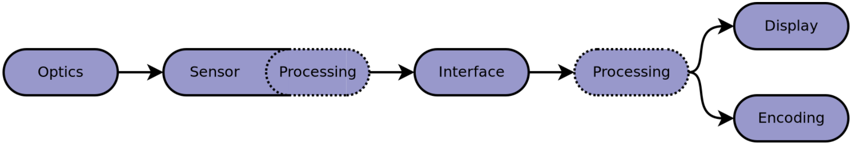
Paul Kocialkowski

- Embedded Linux engineer at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Open-source contributor
  - Co-maintainer 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)*

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

Processing RAW Images

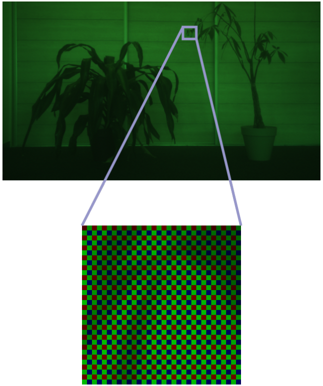
Data coming from a sensor ADC needs processing:

- 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

Processing RAW Images: Illustration



Bayer step

RGB step

YUV step

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

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!

Status of Allwiner Camera Support in Mainline Linux

Allwinner Hardware for Camera Support

- **CSI** controller for parallel/BT.656 interfaces
  - First generation: A10, A13, A20, R40
  - Second generation: A31, A23, A33, A83T, H3, H5, V3, A64
  - Third generation (**CSIC**): A63, H6, V5, V536, V533, H616, D1

Nearly always present

- **MIPI CSI-2** interface controller
  - Specific implementations: A80, A83T
  - First generation: A31, V3, T7?
  - Second generation (**combo** with sub-LVDS, HiSPi): V5, V536, V533

Not always present

- **ISP** processors
  - First generation (glued to CSI): A10, A20, R40?
  - Second generation (separate): A31, A80, (A23), (H3), (H5), A83T, V3
  - Third generation (ISP500/ISP520/ISP521): V5, V536, H616

Usually present when MIPI CSI-2 is present

Mainline Linux Support and Allwinner Camera Support

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 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>;
      };
    };
    ...
  };
};
```

V4L2 Support for Complex Camera Systems : Async Subdevs

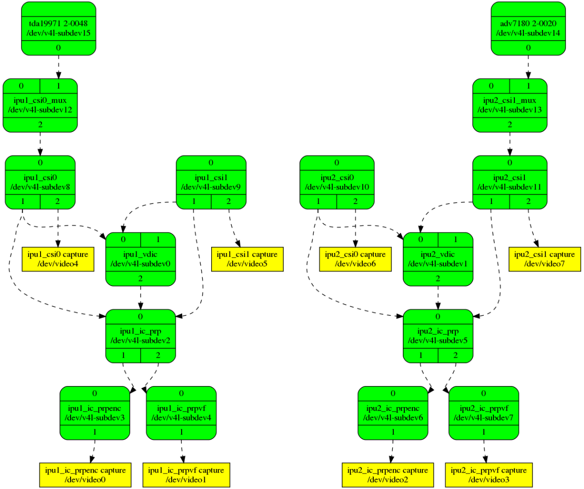
Async registration allows other drivers to use the subdev:

- 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:

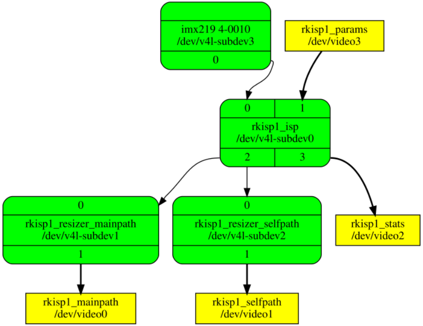
- Usually have an internal pipeline with **multiple blocks**
- Parameters are **highly specific** (not a good fit for V4L2 controls)
- Provide stats **information buffers** (3A, histogram)
- Exposes one or multiple **capture interfaces**

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

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

Scope of Our Work

First phase: OV5648 with MIPI CSI-2 on Allwinner V3s

- Add support for the OV5648 sensor
- Add support for V3 MIPI CSI-2
- Capture raw Bayer data

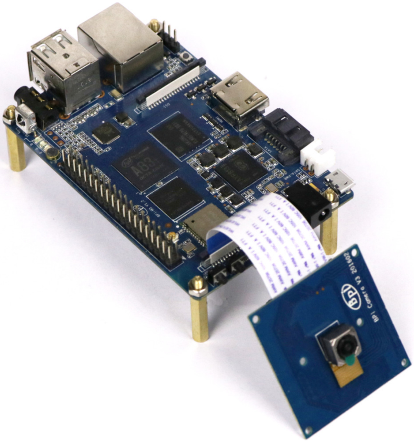
2020 summer internship: OV8865 with MIPI CSI-2 on Allwinner A83T

- Same goal with OV8865 and A83T (different MIPI CSI-2 controller)
- Using the BananaPi M3 board

Second phase: Basic ISP support on Allwinner V3s

- Debayering (to YUV) with gain/offset
- 2D noise reduction

BananaPi-M3 and OV8865



The BananaPi-M3 with OV8865 connected

Support for New Sensors: OV5648 and OV8865

Writing image sensor drivers is hard!

- Reference code abundantly uses **static large arrays** of register/values
- Tailored for a **specific input clock frequency** (usually 24 MHz)
- Documentation is **not very precise**, often lacks some registers

Taking the hard path to write nice drivers:

- **Proper definitions** for all (known) registers
- **Helper functions** for the different parts
- **Descriptive structures** for each supported mode
- Documenting the **clock tree**

Proper Drivers for Image Sensors: OV5648 Clock Tree and Mode

