

SensorGuard

Hardware-Based Sensor Integrity Monitor
for Mobile Robots

Design Document

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1 Introduction

1.1 Problem and solution

Wheel encoders measure wheel rotation, while an inertial measurement unit (IMU) measures body rotation. A mobile robot can receive plausible but inconsistent data when encoder transitions are lost, a reading freezes, or the gyroscope develops a bias. Comparing redundant motion estimates is an established diagnostic approach [1]. Two disagreeing measurements do not, however, reveal which one is wrong. The monitor must report that limitation rather than present an unsupported sensor diagnosis.

SensorGuard compares wheel-derived turning rate with gyroscope turning rate and raises an alarm when disagreement persists. A small differential-drive platform provides repeatable motion; the custom PCB conditions encoder signals, creates physical encoder freezes, regulates sensor power, and drives the motors. A NUCLEO-F446RE handles acquisition and the detector. The expected improvement over isolated range checks is detection of plausible inconsistent readings, with visible evidence and repeatable fault tests. The project does not claim a new detection theory or general safety certification.

1.2 Scope and engineering contribution

The baseline is a slow, tethered laboratory robot with two driven wheels and one caster. It uses fixed forward/turn commands, one yaw-rate comparison, and a serial display. Navigation, mapping, camera processing, wireless control, a Kalman filter, and automatic identification of the faulty sensor are outside scope. Hardware encoder freezing is included. IMU bias, stale payload, and numerical corruption are injected in a separate acquisition-layer test function, after a real I2C read; these are software fault tests, not electrical I2C corruption.

The final PCB is a two-layer board containing a TB6612FNG motor-driver IC, a 3.3 V regulator, Schmitt-trigger input conditioning, a four-bit latch, two multiplexers, test-enable logic, connectors, and test points. The processor and IMU remain replaceable modules. Circuit-level work is concentrated in accessible, independently testable hardware.

The 3 deg/s sensitivity is limited to the stated slow-motion envelope.

1.3 Visual aid and high-level requirements

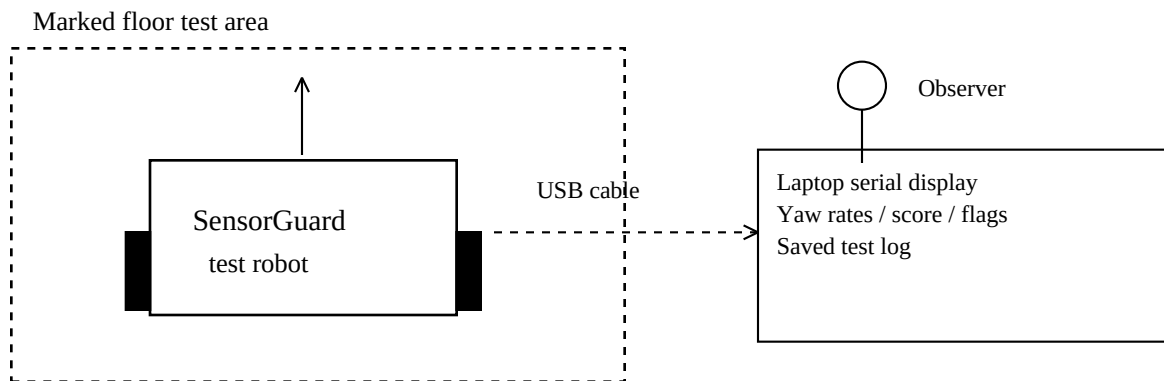


Figure 1: The operator runs a short, low-speed test and observes sensor disagreement. USB connects the robot to the laptop; a physical motor-power switch remains within reach.

1.4 High-level requirements

- **H1:** For a sustained, single-path yaw-rate error of at least 3.0 deg/s, SensorGuard shall assert a local disagreement flag within 1.0 s of the qualifying error onset in each specified acceptance trial, while flagging fewer than 5% of decisions in a separate 600 s healthy-motion test.
- **H2:** SensorGuard shall obtain fresh gyro samples and both encoder counts at a rate of at least 100 Hz, with event timestamp error no greater than 1 ms, and shall update the disagreement metric at least 50 times per second.
- **H3:** SensorGuard shall report the two yaw rates, a 0-100 consistency score, data-validity flags, and alarm state at least 20 times per second, with no more than 200 ms from detector update to host display; an ambiguous mismatch shall be labeled `SOURCE_UNKNOWN`.
- **H4:** During ten minutes of operation and the defined motor-transient tests, the MCU and custom sensor-supply 3.3 V rails shall remain within 3.20-3.40 V, motor-induced deviation shall be no greater than 50 mV, and a missing-data or watchdog fault shall disable drive within 100 ms.

Claimed envelope: dry level floor, ≤ 0.65 kg total mass, forward speed ≤ 0.08 m/s, $|\text{yaw rate}| \leq 15$ deg/s, $|\text{yaw acceleration}| \leq 8$ deg/s², and ambient 20-30 C. H1 faults persist for ≥ 1 s after the qualifying onset. Reversals, deliberate slip, impacts, and lifted wheels are challenge tests outside the detection guarantee. Their results are still reported.

2 Design

2.1 Physical design

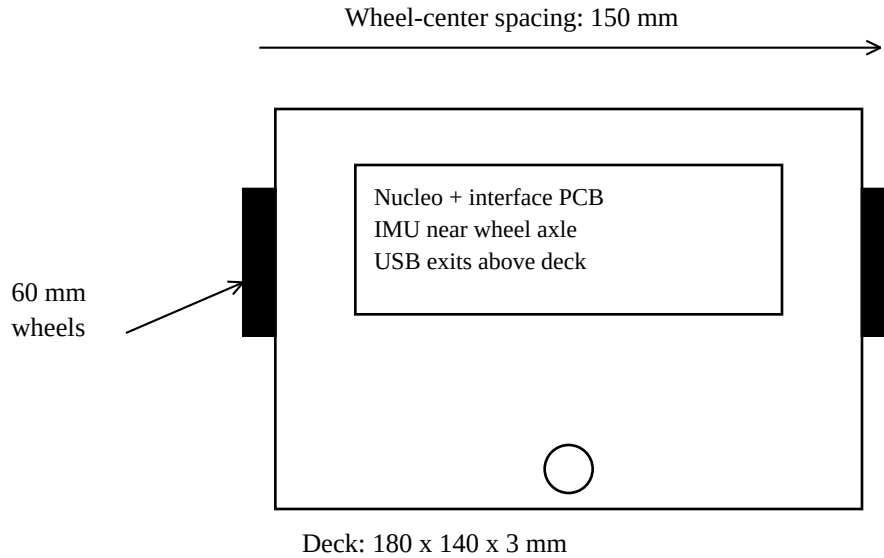


Figure 2: Top-view layout. A flat sheet, two purchased motor brackets, and a spacer-adjusted rear caster replace custom-machined mechanisms. Dimensions are nominal design values, not measured construction results.

Use two Pololu #5112 100:1 low-power 6 V gearmotors with built-in encoders, #1422 60 x 8 mm wheels, #989 brackets, and a #953 caster [3]. The motor encoders are on the motor shafts before the gearbox. Their nominal count scale is $12 \times 100.37 = 1204.44$ quadrature counts per wheel revolution, counting both edges of both channels. Gear backlash and wheel slip are therefore possible even when the electrical signals are correct.

The deck can be drilled acrylic or plywood, with 3 mm nominal thickness for acrylic. Mount the wheels at 150 mm center spacing and the caster approximately 80 mm behind the axle. Use spacers so all three contacts touch a flat surface without rocking. Place the battery low and central; secure the 100 x 80 mm PCB and Nucleo using insulating standoffs. Place the IMU within 20 mm of the axle midpoint with its z axis vertical. Keep wires clear of wheels and support the USB cable above the route.

