

RoadSense

ECE 445 Design Document - Fall 2026

Project #36

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Introduction

1.1 Problem

Many students rely on the roads and bike lanes around campus to get around using their scooters, skateboards, and bikes. However, poor road conditions such as potholes, cracks, and rough pavement can make these forms of transportation uncomfortable and potentially dangerous. These problems are especially important for bikes, scooters, and skateboards because their smaller wheels are more affected by the road conditions than car tires. Current methods for measuring road conditions are also limited. Manual inspection can be slow, subjective, and inaccurate. Additionally, they tend to focus on main roads rather than side roads or roads with bike lanes. Because of these limitations, people traveling around campus may not have reliable information about which streets are hazardous. This can be especially difficult for people who are unfamiliar with the area or traveling when road defects are harder to see.

1.2 Solution

RoadSense is designed to address this problem using a small embedded sensor system that can be mounted to a car or bike. While the vehicle is moving, the system continuously collects motion data from an IMU and analog accelerometer, while a GPS receiver provides the current location and vehicle speed. An STM32 microcontroller processes the sensor data onboard in real time to detect road events such as potholes, speed bumps, and rough pavement. When an event is detected, the microcontroller classifies the event, assigns it a severity level, associates it with its GPS coordinates and vehicle speed, and stores the processed result in onboard memory. This allows the system to build and maintain its own database of road condition information without relying on an external computer for normal operation. As the user travels, the

microcontroller can compare the current GPS location against previously stored hazardous locations. If the user approaches a road or location that has been identified as dangerous, the system will provide an audible warning through a speaker and inform the user of the road conditions ahead. This allows RoadSense not only to collect road condition data, but also to use that data to directly warn the user during future trips. Unlike manual road inspections or expensive survey vehicles, RoadSense provides a portable, cost-effective, self-contained solution for detecting, recording, and warning users about poor road conditions.

