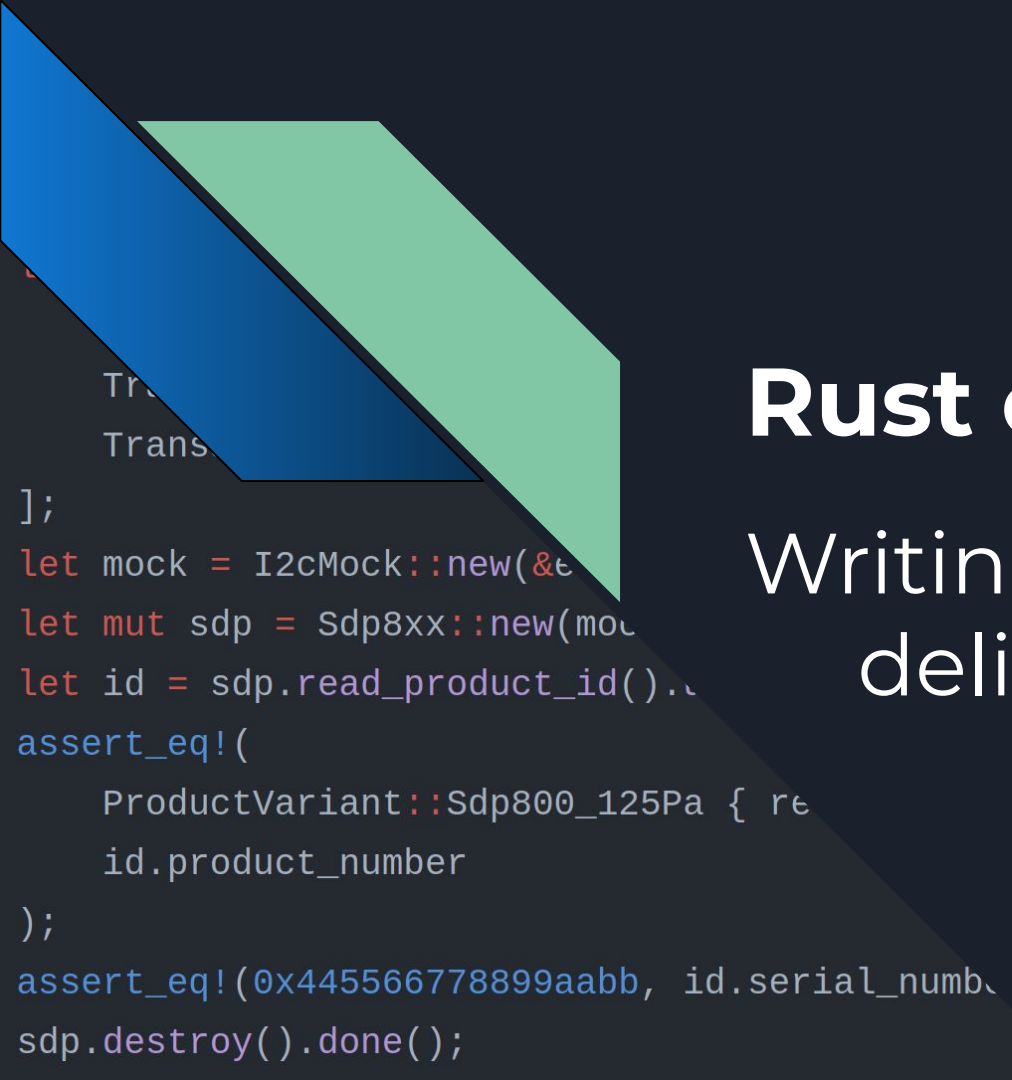


Rust on bare metal:

Writing Sensor Drivers, delightfully.

Rafael Bachmann

Who am I?

Systems Software Developer (Rust)

Always chasing projects

Sometimes finishing projects

- “But this new idea is so interesting!”
- “Why finish a project if I can keep working on it?”

Ideas are cheap!

Implementation is expensive.

https://github.com/barafael

Roadmap

- Context
  - Hardware development
- Software development
  - A sensor driver
  - The embedded-hal project
  - Testing and integration of an embedded-hal driver
- Takeaways

Motivation

Remote Controlled Sailboat (human-operated)

http://www.tippecanoeboats.com/t37-racing-sloop-2

Motivation

Flight Controller Firmware (C++, Frama-C)

- Radio Comms + Motor Control +
  Inertial Measurement Unit + PID control

https://github.com/barafael/raPID

barafael / raPID

Unwatch 5 | Star 11 | Fork 1

Code | Issues | Pull requests | Actions | Projects | Wiki | Security | Insights | Settings

master | 7 branches | 3 tags | Go to file | Add file | Code

barafael Update README.md — 41ab0c8 on 24 Nov 2018 — 374 commits

CalibrateMPU6050 @ 22c69f2	add calibration submodule	4 years ago
include	Revert "port watchdog back to C"	3 years ago
src	Revert "port watchdog back to C"	3 years ago
.clang-format	WS and formatting improvements	3 years ago
.gitignore	re-add git config files	3 years ago

About

flight controller running on ARM Cortex M4

remote-control | teensy | flight-controller | pid-control | flight-mode | transitional-mixers