```c
struct ov5648_pll1_config {
  unsigned int pll_pre_div;
  unsigned int pll_mul;
  unsigned int sys_div;
  unsigned int root_div;
  unsigned int sclk_div;
  unsigned int mipi_div;
};

struct ov5648_pll2_config {
  unsigned int plls_pre_div;
  unsigned int plls_div_r;
  unsigned int plls_mul;
  unsigned int sys_div;
  unsigned int sel_div;
};
```

```c
struct ov5648_mode {
  unsigned int crop_start_x;
  unsigned int offset_x;
  unsigned int output_size_x;
  unsigned int crop_end_x;
  unsigned int hts;

  unsigned int crop_start_y;
  unsigned int offset_y;
  unsigned int output_size_y;
  unsigned int crop_end_y;
  unsigned int vts;

  bool binning_x;
  bool binning_y;

  unsigned int inc_x_odd;
  unsigned int inc_x_even;
  unsigned int inc_y_odd;
  unsigned int inc_y_even;

  /* 8-bit frame interval followed by 10-bit frame interval. */
  struct v4l2_fract frame_interval[2];

  /* 8-bit config followed by 10-bit config. */
  const struct ov5648_pll1_config *pll1_config[2];
  const struct ov5648_pll2_config *pll2_config;

  const struct ov5648_register_value *register_values;
  unsigned int register_values_count;
};
```

Proper Drivers for Image Sensors: Patch Series

- First iteration sent out in October 2020
- Final iteration (v7) accepted in December 2020

```
Documentation/devicetree/bindings/media/i2c/ovti,ov5648.yaml |  115 ++
Documentation/devicetree/bindings/media/i2c/ovti,ov8865.yaml |  124 ++
arch/arm/boot/dts/sun8i-a83t-bananapi-m3.dts                 |  102 ++
drivers/media/i2c/Kconfig                                    |   26 +
drivers/media/i2c/Makefile                                   |    2 +
drivers/media/i2c/ov5648.c                                   | 2624 +++++++++++++++++++++++++++++++
drivers/media/i2c/ov8865.c                                   | 2972 +++++++++++++++++++++++++++++++
7 files changed, 5965 insertions(+)
```

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
- Series later integrated with ISP work