Run only short forward segments and gentle arcs; equal wheel speeds need not be perfect. The detector compares actual measured motion rather than the commanded path. Calibrate left and right travel-per-count separately with a tape measure, and calibrate effective track width with repeated marked turns. Both wheels are stopped before any direction reversal; reversal transients are outside the baseline acceptance run.

2.2 Block diagram and interfaces

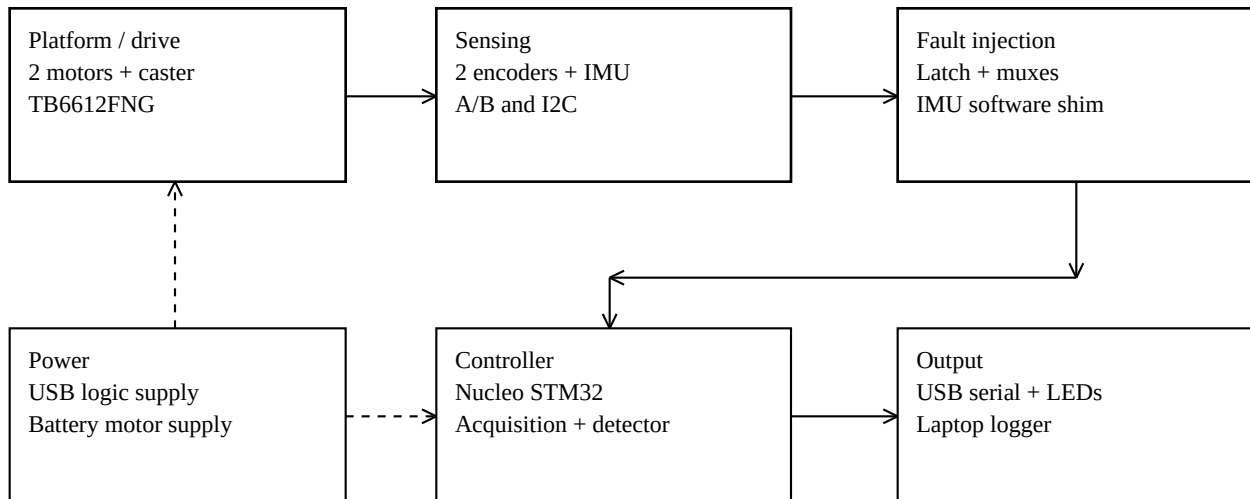


Figure 3: Functional blocks. Solid arrows represent data flow; dashed arrows represent power. The controller also commands the motor driver. The two power sources share ground but their positive rails are never connected.

Sensing supplies the two estimates needed for H1-H2. Injection creates repeatable upstream faults. The controller performs the comparison and safe-stop logic. Output provides the H3 evidence, and power/drive support H4. Each block has its own requirements and verification procedure below; the laptop and commercial modules support, but do not replace, the custom circuit design.

Connection	Defined interface
Encoders to PCB / MCU	Four 3.3 V quadrature lines, conditioned before latch/mux; support 2,000 transitions/s per wheel.
IMU to MCU	3.3 V I2C at 400 kbit/s, 7-bit address 0x6A, gyro DRDY at 208 Hz.
MCU to drive / injector	3.3 V controls; motor PWM 20 kHz; test-enable jumper physically gates both injection selects.
MCU to laptop	Onboard ST-LINK virtual COM port, USART2, 115200 baud, 8-N-1; CSV at 20 Hz.
Power	USB powers logic only; 6-AA NiMH through a buck supplies 5 V motors; custom sensor rail qualified at 100 mA.

2.3 Functional overview and requirements

2.3.1 Controller subsystem

The NUCLEO-F446RE retains the proposal's STM32 family and provides a working programmer, reset circuit, clock, and USB serial interface [4]. This avoids making fine-pitch microcontroller assembly the first project milestone. The final custom PCB connects through labeled harnesses to the Nucleo headers; it does not supply the Nucleo 3.3 V pin. Use STM32CubeIDE/HAL and a simple timed main loop without an operating system.

Two timer peripherals count the encoder A/B inputs continuously. A gyro data-ready interrupt stores a microsecond timestamp and snapshots both counts. The main loop reads the new gyro word, checks the bus result, and adds a time-tagged sample to a ring buffer. A 20 ms task computes the two 0.50 s averaged yaw rates. The detector receives only these readings, timestamps, and validity, not the injection type or expected alarm.

A 30 ms missing-DRDY or I2C-failure condition stops the motors. Configure the independent watchdog so its worst-case reset time is below 100 ms, including oscillator tolerance; verify by deliberately hanging the main loop with wheels raised. The PCB pulls motor standby low during reset and disconnection. A momentary START button arms only after a successful stationary calibration.

Table 1: Controller requirements and verification

Requirement	Verification
C1 (H2): At least 100 fresh snapshots/s; timestamp error ≤ 1 ms.	Logic analyzer: probe DRDY and TP_ISR. Log 10,000 events; compare interrupt service marker to DRDY, require ≤ 1 ms. In 600 s, count fresh samples and require no normal interval > 10 ms.
C2 (H1): 50 Hz detector updates; processing ≤ 2 ms per cycle.	Toggle TP_PROC around the detector and scope it while I2C and serial operate. Require one decision per 20 ms and all execution pulses ≤ 2 ms. Save timing trace.
C3 (H4): Acquisition failure and a hung main loop disable drive ≤ 100 ms.	With wheels raised, remove IMU DRDY, force an I2C error, and run a deliberate software hang separately. Scope fault onset and TP_STBY; require standby low within 100 ms and no restart without START.

2.3.2 Sensing subsystem

The wheel encoders provide distance increments; the LSM6DSOX breakout provides z-axis angular rate [3], [5]. Configure the IMU at 208 Hz, +/-250 deg/s, high-performance gyro mode, block-data update, and auto-increment. Disable gyro high-pass filtering, which would remove a sustained bias; leave optional LPF1 disabled and record all filter settings. Use the official ST register driver to avoid writing a new sensor library [6].

Use the real elapsed time, not a presumed exact 208 Hz rate. For a window of duration T , compute wheel travels s_L and s_R from counts and then $w_E = (s_R - s_L)/(L * T)$, converted to deg/s. Compute w_G as the time-weighted gyro mean over the same reported-event interval after subtracting stationary bias. Encoder counters are sampled when each DRDY arrives, making the endpoints easy to match. Internal gyro filter delay remains a separate bounded error, analyzed in Section 2.7.

Calibrate stationary gyro bias for 10 s with motors off. Measure each wheel's loaded travel over ten turns, then refine effective L using several clockwise and counterclockwise turns marked on paper. Use one set of runs for calibration and new runs for verification. Bias is fixed within a trial; continuously adapting it could hide the very fault being tested. A pair score measures agreement, not which sensor is correct.

Table 2: Sensing requirements and verification

Requirement	Verification
S1 (H1-H2): ≥ 500 counts/wheel revolution; correct direction; no missing counts at 2,000 transitions/s.	Rotate each marked wheel 20 turns and compare counts with the nominal 1204.44 scale. Feed a known quadrature sequence from lab equipment at 2,000 transitions/s for 10 s; require exact count and correct sign. Repeat both directions.
S2 (H1): Stationary 0.50 s gyro means stay within +/-0.20 deg/s after calibration.	Collect a separate 600 s stationary record with the chassis supported and temperature stable. Plot window means. Pass if every mean is within +/-0.20 deg/s; otherwise investigate vibration, drift, or configuration.
S3 (H1): Healthy window discrepancy stays ≤ 1.20 deg/s in the characterization envelope.	After calibration, record separate straight/arc trials at up to 0.08 m/s and 15 deg/s. Plot $ w_E - w_G $. Require ≤ 1.20 deg/s before claiming the analytical 3 deg/s margin; report all violations and do not retune on the final test.