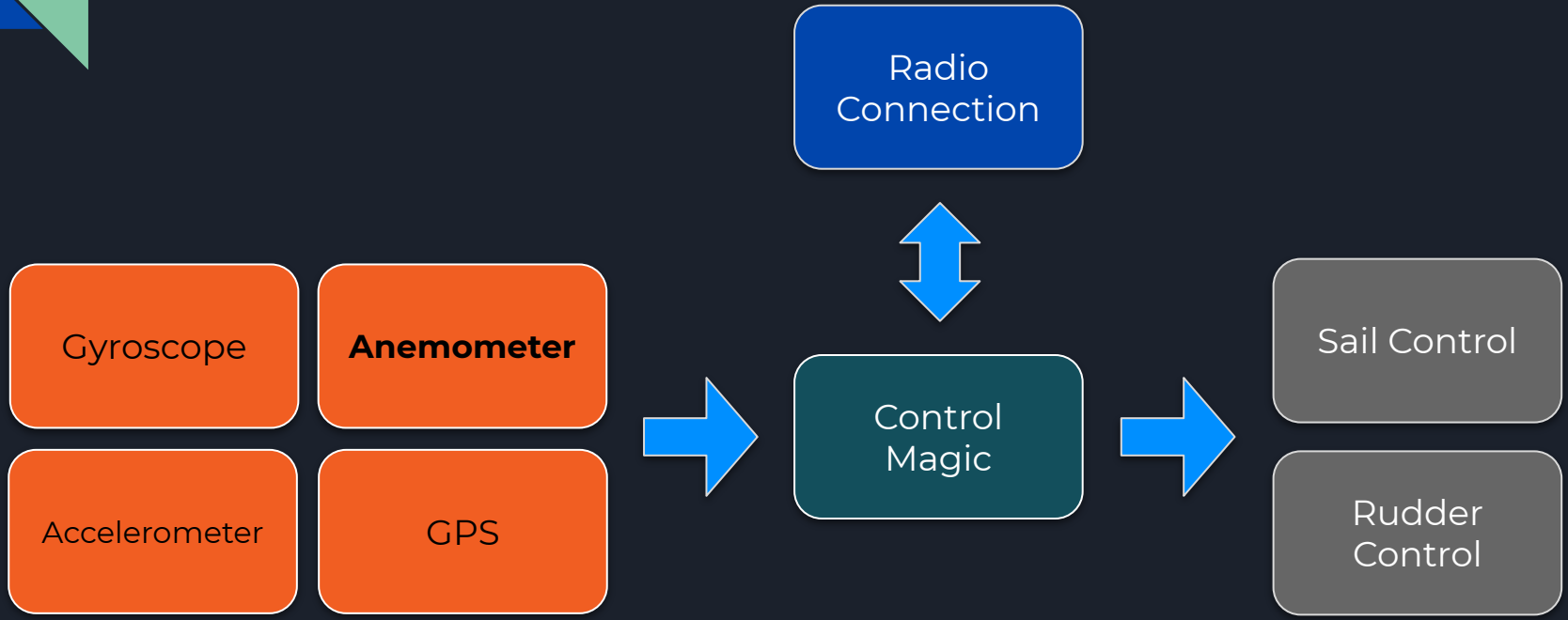
Readme

MIT License

Idea: Autonomous Sailboat

- Combine mini sailboat with
  communication, sensing, control, autonomy
- Lots more sensors than on a multicopter
- Quite a bit more difficult
- Much much less dangerous.

Sailboat modules



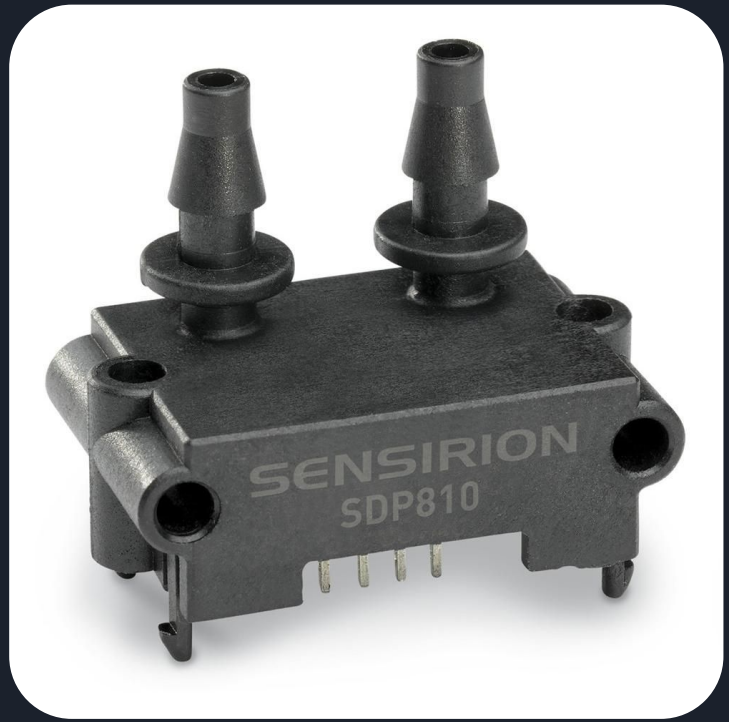
So much stuff => focus on one module at a time.