```
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(-)
```

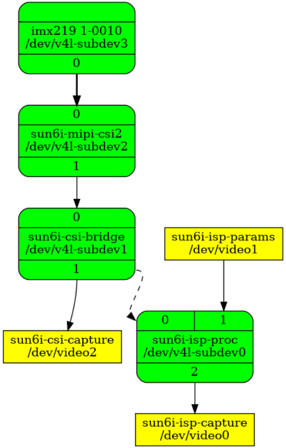
ISP Support and Integration

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



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: Sync Mechanism

Unusual sync mechanism:

- Registers `0x0-0x3f` are **accessed directly**
- Other registers are prepared in a **load buffer**
  - Load and save buffers are allocated in DRAM and provided to ISP
- A **flag** indicates that load buffer was updated
- At next vsync:
  - ISP reads new register values from load buffer
  - ISP writes old register values to save buffer
  - New values become active (can be read from MMIO)

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

```
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

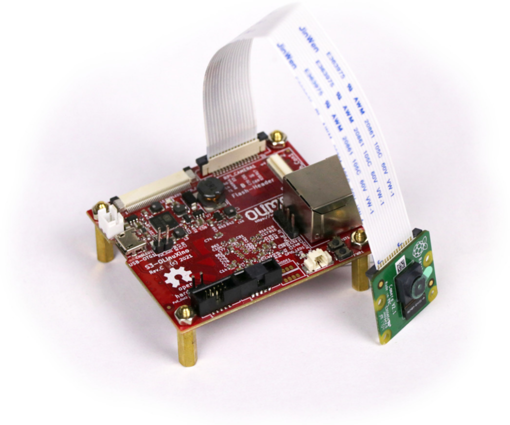
Remaining Features to Implement

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



Olimex announced the S3-OLinuXino, with a RPi-compatible MIPI CSI-2 connector!

Questions? Suggestions? Comments?

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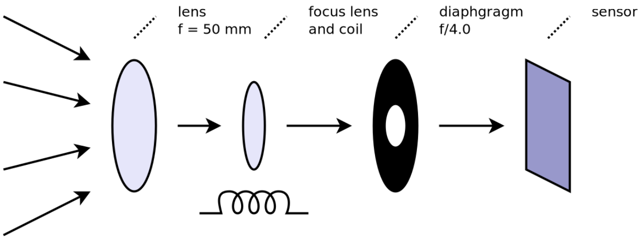
Extra Slides

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

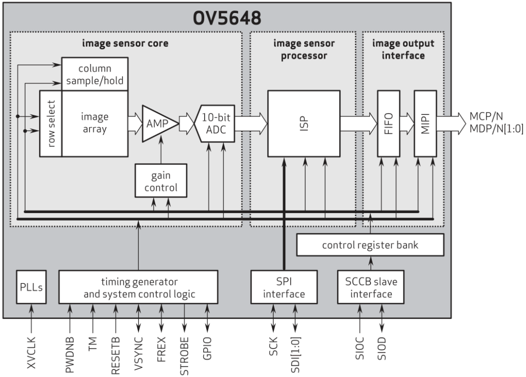
Diaphragm aperture variation *(CC BY-SA 3.0, KoeppiK, Wikimedia Commons)*

Image Sensors

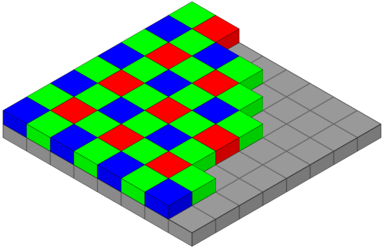
Components of an image sensor:

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

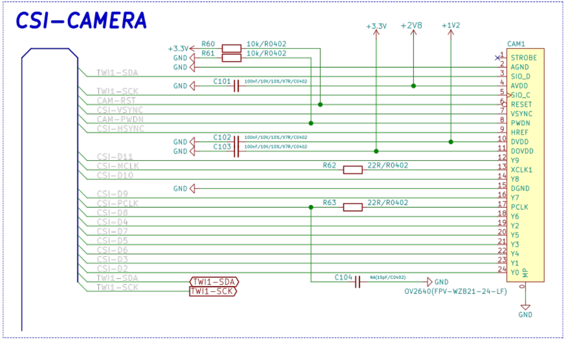
Image Sensors: Illustration

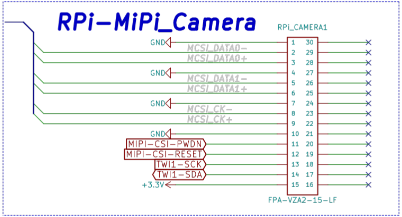


OV5648 block diagram *(Omnivision)*



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





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