1.2 Visual Aid

Figure 1 — RoadSense in Use

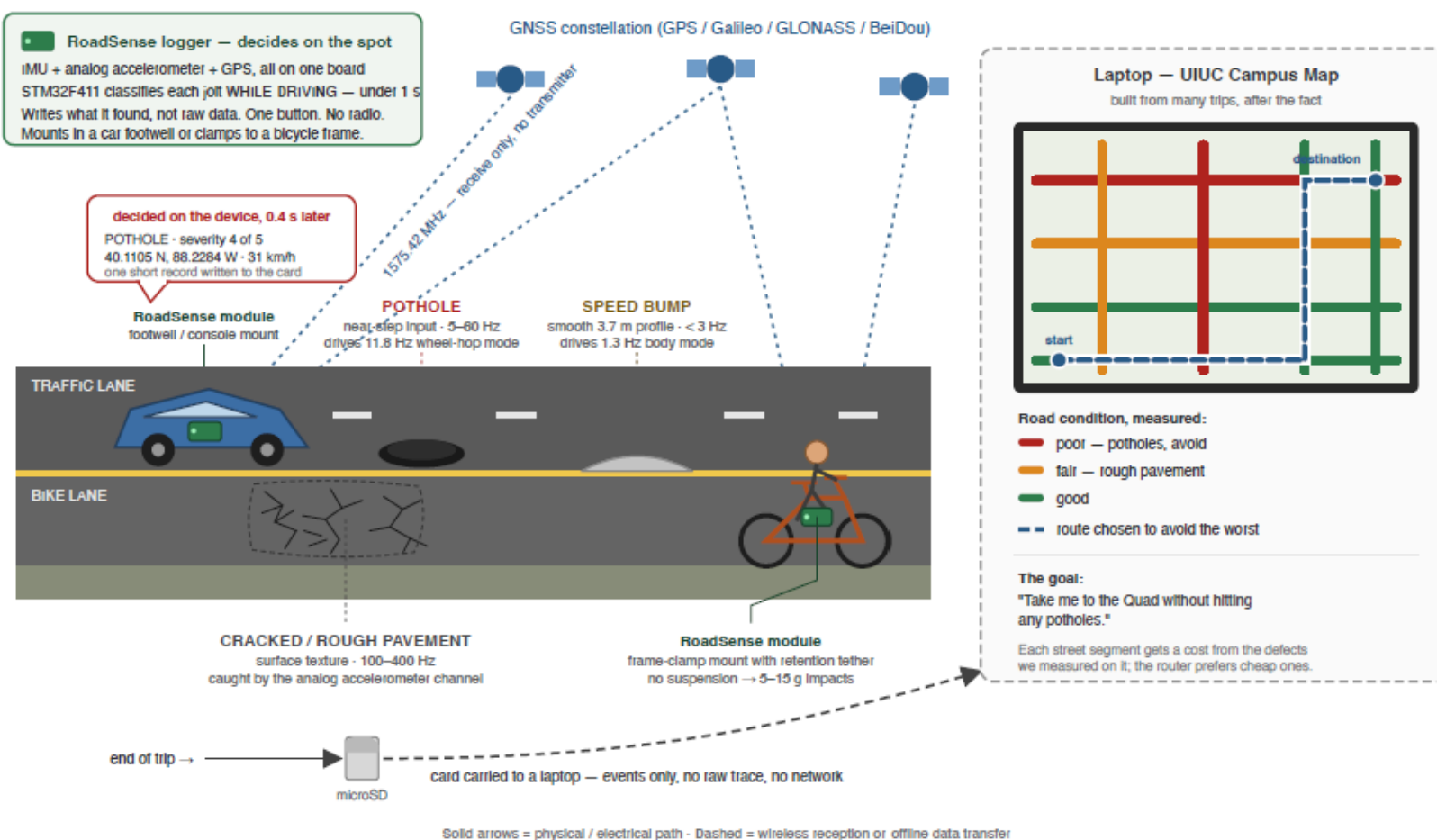


Figure 1. How RoadSense is used. The device mounts on a car or bicycle and decides what each jolt was while you drive. After the trip the card builds a campus condition map that supports pothole-avoiding routing.

From the figure, we can see RoadSense is mounted on a car or a bike and continuously measures the motion of the vehicle while it travels. The onboard sensors collect acceleration, rotation, and GPS information, which is processed by the embedded system to detect and classify road events, such as potholes, speed bumps, and rough pavement in real time. When an event is detected, its classification, severity, location, speed, and timestamp are stored rather than continuously saving all raw sensor data. As data is collected over multiple trips, RoadSense can build a record of poor road conditions throughout campus. This information can then be used to warn users about known road hazards before they encounter them and help them choose routes that avoid poorly maintained roads.

1.3 High-Level Requirements

1. The device should collect motion data at a rate of at least 100 samples per second and analog acceleration data at a rate of at least 1000 samples per second and analog acceleration data at a rate of at least 1000 samples per second. The embedded system shall process the sensor data and classify each detected road event within 1 second of the event occurring. The system shall operate continuously for at least 30 minutes without losing or corrupting recorded event data
2. When tested on a surveyed campus route containing at least 60 potholes and 30 speed bumps at multiple vehicle speeds, the embedded system shall detect at least 90 percent of the potholes and correctly classify at least 80 percent of detected events as potholes or speed bumps. The system shall also produce no more than one false road event per kilometer of smooth road. The primary detection and classification should be performed directly by the embedded system without requiring extra processing from a Raspberry Pi or laptop.

3. Each detected road event shall be recorded within 10 meters of its actual location. Data collected from multiple trips should be combined to create a map of measured road conditions around UIUC campus. This map shall maintain the locations and severity of previously detected road hazards and use this information to warn users of known poor road conditions before they encounter them.