Anemometer design - Sensor

“Where is the wind coming from, and how strong is it?”

Sensirion SDP8xx
Differential Pressure Sensor

- Sensitive measurement of pressure differences
- “Wind is just pressure difference”
- I2C interface

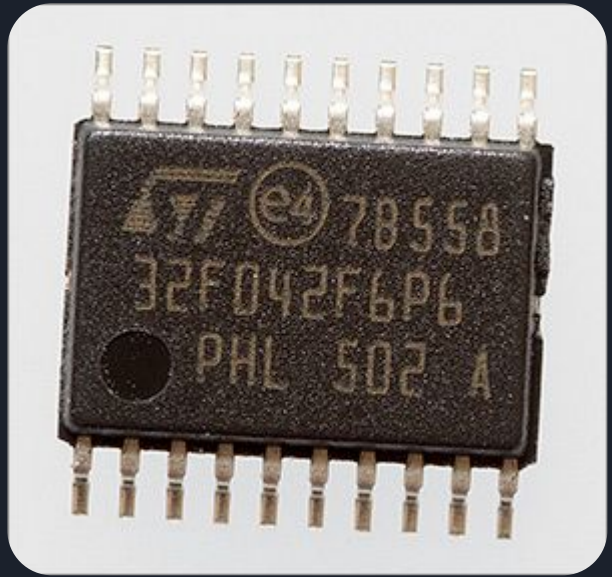


https://www.sensirion.com/de/durchflusssensoren/differenzdrucksensoren/sdp800-proven-and-improved/

Anemometer design - MCU

STM32F042: Tiny Cortex-M0 MCU

- Hand Solderable
- 6kB SRAM, 32kB Flash
- I2C and serial interfaces
- Supported by the awesome rust-embedded ecosystem