2.3.3 Fault-injection subsystem

Fault injection is deliberately hybrid. Physical encoder interruption is implemented on the PCB. IMU numerical faults are introduced after successful I2C acquisition in a dedicated test function. A second microcontroller, bidirectional bus emulator, and asynchronous quadrature regeneration are unnecessary for the baseline. This change requires confirmation against the approved scope, and the report must not describe the IMU tests as electrical bus fault injection.

The four encoder channels pass through a 74HC14 Schmitt inverter. Inverting A and B together preserves the quadrature direction relationship. A CD74HC175 captures all four conditioned states; one SN74HC157 per wheel selects live A/B or their stored values. A pulse on CAPTURE followed by at least 10 us settling, then SELECT, freezes the chosen wheel at its last captured state. Releasing SELECT resumes the real waveform. Short freezes repeated periodically create missing-pulse bursts, not an exact pulse-deletion percentage [7]-[9] .

A 74HC08 AND gate combines each software SELECT request with a physical TEST_ENABLE jumper. Pull-downs make live signals the default. A nearby TEST LED marks enabled test mode. The detector does not read the jumper or test selection. The fixture may switch at an encoder edge; onset/release can create boundary count errors. Characterize these with a logic analyzer and require no more than two counts per switch, rather than claiming a glitch-free quadrature generator.

Table 3: Fault definitions

Fault class	Exact test implementation
Encoder freeze	Capture then hold one wheel's A/B for 1.0 s. The other wheel remains live. Use physical upstream test points to verify continued raw activity.
Dropped-pulse bursts	Repeat 100 ms HOLD / 100 ms LIVE for 2 s on one wheel. Measure actual missing counts; do not assume exactly 50% loss.
IMU bias	After a real gyro read, add +343 or -343 signed counts to z; sensitivity is 0.00875 deg/s/count, giving +/-3.00125 deg/s. Saturate arithmetic rather than wrapping.
Stale/frozen payload	Replay a previously saved stationary z reading while the robot is steadily turning, preserving fresh arrival events. Separately demonstrate that freezing an already constant correct rate may be unobservable.
Corrupted payload / missing data	XOR a selected raw gyro bit in the test shim. Separately unplug the IMU while drive is disabled, then test a timed disconnection on a restrained fixture; missing DRDY/bus errors are transport faults.

2.3.3 Fault injection: verification

Table 4: Fault-injection requirements and verification

Requirement	Verification
F1: Default and bypass modes deliver the original count stream.	With TEST_ENABLE absent, attempt software SELECT. On TP_ENC_RAW and TP_ENC_OUT, verify normal waveforms and exact count on 20,000 generated transitions. No software command may select HOLD when the jumper is absent.
F2: One wheel can be physically held for 1.000 s +/-10 ms.	Feed quadrature, capture, select HOLD, then release. Record raw and output A/B on a logic analyzer. Require no output transitions during hold, live behavior on the other wheel, and ≤ 2 count boundary error at each switch.
F3: Bursts remove measured encoder transitions.	Apply ten 100 ms HOLD / 100 ms LIVE cycles at a fixed known input rate. Count raw and delivered edges. Record hold timing and actual loss; require $>30\%$ loss for the chosen fixed-rate test and no loss on the other wheel.
F4: IMU bias numerical error ≤ 0.02 deg/s; stale/corrupt modes are repeatable.	With drive disabled, feed a saved raw sequence through the shim. Compare input/output words: ± 343 counts for bias; identical stored payload for freeze; XOR exactly the configured bit. Save the before/after file and independently calculate differences.
F5: Detector cannot use injection labels to decide an alarm.	Review function inputs and global reads: detector accepts readings, time, and validity only. Run the same saved healthy/faulty sequence through the detector without test commands; require identical flags. Report that software injection tests a numerical boundary, not physical IMU independence.

A practical boundary between hardware and software

The physical test proves the custom signal path can create and expose a real upstream encoder fault. The IMU shim proves the detector responds to defined numerical failures after acquisition. Missing-data tests exercise the real interface. These are different kinds of evidence and are kept separate in the results. None establishes that every possible physical IMU failure is covered.

Test commands are allowed only while TEST_ENABLE is present and the platform is restrained or in the marked floor area. Write injection-onset time to a separate test log or toggle TP_INJECT for the oscilloscope. Do not use that marker in the detector. The normal production configuration has test mode disabled and no ability to silently change the gyro input.

2.3.4 Drivetrain and power subsystem

Use the low-current motors specified in Section 2.1 and a TB6612FNG on the custom board. A purchased carrier of the same IC is used only for breadboard proof [10]. Drive PWM at 20 kHz; ramp commands for at least one second and restrict baseline motion to slow forward segments and arcs. The safe stop is standby low, which leaves the outputs high impedance; braking and reversing are not needed for the detector demonstration.

Power logic from the laptop through the Nucleo USB connector. Its +5 V output feeds only a TLV75733PDBVR sensor regulator on the custom PCB. The Nucleo retains its own 3.3 V regulator. The custom 3.3 V sensor net and the Nucleo 3.3 V output are **not tied together**. Use separate net names and common ground. The six-cell NiMH battery powers only a 5 V motor buck, with a fuse and manual power cut-off. This removes the shared-battery sag path from logic power, although ground noise still requires testing.

For the specified MB1136 Nucleo, use USB power selection per UM1724 and keep total USB current ≤ 250 mA, below its 300 mA board limit [4]. This is a tethered demonstration; a standalone battery supply for logic is not promised. With USB absent, driver logic loses power and the 10 kohm standby pull-down prevents drive. Turn motor power on last and off first.

Table 5: Drive and power requirements and verification

Requirement	Verification
P1 (H4): Sensor rail 3.20-3.40 V at 0-100 mA; logic USB current ≤ 250 mA.	DMM and adjustable load at TP_3V3_S: test 0, 50, and 100 mA at 4.75-5.25 V input. Measure total USB current with Nucleo connected. Run 100 mA load for ten minutes; require all voltage/current limits and accessible surface < 50 C.
P2 (H4): Motor rail 4.75-5.25 V at up to 2 A; logic perturbation ≤ 50 mV.	At buck input 6.2 V, use an electronic load for 2 A continuous testing; do not stall motors. Scope both 3.3 V rails during ten starts, safe reversals, and 0-to-1.6 A load pulses. Require rail limits, ≤ 50 mV deviations, and no resets.
M1 (H4): Physical cut-off prevents continued propulsion; no automatic restart.	Raise wheels; operate the switch and unplug USB in separate trials. Verify motor outputs cease driving and re-arming is required. On the floor, measure ten coast stops from 0.08 m/s; require travel ≤ 0.15 m.

2.3.5 Output subsystem

Use the Nucleo's existing ST-LINK virtual COM port, so no Bluetooth module, USB-UART adapter, or custom USB firmware is required. USART2 is reserved for this function. A basic serial terminal is sufficient for initial debugging; the final host program records lines and displays rates, score, alarm, and data age.