Design

2.1 Physical Design

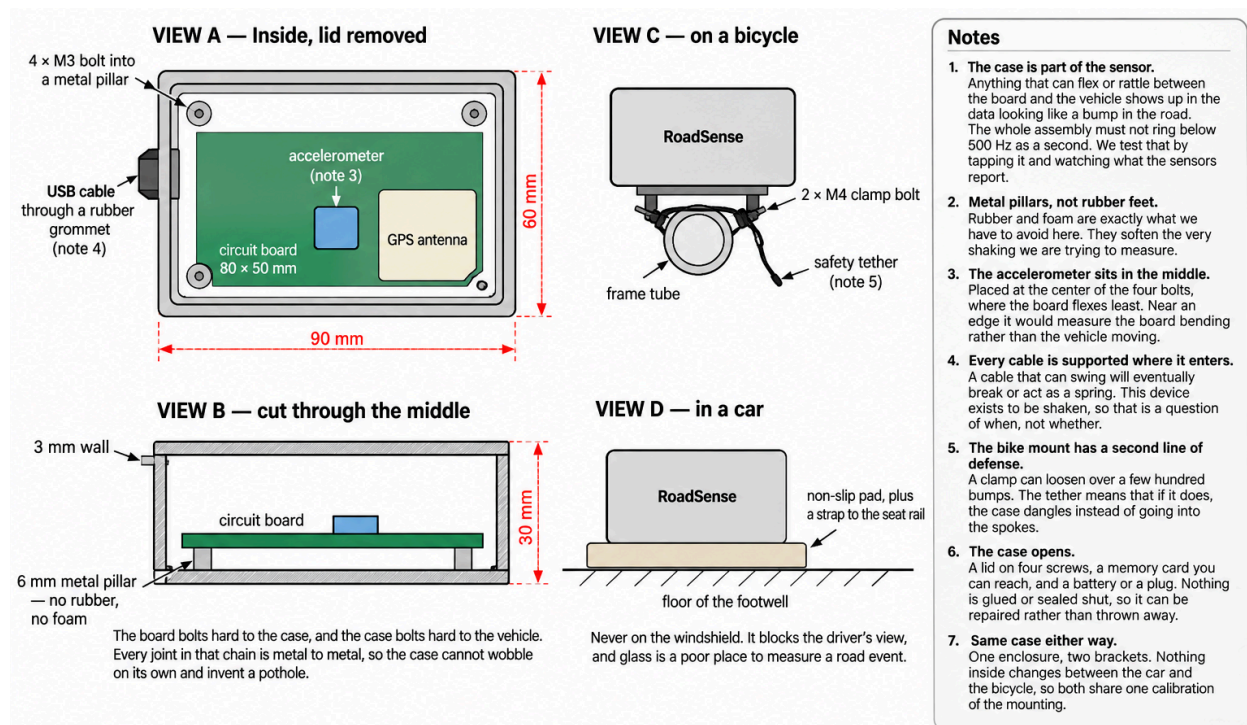
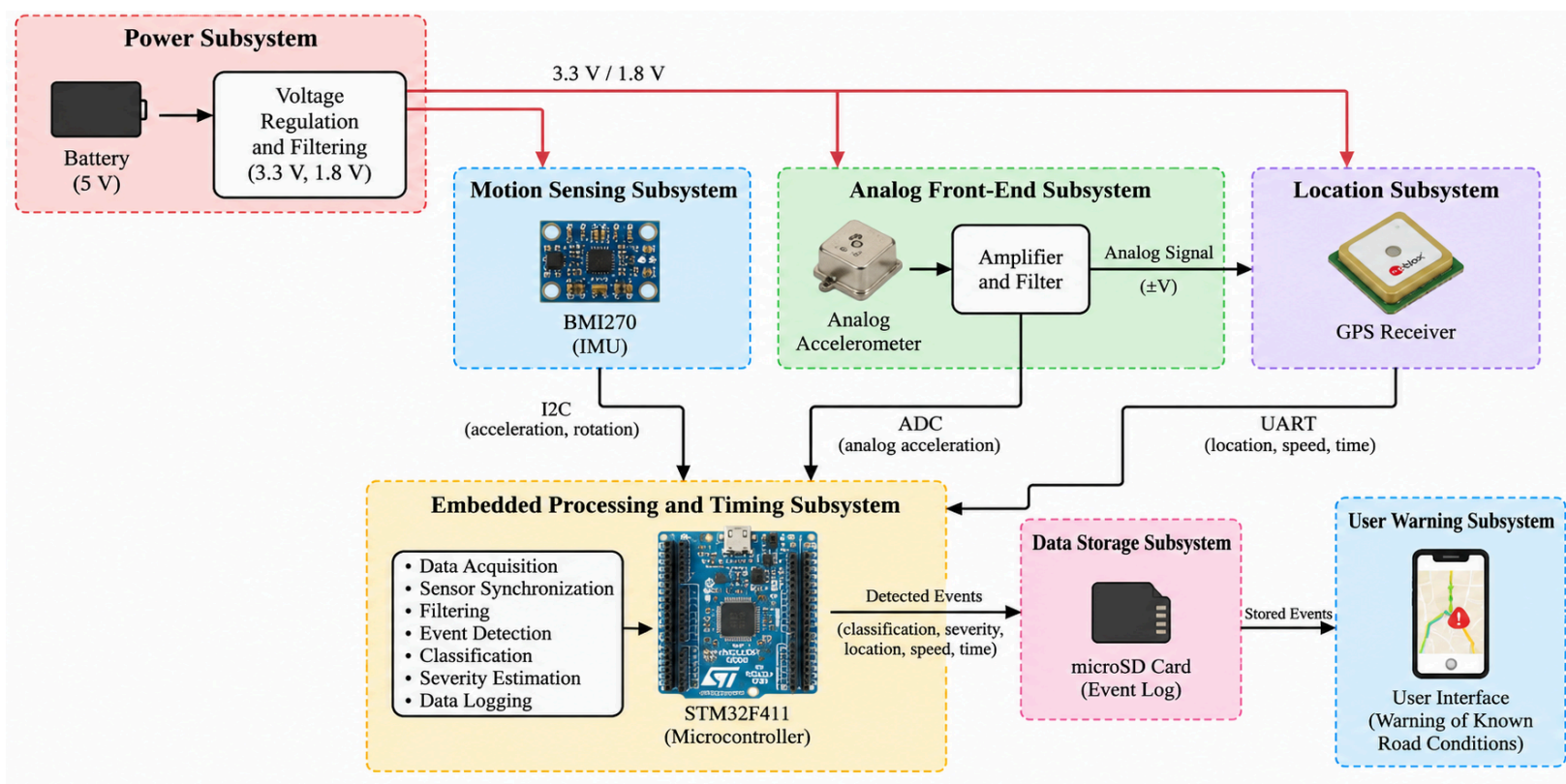