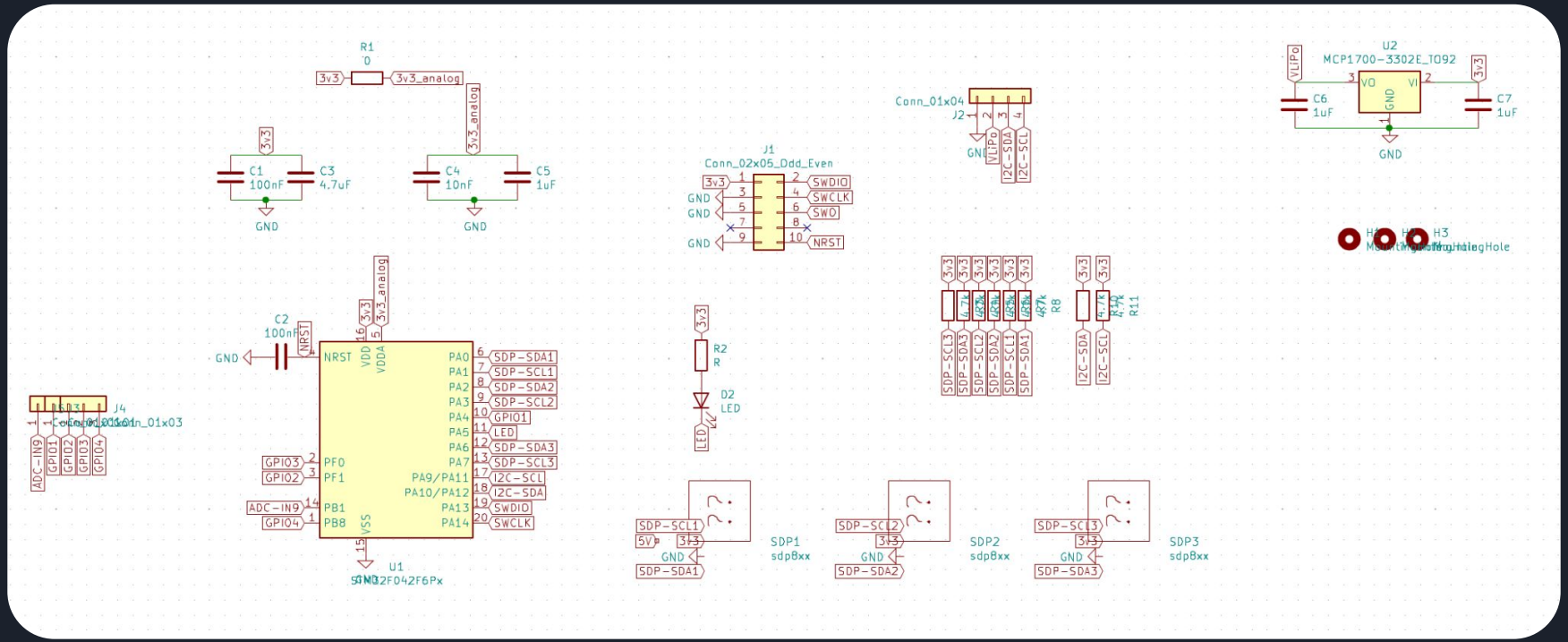


https://github.com/stm32-rs/stm32f0xx-hal

https://www.st.com/en/microcontrollers-microprocessors/stm32f042f6.html

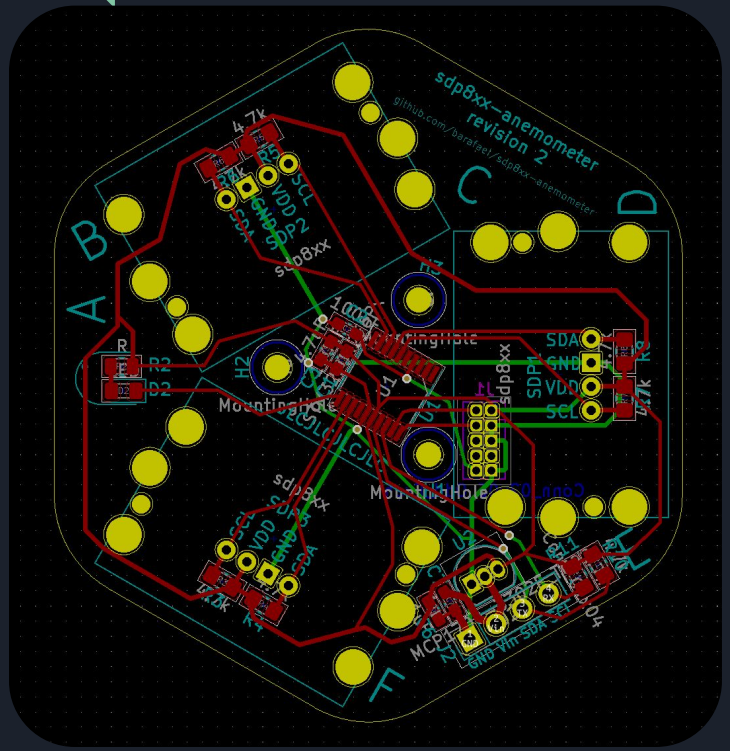
Anemometer design - Schematic

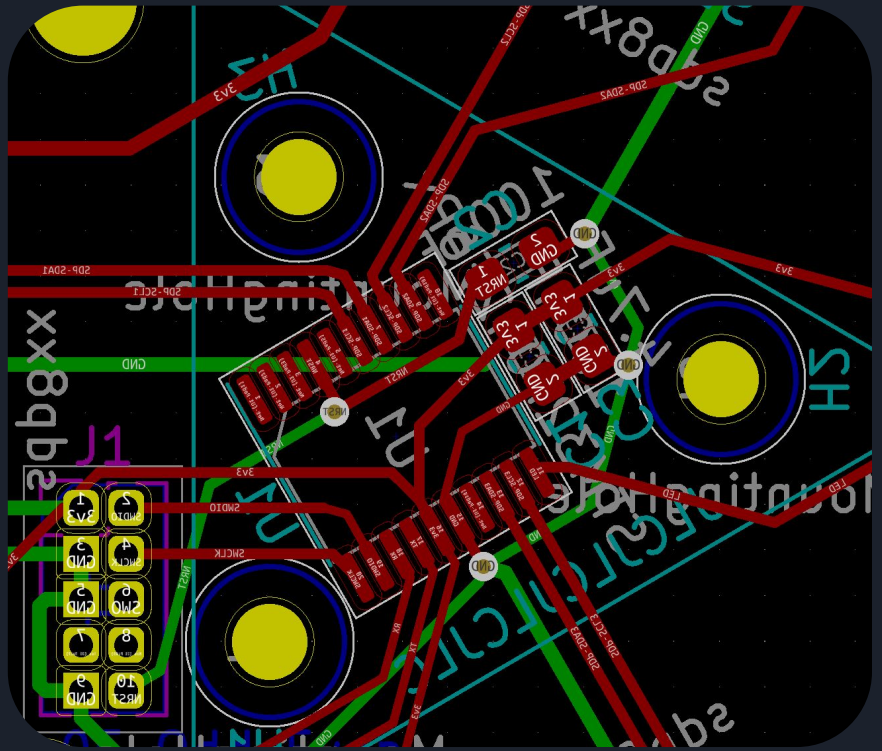
https://github.com/barafael/sdp8xx-anemometer-pcb



Anemometer design - PCB Layout

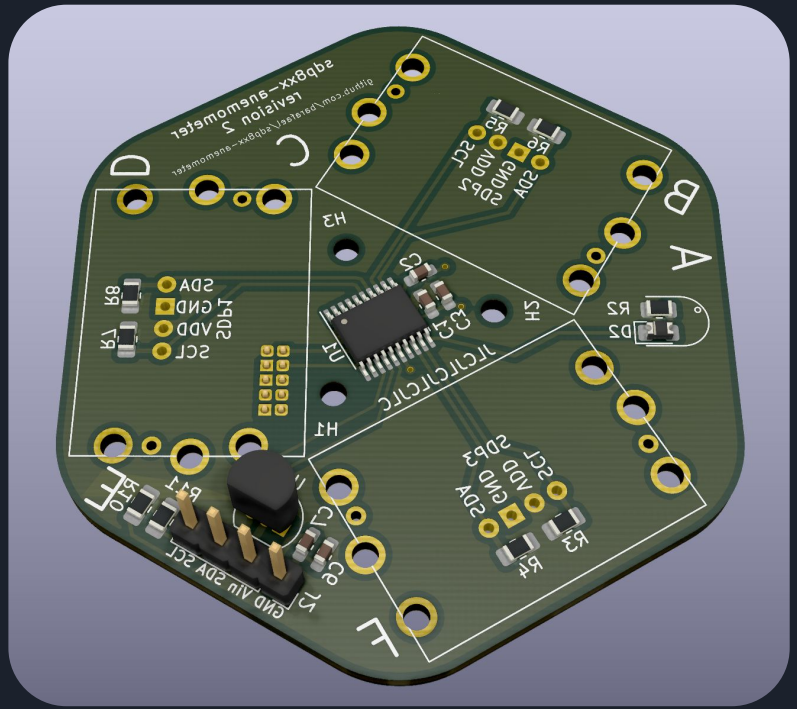
https://github.com/barafael/sdp8xx-anemometer-pcb