Send a newline-terminated CSV line every 50 ms, limited to 120 ASCII characters: sequence, MCU time in ms, wE, wG, signed residual, pair score, encoder-valid bit, IMU-valid bit, state, and source status. Use bounded formatting with three decimal places for angular rates. Set SOURCE_UNKNOWN on a plausible disagreement. A bus failure may identify IMU_DATA_INVALID, which describes the path, not proof of defective IMU silicon.

At 120 bytes x 10 bits/byte x 20 lines/s, UART load is 24,000 bit/s, or 20.8% of 115200 baud. Allocate 50 ms until the next line, 10.42 ms line transmission, 40 ms USB/OS delay, and 50 ms display refresh: 150.42 ms. This is a budget; measure the actual update-to-display latency. Reject malformed lines, check sequence numbers, and display LINK_LOST after 200 ms without a valid new line.

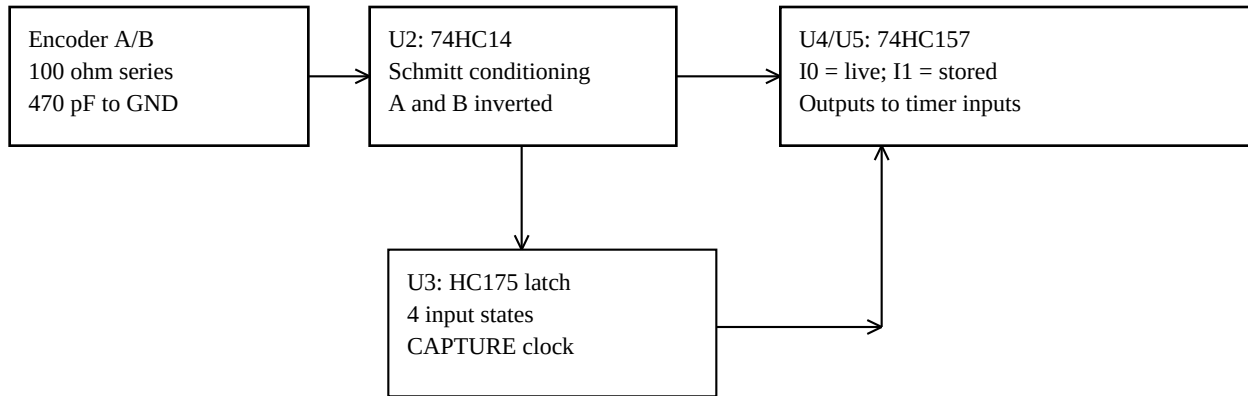
Table 6: Output requirements and verification

Requirement	Verification
O1 (H3): ≥ 20 lines/s, ≤ 120 bytes/line, update-to-display ≤ 200 ms.	Record 600 s of lines and count sequence increments. Require no dropped normal lines and at least 12,000 records. Film TP_ALARM LED and host display in the same video for ten alarms; at ≥ 60 fps, require each display change within 200 ms of LED change, accounting for one-frame uncertainty.
O2 (H3): Stale and malformed output is not presented as healthy.	Disconnect USB; replay a truncated line, nonnumeric field, and repeated sequence number to the host parser. Require errors counted and LINK_LOST by 200 ms after the last new valid line; old values visibly marked stale.
O3 (H3): Ambiguous disagreement has no unique sensor attribution.	Run software bias and physical encoder-freeze trials. Require SOURCE_UNKNOWN in all plausible-data alarms. Disconnect IMU on the restrained fixture and verify data-path invalidity is distinguished from disagreement.

The PCB provides three LEDs with 1 kohm resistors: power, alarm, and test-enabled. Labels accompany the colors. Telemetry and LED indications are diagnostics, not a certified safety channel. The physical motor-power switch remains the immediate operator override.

2.4 Hardware design

2.4.1 Encoder conditioning and hold circuit



SELECT = software request AND physical TEST_ENABLE (U6: 74HC08).

Figure 4: Implement one mux per wheel so a single path can be held. U3 stores all four bits; only the selected wheel uses the held values. All logic runs from 3V3_S.

Device	Connections that define the schematic
U2 SN74HC14N, DIP14	VCC=14, GND=7. Raw LA/LB/RA/RB to inputs 1/3/5/9; outputs 2/4/6/8 are LA_C/LB_C/RA_C/RB_C. Unused inputs 11/13 to GND; outputs 10/12 not connected.
U3 CD74HC175E, DIP16	VCC=16, GND=8, active-low reset pin 1 held high by 10 kohm. D pins 4/5/12/13 receive LA_C/LB_C/RA_C/RB_C; Q pins 2/7/10/15 hold those values. CLK pin 9 = CAPTURE; complementary Q outputs unused.
U4/U5 SN74HC157N, DIP16	VCC=16, GND=8, enable pin 15=GND. Per wheel: A live/stored to pins 2/3, output 4; B live/stored to pins 5/6, output 7. SELECT pin 1 from U6. Unused inputs 10/11/13/14 to GND; unused outputs 9/12 NC.
U6 SN74HC08N, DIP14	VCC=14, GND=7. Gate 1: pins 1=REQ_L, 2=TEST_EN, 3=SEL_L. Gate 2: pins 4=REQ_R, 5=TEST_EN, 6=SEL_R. Unused inputs 9/10/12/13 to GND; unused outputs 8/11 NC.

Place 100 nF at every IC. Pull REQ_L, REQ_R, CAPTURE, TEST_EN, SEL_L, and SEL_R down with 10 kohm; the TEST jumper ties TEST_EN to 3V3_S. Provide 3-pin bypass headers selecting conditioned-live or mux-output A/B for all four channels, changed only with power off. Device pin names and the exact ordered package must be checked against the manufacturer drawing before layout [7]-[9] .

2.4.2 Motor and power circuit

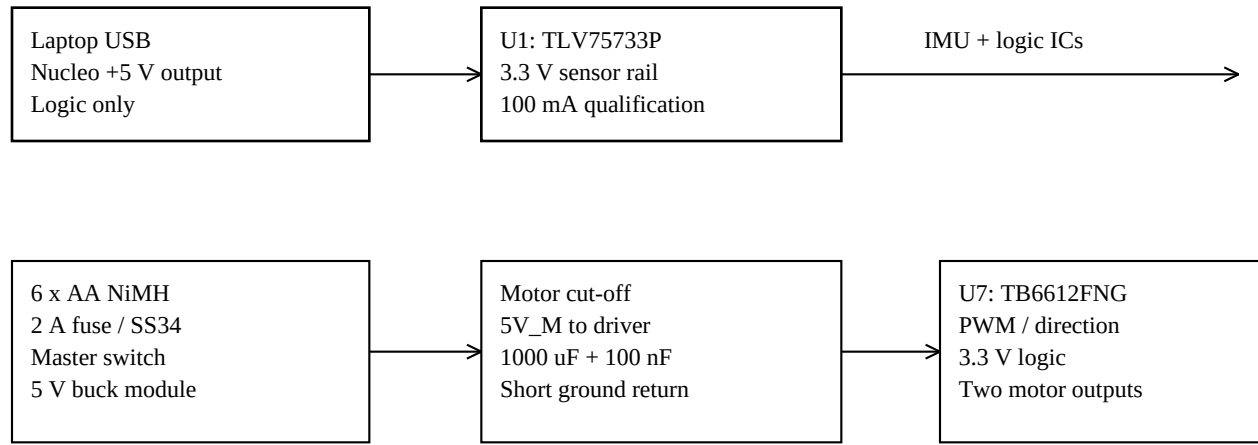


Figure 5: Separate positive supplies. Grounds meet at the driver power-return junction. The motor buck output must never connect to Nucleo +5 V, USB VBUS, or the sensor-regulator input.