Figure 2. Enclosure and Mounting. Every joint between the board and the vehicle is metal to metal, so the case cannot wobble on its own and register a road event that did not happen.

The figure above shows the physical design of the RoadSense enclosure and how the system is mounted to either a bike or a car. The circuit board is rigidly mounted inside the enclosure so that the movement measured by the sensor comes from the vehicle and road rather than from the enclosure shifting or vibrating independently. The accelerometer is placed near the center of the board to reduce the effect of board flex, while the GPS antenna is positioned inside the enclosure with a clear mounting location. For bikes, the enclosure is attached to the frame using a clamp and a safety tether, while for car use, it is secured in the footwell using a non-slip pad and strap. The enclosure is also designed so that cables are supported at their entry points, and the internal components remain accessible for maintenance.

2.3 Block Diagram



2.3 Functional Overview and Block Diagram Requirements

2.3.1 Power Subsystem

The power subsystem is responsible for providing stable and regulated power to all electronic components in RoadSense. A 5V power source is passed through input protection and filtering before being regulated to 3.3V for the STM32F411 microcontroller, BMI270 motion sensor, GPS receiver, data storage, and other digital components. The analog sensing circuitry uses an additional filtered 3.3V supply and a stable reference voltage to prevent electrical noise from interfering with the vibration measurements. The subsystem contributes directly to the first part of the high-level requirement because unstable power could interrupt real-time processing, reset the microcontroller, or corrupt recorded road event data during operation.