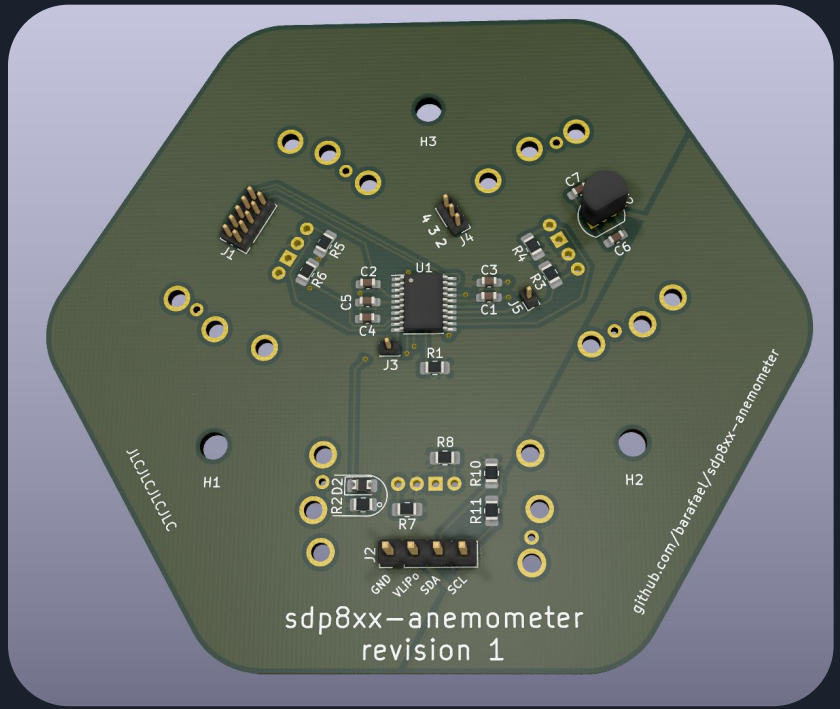




Anemometer design - Board Renders

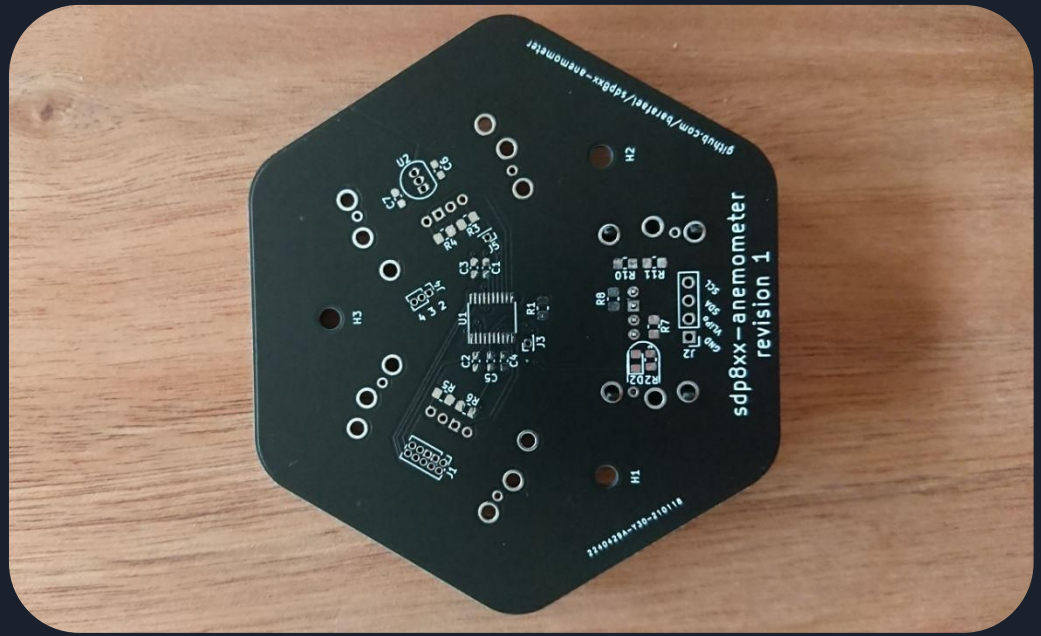
https://github.com/barafael/sdp8xx-anemometer-pcb