U1 is TLV75733PDBVR in SOT-23-5: pin 1 IN=USB5V; pin 2 GND; pin 3 EN to IN through 10 kohm; pin 4 NC; pin 5 OUT=3V3_S. Fit 4.7 uF + 100 nF at IN and 10 uF + 100 nF at OUT, with at least 1 uF effective capacitance after derating [11]. This small regulator is easier to assemble than a bare STM32 and does not carry motor current.

TB6612FNG pins [10]	Net / connection
1, 2 / 5, 6	Left motor terminals AO1 / AO2; tie each duplicate pin pair together.
11, 12 / 7, 8	Right motor terminals BO1 / BO2; tie each duplicate pair together.
3, 4, 9, 10, 18	Ground; use short wide power returns and ground copper.
13, 14, 24 / 20	5V_M / 3V3_S; 100 nF at each supply group plus local bulk at VM.
21, 22, 23	AIN1, AIN2, PWMA from MCU; 10 kohm pull-downs.
17, 16, 15, 19	BIN1, BIN2, PWMB, STBY from MCU; 10 kohm pull-downs. STBY low is default.

A 470 uF/16 V capacitor supports buck input; 1000 uF/10 V plus 100 nF supports motor VM after the cut-off. Add 100 nF directly across each motor, twisted motor wires, keyed power plugs, and a 2 A fuse near the pack. Use the same purchased motor-driver carrier for initial bench proof; the final PCB implements the IC and support circuit itself.

2.4.3 PCB layout and connector map

The PCB target is 100 x 80 mm, two copper layers, 1.6 mm FR-4, 1 oz copper. Use DIP sockets for the logic ICs, 0805 or through-hole passives, screw terminals for power, and 2.54 mm signal headers. The TB6612FNG SSOP24 and regulator SOT-23 are the two small IC packages requiring assembly help; budget supervised assembly or assembly service for those parts. A two-layer board is sufficient for these low-rate interfaces when placement and current returns are deliberate.

Signal	Nucleo pin / connector	PCB destination
Left A/B	PA0/PA1; CN7-28/30	J_SIG1-1/2 -> TIM2 inputs
Right A/B	PA6/PA7; CN10-13/15	J_SIG1-3/4 -> TIM3 inputs
I2C SCL/SDA	PB8/PB9; CN10-3/5	J_SIG1-5/6 -> IMU header
IMU DRDY / GND	PC6; CN10-4 / CN10-20	J_SIG1-7/8
PWMA/PWMB	PB6/PB7; CN10-17 / CN7-21	J_SIG2-1/2 -> U7
AIN1/AIN2	PC0/PC1; CN7-38/36	J_SIG2-3/4 -> U7
BIN1/BIN2 / STBY	PC2/PC3/PC4; CN7-35/37, CN10-34	J_SIG2-5/6/7 -> U7
REQ_L/REQ_R/CAPTURE	PC8/PC9/PC10; CN10-2/1, CN7-1	J_SIG3-1/2/3 -> U6/U3
ALARM / START	PC5/PC7; CN10-6/19	J_SIG3-4/5 -> LED / pushbutton
USB5V / GND	CN6-5 / CN6-6	J_PWR-1/2 -> U1 / common ground

J_SIG2-8 and J_SIG3-6 are ground. J_DBG: 1=PC11 (CN7-2, TP_ISR), 2=PC12 (CN7-3, TP_PROC), 3=PB0 (CN7-34, TP_INJECT), 4=GND. Use USART2 PA2/PA3 only for the onboard virtual COM port, not an encoder or DRDY. Confirm the purchased board is MB1136 and verify the connector table for that revision [4]. MCU port names are authoritative; wire by net and pin number, not cable color alone.

Place the motor driver and its terminals at one board edge; place U1 and logic in a quieter area. Route motor supply/output copper at ≥ 1.5 mm where possible and short; use ≥ 0.25 mm for low-current signals, ≥ 0.25 mm clearance, and manufacturer-approved vias. Keep a largely continuous ground plane with no motor return under the IMU harness. Add labeled test points for USB5V, 3V3_S, 5V_M, GND, raw/output A/B, CAPTURE, STBY, ISR, and ALARM. Final widths must pass the board vendor's rules and measured heating tests.

2.5 Software design and timing

The firmware consists of five small modules: motor commands, acquisition, test injection, detector, and serial output. The normal path is acquire -> validate -> optional numerical test shim -> window averages -> detector -> report. The test module is compiled/enabled only for evaluation; no test-mode variable is passed to the detector. Use library/HAL calls for hardware access and fixed-size buffers, without dynamic allocation.

Task	Rate / budget / behavior
Gyro DRDY interrupt	208 Hz nominal; timestamp and encoder snapshots only. Target service ≤ 100 us; acceptance ≤ 1 ms. No printing or I2C transaction inside the interrupt.
Main-loop I2C read	Read coherent gyro data after each event, complete within 2 ms and before the next event. A six-byte burst needs about 81 clock periods, or 203 us at 400 kbit/s, before software overhead.
Window / detector	At 50 Hz, use approximately 104 gyro intervals (0.50 s) and actual timestamps. Sum time-weighted samples; use count differences from the same endpoints.
Alarm logic	$E = wE - wG $; flag if $E > 1.5$ deg/s for 8 consecutive 20 ms decisions (0.16 s). Clear live alarm after $E < 1.0$ deg/s for 1 s; retain a latched event until acknowledgment.
Display score	$P[k] = 0.9960 * P[k-1] + 0.0040 * q[k]$, $q = 100 * \max(0, 1 - E/3)$. This five-second score is explanatory; alarm timing does not depend on score decay.
Output and stop	CSV at 20 Hz; nonblocking UART transmission. Stop on alarm, missing data, expired 5 s motion command, or watchdog reset. Default driver standby is low.

Gyro output time differs from physical sampling time. Rather than demanding sub-2 ms calibrated filter alignment, this design budgets ≤ 30 ms total effective lag and limits yaw acceleration to 8 deg/s^2 . Verify that lag with repeated smooth turns and the two raw-rate traces; measure any shift needed to align their changes. Do not silently compensate a large unknown delay. If lag exceeds 30 ms, reduce filtering or formally reduce allowed acceleration, then repeat the analysis.

Cold start: initialize low motor outputs; verify IMU identity/configuration; collect 10 s stationary bias; require START. A missing gyro sample is invalid, not a repeated fresh sample. A zero encoder count at rest is valid. Full 5 s histories are retained for plotting; a buffer of roughly 1,040 samples is modest for the STM32. UART loss marks the host stale, and USB loss removes logic power.

2.6 Component choices and scope revisions

Table 7: Selected implementation and justification

Decision	Reason and effect on the project
NUCLEO-F446RE remains in final build	Keeps debugger, clock, reset, and USB working. Custom PCB carries the signal/driver/power circuits. Confirm this hardware partition with the TA; module use alone is not enough.
Motor-shaft integrated encoders	Avoid external shaft coupling and optical alignment. Provides >1,200 counts/rev. Backlash and traction still require slow-motion tests.
LSM6DSOX breakout	Avoids soldering a tiny IMU package and provides a documented data-ready signal and official driver. If unavailable, source the same sensor or redo timing/noise qualification for a substitution.
Latch + mux encoder fixture	Uses common logic gates that can be probed and breadboarded. Tests freezes and burst losses; does not claim exact arbitrary pulse deletion.
Software IMU numerical faults	Removes a second processor and I2C-target emulation. Bias, stale payload, and bit corruption are introduced before the detector. Physical I2C corruption is outside scope.
USB logic / battery motor power	Eliminates common positive-supply motor sag; remaining ground coupling is measured. Tethered operation is part of the design.
One PCB, two layers	Keeps original circuit design while limiting fabrication and assembly risk. Use prototype modules first, then implement verified circuits on the PCB.

