Building a Tilt-Compensated Compass Optimized for a Sailboat

A practical implementation using LSM6DSO + LIS3MDL and lightweight fusion

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Why a "Normal" Compass Fails at Sea

A simple magnetometer heading works fine on a lab bench.
On a sailboat, it fails almost immediately.

The boat is constantly:

- Rolling
- Pitching
- Yawing from waves
- Vibrating from hull slap and rigging
- Passing through local magnetic disturbances

To get a stable, trustworthy heading offshore, you need:

1. **Tilt compensation**
2. **Smart filtering**
3. **Magnetic anomaly rejection**
4. **Adaptive fusion tuned for sea state**
5. **Low CPU load (embedded-friendly)**

This post describes an implementation designed specifically for a sailboat using:

- **LSM6DSO** (gyro + accelerometer)
- **LIS3MDL** (magnetometer)
- STM32Duino libraries
- 50 Hz fusion loop

The result: a stable, low-noise, responsive marine heading solution.

System Architecture

The design uses three sensor paths:

- **Gyroscope** → short-term yaw stability
- **Accelerometer** → tilt reference
- **Magnetometer** → long-term heading reference

Fusion is performed using:

- A **super-minimal complementary structure**
- Adaptive yaw correction
- Motion-aware magnetic trust weighting

Sensor Configuration (Marine-Optimized)

LSM6DSO (Gyro + Accelerometer)

ODR

- **52 Hz**

Why 52 Hz?

- High enough to capture wave motion
- Low enough to reduce CPU load
- Close to 50 Hz fusion loop rate
- Avoids unnecessary power consumption

Gyroscope Filtering

- LPF1: **9.7 Hz**
- LPF2: fixed 16.6 Hz (always enabled)

Why 9.7 Hz?

Because sailboats do not rotate at high frequencies.

Typical motion spectrum:

Motion	Frequency
Helm input	0.05–0.3 Hz
Wave yaw	0.1–0.5 Hz
Violent motion	< 2 Hz
Vibration	5–20 Hz

By selecting 9.7 Hz:

- Hull vibration is attenuated
- Yaw integration becomes cleaner
- RMS motion estimator becomes stable
- No steering responsiveness is lost

Accelerometer Filtering

- LPF2 enabled
- Similar bandwidth strategy
- Reduces vibration before tilt calculation

LIS3MDL (Magnetometer)

ODR

- **10 Hz**

Why not faster?

Because:

- Earth's magnetic field does not change quickly
- Faster ODR increases noise
- 10 Hz is more than sufficient for helm dynamics

Performance Mode

- **Ultra-High Performance**

This reduces internal noise — critical when using a 2nd-order low-pass filter and tilt compensation.

Filtering Strategy

Magnetometer Filtering

A **2nd-order low-pass filter** is applied:

- Bandwidth ≈ **2 Hz**

Why 2 Hz?

- Passes helm-induced heading changes
- Rejects wave spikes
- Rejects local magnetic jitter
- Maintains natural steering feel

Anything lower would feel sluggish.
Anything higher lets wave noise through.

Gyro Integration

The gyro provides:

- Smooth short-term yaw
- Stability between magnetic updates
- Resistance to temporary magnetic disturbance

Tilt Compensation

Tilt compensation uses accelerometer-derived roll and pitch.

Process:

1. Normalize accelerometer vector
2. Compute roll & pitch
3. Rotate magnetometer vector into horizontal plane
4. Compute yaw using local-level components

This ensures correct heading even at 20°–30° heel — common under sail.

Adaptive Yaw Fusion (Sea-State Aware)

This is where the implementation becomes truly marine-optimized.

Instead of fixed complementary gain:

```
heading = gyro_integrated + k * magnetic_error
```

We make **k adaptive**.

Motion RMS Estimation

We compute a rolling RMS of gyro magnitude:

- Calm water → low RMS
- Heavy sea → high RMS

Then:

- Calm → increase magnetic trust
- Rough sea → reduce magnetic trust

This prevents:

- Magnetic noise from waves causing jitter
- Over-correction during heavy motion

Automatic Magnetic Anomaly Rejection

Local disturbances (engine, winches, wiring, tools) cause:

- Sudden magnitude change
- Sudden heading jump

We reject magnetometer updates when:

- Field magnitude deviates from calibrated norm
- Heading change exceeds plausible rate

During rejection:

- System runs gyro-only temporarily
- Heading remains stable
- When field normalizes, correction resumes smoothly

This is essential for real-world sailboat installation.

Why Not Use a Full AHRS (Mahony/Madgwick)?

Because on a sailboat:

- Yaw bandwidth is very low
- Roll and pitch do not need high dynamics
- We want deterministic behavior
- We want low CPU usage (AVR-class capable)

A super-minimal complementary fusion:

- Is predictable
- Uses minimal math
- Fits on 8 MHz AVR
- Runs effortlessly on STM32

It is not overkill — it is appropriate.

Loop Rate Strategy

Fusion loop: **50 Hz**

Sensors:

- Accel/Gyro ODR: 52 Hz
- Magnetometer: 10 Hz

Using a loop rate close to sensor ODR avoids:

- Aliasing
- Phase jitter
- Missed samples

50 Hz is ideal for:

- Marine steering dynamics
- Low computational load
- Stable filtering

Power & Efficiency

This configuration:

- Keeps ODR modest
- Uses hardware filtering
- Minimizes floating-point overhead
- Avoids unnecessary trigonometry

It runs comfortably on:

- STM32
- ATmega328 (with care)
- Lightweight marine microcontrollers

Perfect for long-term onboard operation.

Final Behavior at Sea

In practice, this structure produces:

- Smooth heading in swell
- Fast but natural helm response
- No twitching from vibration
- Stable heading during temporary magnetic disturbance
- Minimal drift when magnetometer is rejected

It feels like a real marine compass — not a lab instrument.

Why This Works

Because the design respects:

- The physics of sailboat motion
- The frequency content of marine dynamics
- The limits of MEMS sensors
- Embedded CPU constraints
- Real-world installation issues

It is not just a tilt-compensated compass.

It is a **marine-optimized heading system**.