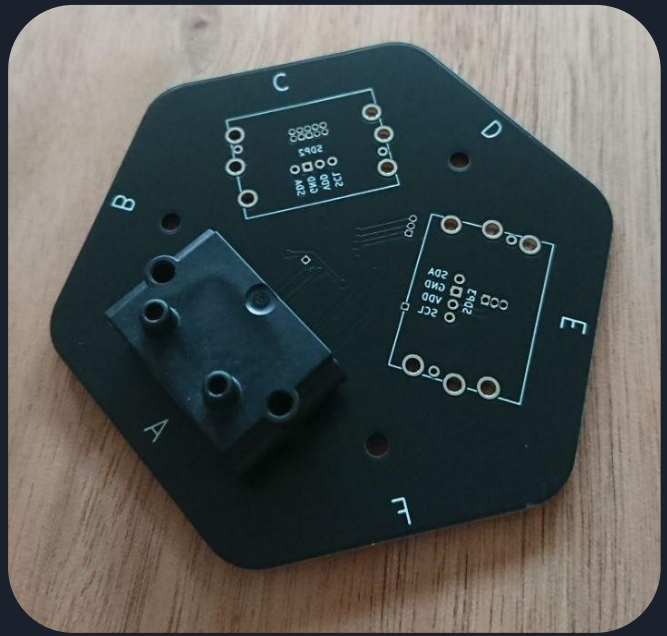




Anemometer design - Finished PCBs

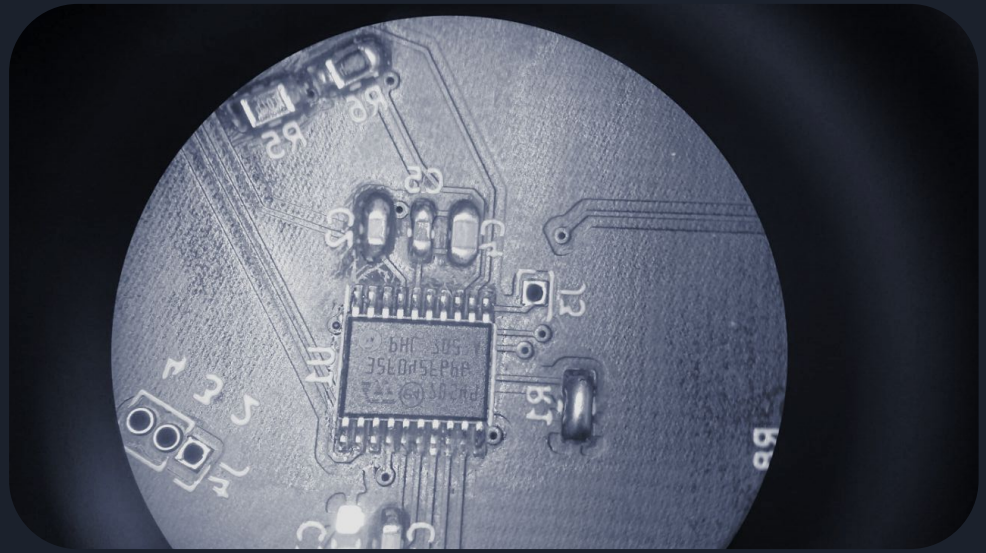
https://github.com/barafael/sdp8xx-anemometer-pcb

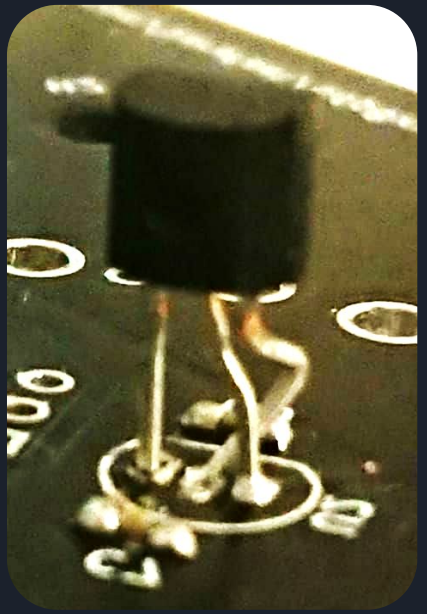




Anemometer design - Soldering

#FixThePart #NotTheLayout





Anemometer design - Finished Module

3D-Printed “Air Pods”

Anemometer design - Software

Hardware dev is tedious (for me);

Lots of waiting (ordering parts and PCBs);

=> Concurrently do software and firmware, then integrate!

Now comes the easy part - software.