Changes to the original proposal

Retained: STM32 processing, two encoder paths and one IMU, ≥ 100 Hz acquisition, ≤ 1 ms event timestamp error, 3 deg/s fault goal, 1 s local detection, ≤ 200 ms reporting, and a custom hardware fault path. Removed: the unsupported 90% general sensor-source identification claim. Replaced: unspecified I2C hardware corruption with explicitly labeled software numerical injection; a 500 mA common logic-supply requirement with a 100 mA custom sensor rail plus independently USB-powered MCU. Power robustness remains a system requirement.

These changes define the implemented scope. Confirm TA acceptance before the design review and PCB ordering. If a bare MCU or physical IMU emulator is mandatory, revise the design before proceeding; those features would require additional development and are not small last-minute additions.

2.7 Tolerance analysis

2.7.1 Detection threshold and timing margin

The critical challenge is separating a 3 deg/s fault from normal disagreement. Let $r=0.030$ m, $L=0.150$ m, $N=1204.44$ counts/rev, and $T=0.50$ s. One differential encoder count changes heading by $360r/(NL)=0.05978$ degrees. Allowing one endpoint-count error per wheel yields rate uncertainty $2(0.05978)/0.50=0.239$ deg/s. At a 20 ms window the same bound would be 5.98 deg/s, which is why the detector uses a longer average.

Table 8: Conservative additive error budget

Healthy-error contribution	Allocation (deg/s)	How established
Encoder count quantization	0.239	Calculated from counts, geometry, and 0.50 s window.
Residual wheel/track/gyro scale	0.300	Calibration target, checked on new straight/arc runs.
Stationary bias / drift	0.200	Ten-second zeroing; separate warm-run test.
Effective timing lag	0.240	$8 \text{ deg/s}^2 \times 0.030 \text{ s}$.
Filtered noise	0.050	Empirical allowance above the typical white-noise estimate.
Normal traction residual	0.200	Smooth surface and low-speed measured allowance.
Total B	1.229	Conditional engineering budget, not a measured result.

A separating threshold must satisfy $B < \text{threshold} < 3B$. Here $1.229 < 1.50 < 1.771$ deg/s, giving a 0.271 deg/s margin. The additional sensing gate $E \leq 1.20$ deg/s during characterization is slightly tighter than the budget. LSM6DSOX typical gyro noise is 0.0038 deg/s/sqrt(Hz); a 0.50 s average has approximate equivalent noise bandwidth 1 Hz, giving 0.0038 deg/s RMS under a white-noise assumption [5]. Slip and bias are not white noise and are budgeted separately.

Worst-case local delay budget is 0.50 s for a full fault-containing window +0.16 s persistence +0.03 s sensor lag +0.02 s scheduling = **0.71 s**. Even allowing the full 0.20 s reporting requirement gives 0.91 s to host display. These bounds assume a sustained qualifying error, valid data, and the operating envelope. If healthy error reaches 1.5 deg/s, merely raising the threshold cannot preserve 3 deg/s sensitivity; repair mechanics, filtering, or calibration before proceeding.

2.7.2 Worst-case power analysis

The motor manufacturer lists 0.36 A stall at 6 V [3]. Approximate winding resistance is $6/0.36=16.7$ ohm. At the allowed 5.25 V rail maximum and an assumed 20% lower resistance, each stall current is $5.25/(0.8 \times 16.7)=0.393$ A; both motors draw about **0.786 A**. An immediate reversal can momentarily approach twice that total, 1.572 A. The supply is qualified at 2 A; actual commanded reversals include a 300 ms stopped interval and are tested separately.

At 2 A motor load, 5 V output, 80% assumed buck efficiency, and 6.2 V input, input current is $10/(0.8 \times 6.2)=2.02$ A. Therefore sustained 2 A qualification uses a fused bench supply directly into the buck; it is not a continuous battery operating claim. The actual modeled simultaneous stall requires about 0.80 A input and remains below a 2 A pack fuse. The fuse protects wiring, not motor thermal damage.

Measure pack plus holder resistance and require ≤ 0.20 ohm. At a 1.5 A input transient, sag is ≤ 0.30 V. Require pre-run loaded pack voltage ≥ 7.0 V and allow 0.50 V reverse-diode drop: buck input remains ≥ 6.20 V. Check voltage before every run and stop on low voltage. Catalog maximum current is input- and temperature-dependent, so verify regulation at 6.2 V directly [12].

Table 9: Logic current and thermal budget

Logic load / budget	Current
Nucleo including ST-LINK, design allocation	150 mA from USB
Custom rail: two encoders, IMU, logic ICs, LEDs	50 mA estimated; 100 mA qualification
Total USB with qualification load	250 mA, below 300 mA Nucleo limit
Custom-regulator dissipation at 100 mA	$(5.25-3.3) \times 0.1 = 0.195$ W
Thermal rise at ~ 100.8 C/W DBV package [11]	19.7 C; approximately 50 C junction at 30 C ambient

At 1000 uF bulk capacitance derated by 20%, $ESR \leq 50$ milliohm, and a 1.6 A step lasting 50 us, approximate motor sag is $I \cdot dt/C + I \cdot ESR = 0.10 + 0.08 = \mathbf{0.18}$ V. This estimates the earliest transient only; regulator response must be scoped. With separate USB positive supply, no motor current flows through the logic regulator, but shared ground inductance remains. Keep motor loops short and measure Nucleo 3.3 V and 3V3_S at the MCU/sensor connector. The IMU carrier has its own downstream regulator; check its 3Vo separately within the sensor operating range [5].

A conservative 1.5% regulator accuracy allocation is 49.5 mV; combined with ≤ 50 mV total dynamic deviation, it fits the ± 100 mV target narrowly. Characterize DC and transient extrema rather than assuming typical regulator plots prove the system limit. USB and ground noise are included in the measurement.

2.8 Integrated verification and demo

Pass all subsystem tests before integrated acceptance. Freeze the detector threshold, firmware version, calibration constants, and filter settings before the final dataset. Keep raw measurements and the separate injection record. Failed and interrupted trials remain in the record with reasons; they are not silently deleted.

Table 10: Integrated acceptance matrix

Test	Procedure and pass condition
Healthy driving, 600 s	Use repeatable slow straight/arc segments with no injected faults. Include normal starts and stops within the envelope. Record 30,000 detector decisions; fewer than 1,500 may be disagreement-flagged. Report alarm-event count too. Invalid/out-of-envelope time must be shown and cannot count as healthy passed time.
Minimum gyro bias	At rest and during a steady arc, inject +343 and -343 counts for 2 s, five trials per condition/sign (20 trials). Each local alarm must occur ≤ 1.0 s after injection; require SOURCE_UNKNOWN.
Physical encoder freeze	At 0.08 m/s straight motion, freeze left then right for 1 s, five trials each. Expected initial yaw error is about $(0.08/0.15) \times 180/\pi = 30.6$ deg/s, well above 3. Require all alarms ≤ 1 s; confirm raw encoder activity continues.
Missing-pulse bursts	Five trials per wheel at 0.08 m/s straight motion, 100 ms HOLD /100 ms LIVE for 2 s. Capture raw/output signals to show loss. Require alarms ≤ 1 s after a sustained ≥ 3 deg/s equivalent error is established.
Stale IMU / corrupt values	Replay stationary gyro payload during a steady 10-15 deg/s turn; five trials. Test selected numerical bit flips separately. Only cases producing a sustained ≥ 3 deg/s equivalent error qualify for H1; small harmless changes are not expected to alarm.
Stops / transients / stale link	Execute C3, P2, M1, and O2. Present scope traces, maximum voltage deviation, maximum stop time, and host stale indication.