The SDP8xx Driver - Objective

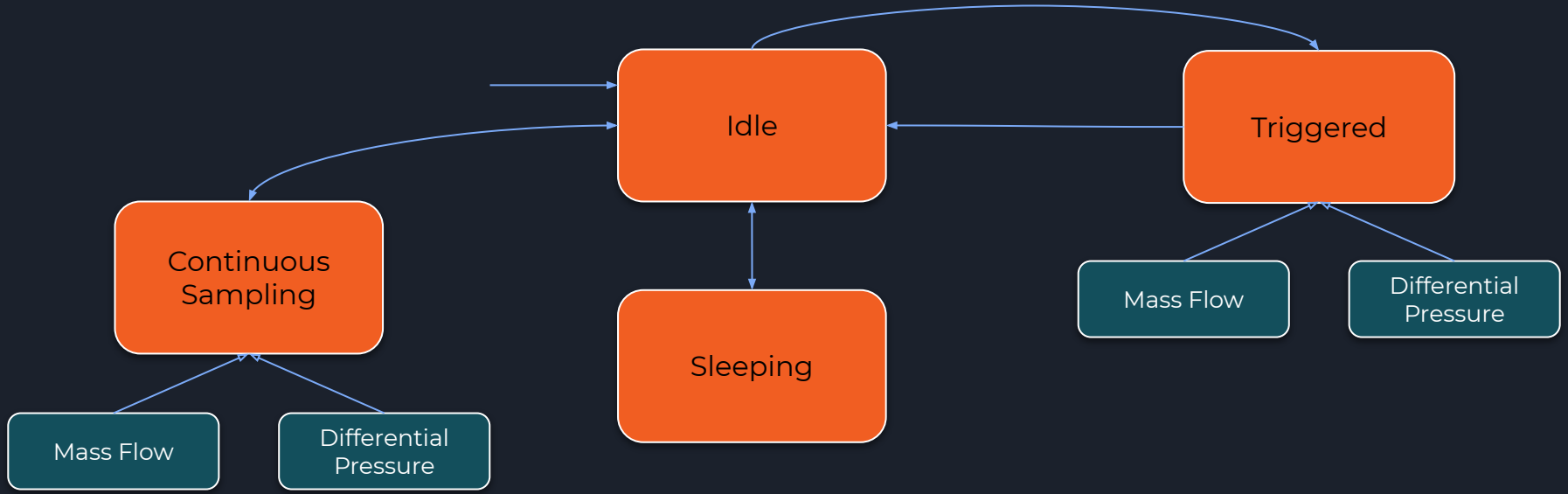
Objective:

Library for using the sdp8xx sensor!

Support for configuration, sampling, conversion.

The SDP8xx Operation Modes

Read the datasheet :) find the operation modes



https://www.sensirion.com/de/durchflusssensoren/differenzdrucksensoren/sdp800-proven-and-improved/

Type State Programming

Implement the operation modes as marker types

```rust
pub struct IdleState;
pub struct TriggeredState;
pub struct SleepState;

pub struct ContinuousSamplingState<MeasurementType> {
    data_type: PhantomData<MeasurementType>,
}

pub struct DifferentialPressure;
pub struct MassFlow;
```

Type State Programming

State the possible state transitions with newtypes

```rust
/// Transition from Idle to Differential Pressure Sampling
pub type ToDifferentialPressureSampling<I2C, D> = Result<
    Sdp8xx<I2C, D, ContinuousSamplingState<DifferentialPressure>>,
    SdpError<I2C, I2C>,
>;

/// Transition from Continuous Sampling to Idle
pub type ToIdle<I2C, D> = Result<Sdp8xx<I2C, D, IdleState>, SdpError<I2C, I2C>>;

/// Transition from Idle to Sleep state
pub type ToSleep<I2C, D> = Result<Sdp8xx<I2C, D, SleepState>, SdpError<I2C, I2C>>;
```

Type State Programming

Construction of initial state requires **ownership** of resources!

```
impl<I2C, D, E> Sdp8xx<I2C, D, IdleState>
    where /* snip */ {
    pub fn new(i2c: I2C, address: u8, delay: D) -> Self {
        Sdp8xx {
            i2c,
            address,
            delay,
            state: PhantomData::<IdleState>,
        }
    }
}
```

No “&” or “&mut” anywhere!

Type State Programming

Construction of initial state requires **ownership** of resources!

```
impl<I2C, D, E> Sdp8xx<I2C, D, IdleState>
    where /* snip */ {
    pub fn go_to_sleep(mut self) -> IdleToSleeping<I2C, D> {
        self.send_command(Command::EnterSleepMode)?;
        Ok(Sdp8xx {
            i2c: self.i2c,
            address: self.address,
            delay: self.delay,
            state: PhantomData::<SleepState>,
        })
    }
}
```

No “&” or “&mut” anywhere!

Type State Programming

Implement the operation modes as type-state transitions

```
impl<I2C, D, E> Sdp8xx<I2C, D, SleepState>
    where /* snip */ {
    pub fn wake_up(mut self) -> SleepingToIdle<I2C, D> {
        // snip...
        Ok(Sdp8xx {
            i2c: self.i2c,
            address: self.address,
            delay: self.delay,
            state: PhantomData::<IdleState>,
        })
    }
}
```

No “&” or “&mut” anywhere!

Type State Programming

Operations are available in their state only

The state transitions take **ownership** - no left-over invalid objects

All of this for free! No memory, binary, computation cost.

```
core::mem::size_of::<ContinuousSamplingState<MassFlow>>() == 0
```

Deep Type State

```
let tx: TxMode<
    embedded_nrf24l01::NRF24L01<
        Infallible,
        gpio::gpioa::PA8<Output<PushPull>>,
        stm32f0xx_hal::gpio::gpioa::PA10<Output<PushPull>>,
        Spi<
            stm32::SPI1,
            gpio::gpioa::PA5<Alternate<gpio::AF0>>,
            gpio::gpioa::PA6<Alternate<gpio::AF0>>,
            gpio::gpioa::PA7<Alternate<gpio::AF0>>,
        >,
    >,
> = nrf24.tx().unwrap();
```

Interlude: Embedded Ecosystem

Lots of sensors and actuators out there:

- Thermometers, LCD screens, Potentiometers, IMUs, Barometers, GPS sensors, Health Monitoring, Air Quality, ...

Arduino Libraries are nice (well, kinda...)

Problem: Drivers, Hardware Abstraction Layers (HALs), etc.

- not interoperable!

Embedded HAL

Provides universal interfaces for common peripherals

- Analog to Digital Converters
- Communication Peripherals
- Timers (in/out)
- Watchdogs
- ...

Target-specific implementations for wildly varying platforms

https://crates.io/crates/embedded-hal

Embedded HAL

```
// get pins
let din = port0.p0_12.into_push_pull_output(Level::Low).degrade();
    more pins
let busy = port1.p1_09.into_floating_input();

// given pins, get SPI
let spi = Spim::new(p.SPIM3, spi_pins, Frequency::K500, spim::MODE_0, 0);

// given SPI, get display
let mut epd4in2 = EPD4in2::new(spi, cs, busy, dc, rst, delay).unwrap();
```

Embedded HAL

- Ownership + Move semantics: It is impossible to configure resources which are in use elsewhere
  - A peripheral **owns** its resources
  - A driver **owns** its peripherals

- Types + Traits + Generics:
  - Construct a peripheral with valid resources

Embedded HAL Portability

Driver works on:

- Raspberry Pi
- Arduino
- STM32
- RISC-V Longan Nano
- … any target for which embedded-hal implements i2c!

Embedded HAL Mocking

Not just hardware targets - Mocking I2C for unit tests!

```rust
#[test]
fn trigger_mass_flow_read() {
    let bytes: [u8; 2] = Command::TriggerMassFlowRead.into();
    let data = vec![3, 4, 0x68, 6, 7, 0x4c, 0, 1, 0xb0];
    let expectations = [
        Transaction::write(0x10, bytes.into()),
        Transaction::read(0x10, data.clone()),
    ];
    let mock = I2cMock::new(&expectations);
    let mut sdp = Sdp8xx::new(mock, 0x10, DelayMock);
    let _data = sdp.trigger_mass_flow_sample().unwrap();
    sdp.release().done();
}
```

https://crates.io/crates/embedded-hal-mock

Embedded HAL Bitbanging

Drop-in replace real I2C interfaces with software-based ones!

```
let scl = gpioa.pa0.into_open_drain_output(cs);
let sda = gpioa.pa1.into_open_drain_output(cs);

let timer = Timer::tim1(dp.TIM1, 200.khz(), &mut rcc);

// Make bit-banged I2C with arbitrary pins
let i2cbb = I2cBB::new(scl, sda, timer);

let mut sdp8xx = Sdp8xx::new(i2cbb, 0x25, delay);
```

https://github.com/sajattack/bitbang-hal

Tool Shoutout: Tarpaulin!

SUPER EASY line coverage analysis.

```
May 16 23:31:18.162  INFO cargo_tarpaulin::report: Coverage Results:
|| Tested/Total Lines:
|| src/command.rs: 12/14
|| src/lib.rs: 95/125
|| src/product_info.rs: 31/34
|| src/sample.rs: 28/31
|| src/test.rs: 162/163
||
89.37% coverage, 328/367 lines covered
```

https://crates.io/crates/cargo-tarpaulin

Tarpaulin Example

https://github.com/barafael/cd74hc4067/blob/main/coverage.pdf

```
impl<P, E> CD74HC4067<P, E, EnabledState>
where
    P: OutputPin,
    P: OutputPin,
    P: OutputPin,
    P: OutputPin,
    E: OutputPin,
{
    /// Disable the mux display by pulling `pin_enable` high
    pub fn disable(mut self) -> Result<CD74HC4067<P, E, DisabledState>, Error<P, E>> {
        self.pin_enable.set_high().map_err(Error::EnablePinError)?;
        Ok(CD74HC4067 {
            pin_0: self.pin_0,
            pin_1: self.pin_1,
            pin_2: self.pin_2,
            pin_3: self.pin_3,
            pin_enable: self.pin_enable,
            state: PhantomData::<DisabledState>,
        })
    }
}
```

https://crates.io/crates/cargo-tarpaulin

Crate Shoutout: Proptest!

Fuzz, but cleverly!

Example: https://github.com/barafael/sdp8xx-rs/blob/main/src/test.rs#L224

Idea: combine embedded-hal-mock with proptest

=> emulate misbehaving hardware / interference

https://crates.io/crates/proptest

What does all this get me?

When I finally got the hardware, software worked first try!

For prototyping, used raspberry pi (actual target is `#![no_std]`)

When I needed to connect 3 I2C sensors to one MCU,
I changed the I2C implementation to bitbanging.
Worked first try.

https://github.com/barafael/sdp8xx-rs

Long-term sustainable projects

Some code bitrots quicker than I can write it

- Cross-toolchains, build environments, dependencies

High confidence in software

- Easy Unit tests, Mocking, Coverage
- Type-state programming
- Dependency management

Reduce SAAAD: “Spooky action at a distance”!

Long-term sustainable projects

Solid building blocks to rely on

Pick up a project where I left it a while ago

Build abstractions on existing blocks

=> long-term projects have a chance of success!

Thanks :)

https://docs.google.com/presentation/d/17Ij4O7XQRL_hAvmpx7cocYC6kq3MZQ6WWw-U1W2Nn-0/edit?usp=sharing