Demonstration sequence: show healthy rates agreeing, physically hold one encoder and show the alarm, reset/re-arm, inject a small gyro bias and show the alarm, then show the physical cut-off. Explain why the detector reports SOURCE_UNKNOWN. Include a short log plot showing fault onset, both rates, the 1.5 deg/s threshold, and alarm time.

3 Cost and schedule

3.1 Parts budget

USD estimates for one prototype, assuming reusable bench equipment is available. P = catalog-based allowance; E = planning estimate requiring a current cart. Prices and availability must be reconfirmed before purchase; the bill covers prototype hardware and one PCB iteration. Reconcile grouped allowances with the final BOM.

Description	Manufacturer / part	Qty	Total \$
Controller	ST NUCLEO-F446RE	1	25.00 E
Motors + encoders	Pololu 5112	2	59.90 P
60 mm wheel pair	Pololu 1422	1	8.00 E
Bracket pair	Pololu 989	1	5.00 E
Caster	Pololu 953	1	3.00 E
IMU breakout	Adafruit 4438 (LSM6DSOX)	1	11.95 P
Motor buck	Pololu 2858 (D24V22F5)	1	18.95 P
Prototype driver	Pololu 713 carrier	1	7.00 E
Final motor IC	Toshiba TB6612FNG SSOP24	1	3.00 E
Sensor regulator	TI TLV75733PDBVR	1	1.00 E
Input conditioner	TI SN74HC14N DIP14	1	1.00 E
Four-bit latch	TI CD74HC175E DIP16	1	1.00 E
Wheel multiplexers	TI SN74HC157N DIP16	2	2.00 E
Test-enable gates	TI SN74HC08N DIP14	1	1.00 E
Rechargeable cells	Panasonic BK-3MCCA NiMH AA	6	21.00 E
Holder and charger	Pololu 1155; Panasonic BQ-CC55	1	37.00 E
PCB lot, bare boards	Team SG-IO-R2, 2 layers	1	25.00 E
Passives / sockets / harness	SG-PASS and SG-HARN sets	1	25.00 E
Fuse / switches / diode	2 A fuse, DC switches, SS34	1	12.00 E
Deck / spacers / fasteners	SG-MECH flat-deck assembly	1	15.00 E
USB cable	Data-capable cable for Nucleo revision	1	5.00 E

Parts subtotal: \$287.80. SG sets are custom assemblies to be itemized in the final BOM.

3.2 Labor, services, and total cost

Use \$50/hour as an engineering labor estimate. Apply the required 2.5 overhead multiplier. Plan 120 hours per partner for learning, circuit design, assembly, testing, and documentation. These labor hours are planning estimates.

Table 11: Labor cost

Partner	Calculation	Cost
Chinmay Naveen	\$50/h x 2.5 x 120 h	\$15,000.00
Sanjiv Kondin	\$50/h x 2.5 x 120 h	\$15,000.00
Total labor	240 team hours	\$30,000.00

Plan \$30 for assistance assembling the small motor-driver and regulator packages and \$25 for shipping. No machine-shop work is included in the current design. If the shop is used to cut or drill the deck, obtain an actual quote and add it before release. Reserve one extra board/rework allowance rather than assuming the first board will work.

Table 12: Total project cost

Category	Cost (USD)
Parts	287.80
Shipping allowance	25.00
Tax allowance: 10% of parts	28.78
Fine-pitch assembly assistance allowance	30.00
PCB rework / replacement reserve	50.00
Nonlabor funding allowance	421.58
Engineering labor	30,000.00
Grand total	30,421.58

Required borrowed resources: oscilloscope, logic analyzer or quadrature signal source, DMM, current-limited supply, electronic load, soldering tools, and calipers/tape measure. A laptop and serial plotting software are also needed. Incremental equipment purchase is budgeted at \$0 only if course access is available. Confirm reservations and obtain an alternative quote if borrowing fails.

The nonlabor estimate replaces the proposal's incomplete ~\$106 budget. A strict \$100 cap would require borrowed parts or an agreed scope revision.

3.3 Schedule and responsibilities

The schedule is organized into eight project weeks. Each partner budgets about 15 hours/week, totaling 120 hours.

Chinmay leads circuits and assembly; Sanjiv leads firmware and logging. Both understand the detector and participate

in scope review, testing, and the oral design review.

Wk	Chinmay Naveen	Sanjiv Kondin	Exit evidence
1	Confirm hardware partition; buy/borrow parts; assemble simple deck.	Blink/serial tutorial; read real IMU; save first stationary log.	TA scope discussion; exact parts cart; working serial and gyro.
2	Breadboard conditioner/latch/mux; use driver carrier for motors.	Count encoder pulses; slow open-loop motion; implement timestamps.	A/B traces; one-wheel motion; physical freeze demonstrated.
3	Complete PCB schematic, footprints, pin map, and power budget.	Implement 0.50 s averages, thresholds, injection shim, and CSV.	Breadboard baseline; schematic review; no new circuit first tried on PCB.
4	Route 2-layer PCB; ERC/DRC; submit through course ordering process.	Calibrate wheel scale and gyro; collect healthy/error traces.	Reviewed Gerbers/drills; initial tolerance margin demonstrated.
5	Assemble received PCB in stages; inspect and power-test.	Port tested harness to PCB; verify pins; test stop/watchdog.	Regulator, logic, and motor sections independently pass.
6	Motor transient and thermal tests; repair hardware issues.	Run independent healthy dataset; freeze settings and firmware.	R&V; records; healthy discrepancy ≤ 1.20 deg/s.
7	Execute fault matrix and physical stop demonstrations.	Analyze latency/false alarms; prepare plots and host display.	Completed evidence table; failed trials preserved; rework reserve used if needed.
8	Final assembly inspection and spare-parts preparation.	Finalize document and demo script; rehearse questions.	Both can explain every block; final PDFs and logs ready.

Do not add wireless, SLAM, exact pulse regeneration, a bare MCU, or a new IMU late in the schedule. These changes affect multiple interfaces and should be treated as new work.

4 Societal impact, ethics, and standards

SensorGuard can help small robotics teams discover inconsistent motion readings and explain failures using inexpensive, inspectable hardware. That supports safer experimentation and lowers the time spent diagnosing sensor problems. False alarms can interrupt useful work, and missed faults can create misplaced confidence. The design therefore reports measured limits and ambiguous cases rather than assigning a probability of safety.

Economic and global factors favor common components, replaceable modules, published interfaces, and a reusable test fixture. Social and cultural accessibility is supported by clear labels, SI units, and text indications instead of color alone. The prototype stores robot telemetry, not personal information. Video used for timing should show only the device/display and avoid unrelated people. Environmental impact is reduced by rechargeable cells, reusable hardware, and recycling failed boards and cells through approved channels; no quantified life-cycle benefit is claimed.

Table 13: Applicable technical and professional guidance

Standard / guideline	Application
NXP UM10204 I2C specification [13]	Follow Fast-mode electrical timing and open-drain pull-ups. Target bus capacitance ≤ 100 pF and effective pull-up about 2.2 kohm, giving $t_r \sim 186$ ns; verify actual rise time ≤ 300 ns.
IEEE Code of Ethics [14]	Prioritize public welfare, credit sources, and state estimates honestly. Correct the proposal's unsupported fault-attribution claim.
ACM Code 1.2, 1.3, and 2.5 [15]	Avoid harm, be truthful about limitations, and evaluate risk. Preserve negative tests and separate numerical injection from physical failure evidence.
Project ethical and safety commitments Complete required training, use the buddy system, discuss project-specific hazards, and explain relevant professional and personal ethical commitments.	
ISO 12100 risk-assessment principles [16]	Identify hazards, reduce exposure through low speed and guarding, and record residual risks. No certified machinery or functional-safety conformity is claimed.

When the two sensors disagree, the output remains SOURCE_UNKNOWN unless an independent condition identifies a data-path failure. A high consistency score also cannot detect common-mode error. The design prioritizes a smaller set of verified functions over unsupported claims. Test-shim independence, timing assumptions, USB/motor backfeeding, and the hardware contribution will be checked during integration and design review.

4.1 Safety procedures and residual risks

Table 14: Project safety controls

Hazard	Required mitigation
Unexpected motion / pinch	First power-up with wheels raised; guard wheel wiring; test on a marked floor area with two people and no bystanders. Speed ≤ 0.08 m/s; measured coast distance ≤ 0.15 m. Stop immediately for loose parts or an uncontrolled command.
Electrical short / heat	Fuse the battery near its positive terminal; use keyed plugs and insulated terminals. Use current-limited bench supply during bring-up. Never power motors through a solderless breadboard. Stop for accessible surface >50 C, odor, or unstable voltage.
Rechargeable cells	Use matched NiMH cells and the manufacturer-compatible commercial charger outside the robot. No lithium substitution, charging circuit, mixed cell chemistries, or unattended charging. Charge six cells in two batches with the four-slot BQ-CC55. Remove damaged/hot/leaking cells from service under lab procedures.
Dual power sources	USB5V and 5V_M remain separate. Ground is common. Connect logic first; verify standby low; enable motor power last. Turn motors off before USB. Disconnect both sources before rewiring.
Fault injection	Physical TEST jumper enables injection; mark test state visibly. Use restrained setup first. Inject data or signal holds, never overvoltage or power shorts. Return to bypass and verify normal operation after each session.
Assembly and tools	Use required lab training, fume extraction, eye protection, ESD precautions, and a second person. Obtain assistance for the SSOP/SOT-23 packages and approved supervision for cutting/drilling.

Before a run: inspect wiring, battery, fuse, motor brackets, and caster; check pack voltage under load; confirm the stop switch and USB-loss behavior; verify fresh telemetry, calibration, and clear area. Record operators and firmware version. No automatic restart is permitted after reset or alarm.

During an incident: open the motor cut-off. If electrical symptoms persist, turn off both sources when safe, keep away from hot cells, and alert laboratory staff. Smoke/fire response follows campus emergency procedures; do not resume until the cause is reviewed. Never grab spinning wheels to stop them.

After a run: stop drive, save data, turn off motor power, disconnect USB and battery, let components cool, and inspect for damage. Battery charging and storage follow the charger/cell instructions. The physical switch, low speed, and supervised area reduce risk independently of the monitor; the prototype is not intended for unsupervised operation near people.

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Appendix A: Requirement traceability

Assignment / TA issue	Where this revision addresses it
Problem, improvement, and references	Section 1.1 and references [1]-[2].
Use-context visual; 3-4 high-level requirements	Figure 1 and four complete-sentence bullets in Section 1.4.
Block and physical diagrams with explanations	Figures 2-3, geometry, purchased mechanics, and interface definitions.
Detailed subsystem design and R&V;	Sections 2.3.1-2.3.5; Tables 1-6; circuit connections in Section 2.4.
Challenging tolerance analysis	Section 2.7: quantization, geometry, bias, timing, threshold separation, current, thermal, and transient limits.
Parts, labor, services, grand total, schedule	Section 3. No fabricated quote; zero planned machine-shop work; named ownership and exit evidence.
Impact, standards, ethics, safety, citations	Section 4 and references; concrete pre-run and incident procedures.
TA: unclear robot geometry	Specified wheel radius, track, motors, gear ratio, encoder placement, and caster.
TA: two sensors cannot isolate a fault	General attribution removed; unknown-source disagreement preserved.
TA: vague injection / digital I2C	Hardware encoder hold is defined at pin level; IMU numerical injection is explicitly software; real transport errors are separate tests.
TA: current budget and timing omissions	Worst-case motor current and split power; identical reported windows; bounded effective gyro delay and slow acceleration.

Before fabrication, confirm with the TA: (1) keeping Nucleo and IMU modules while implementing the custom driver/conditioning/injection/regulator board; (2) hybrid injection and revised rail capacity; (3) the selected tolerance block and slow-motion envelope. These confirmations matter because course staff assess hardware scope, and original proposal commitments have changed. They do not prevent drafting and breadboard preparation.

This document covers the requested design-document content. It is not an as-built schematic, a manufactured PCB, or evidence that the system already meets the numerical requirements. After the breadboard passes, replace circuit figures with exported KiCad schematics and any measured plots available before submission. Keep citations and design assumptions visible; submit the final PDF using the actual course calendar.

Appendix B: Connector and carrier wiring

These details complete the interface definitions for schematic capture. All connector pin numbers refer to the PCB side; mark pin 1 on both ends of every cable. Inspect the exact purchased carrier before connecting power.

Connector / item	Defined connections
J_ENCL and J_ENCR, 6 pins	1=GND; 2=raw B; 3=raw A; 4=3V3_S encoder supply; 5=motor terminal 2; 6=motor terminal 1. Matches the #5112 cable ordering; verify the drawing/view before making a harness.
J_IMU, 7 pins	1=3V3_S to carrier VIN; 2=GND; 3=PB8/SCL; 4=PB9/SDA; 5=I1/INT1 to PC6 DRDY; 6=CS high to 3V3_S; 7=DO/SA0 to GND for 0x6A. Configure INT1 as gyro data-ready. Leave other carrier pins unused.
IMU carrier power	The Adafruit carrier accepts 3 V logic power at VIN and has a downstream regulator. Its 3Vo is an output, not a supply input. H4 applies to Nucleo 3.3 V and custom 3V3_S; separately measure 3Vo within LSM6DSOX operating limits (1.71-3.6 V).
I2C pull-ups	Carrier has 10 kohm pull-ups. Provide optional 2.7 kohm pull-ups to 3V3_S on the PCB: 10k parallel 2.7k is about 2.13 kohm. Inspect actual hardware first; fit only the values needed to meet ≤ 300 ns rise time without excessive sink current.
START and LEDs	PC7 has 10 kohm to 3V3_S and a momentary switch to GND; debounce 20 ms. Alarm LED: PC5 -> 1 kohm -> LED -> GND. Power and TEST LEDs similarly use 1 kohm from 3V3_S and TEST_EN respectively.
Power terminals	J_BAT: +pack/GND via fuse, switch, SS34 to buck. J_VM: +5 V buck via cut-off/GND to 5V_M. J_PWR: Nucleo +5 V/GND to USB5V. Positive motor and USB paths remain separate; all grounds common.
Test points and bypass	Four bypass headers: pin 1=conditioned live, pin 2=MCU encoder input, pin 3=mux output. Select 1-2 for bypass or 2-3 for injection. Change jumpers with both supplies off. J_DBG and other MCU connections are defined in Section 2.4.3.

Carrier pinout and supported power connection: Adafruit LSM6DSOX carrier pinouts. Additional logic reference: TI SN74HC08 datasheet. Verify connector polarity with continuity tests before power-up.