Requirement

Verification

The Power Subsystem shall maintain the main supply at 3.3V $\pm$.1V during normal RoadSense operation.	Power the complete system and measure the voltage at the STM32F411 power pin using an oscilloscope or multimeter. Verify that the voltage remains between 3.2V and 3.4V throughout a 15-minute operating period.
The digital 3.3V supply shall have less than 50mV peak-to-peak noise, while the filtered analog supply shall have less than 10mV peak-to-peak noise.	Measure each rail using an oscilloscope while RoadSense is actively reading sensors, processing events, and writing data to storage. Verify that the measured peak-to-peak noise remains below the specified limits.
The 3.3V rail shall remain within $\pm$ 100 mV of its nominal voltage during changes in electrical load.	Monitor the 3.3V rail using an oscilloscope while the system transitions between normal sensing and higher load operations such as writing to storage and activating the warning system. Verify that the voltage does not vary by more than $\pm$ 100 mV
The power subsystem shall continuously power RoadSense for at least 30 minutes	Operate the complete RoadSense system continuously for at least 30 minutes while

without causing a system reset or loss of recorded event data.	collecting and storing data. Verify that no unexpected resets occur and that the stored data can still be read after the test.
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2.3.2 Motion Sensing Subsystem

2.3.3 Analog Front End Subsystem

2.3.4 Location Subsystem

2.3.5 Embedded Processing and Timing Subsystem

The embedded processing and timing subsystem is the center of the design and is where the system decides what happened on the road. It is built around an STM32F411 microcontroller, which reads the motion sensing subsystem over I2C, samples the analog front end through its internal analog-to-digital converter, and receives position and speed from the location subsystem over UART. It stamps every reading against the timing pulse from the location subsystem so that all three sources share a single timeline, filters the incoming data, detects candidate road events, classifies each one as a pothole, a speed bump, or rough pavement, estimates a severity, and passes the finished record to the data storage subsystem. All of this happens while the vehicle is moving rather than afterwards on a separate computer. The subsystem also compares the current position against previously recorded hazards and signals the user warning subsystem when the vehicle approaches one. It receives regulated power from the power subsystem. This subsystem

is responsible for both the first and second high-level requirements in full, since it performs the sampling, the timing, the classification, and the logging that those requirements describe

Requirement	Verification
The subsystem shall sample all three sensor sources at their full rates at the same time and record 30 minutes of continuous operation without losing or corrupting any event record.	Operate the complete system for 30 minutes while driving. Read the recovered log and confirm that every block carries a valid checksum and that the sequence numbers are continuous with no gaps
The subsystem shall produce a classification for each detected road event within 1 second of the event occurring.	Apply a repeatable mechanical impulse to the mounted enclosure while recording both the moment of impact and the resulting log entry. Confirm the time between the impact and the completed classification record is less than 1 second across at least 20 trials
The processor load shall remain below 25 percent while the system is running the complete processing chain, leaving margin for storage delays.	Toggle a spare output pin high while the processing chain is executing and low while idle. Measure the duty cycle on an oscilloscope during normal driving and confirm it remains below 25 percent.
The subsystem shall hold at least two buffers of 16 kB each, allowing it to continue collecting data for at least 800 ms while the storage subsystem is unavailable, and shall count and report any buffer overrun rather than discarding data silently.	Force the storage subsystem to stall by holding its interface busy for 800 ms during a recording. Confirm no data is lost. Then extend the stall until an overrun occurs and confirm the overrun counter increments and the status indicator reports it.
The subsystem shall keep its internal clock locked to the timing pulse from the location subsystem, drifting less than 100 microseconds between pulses	Capture successive timing pulse edges with the microcontroller's timer over a full trip. Compare the measured interval against the expected onesecond interval and confirm the difference stays below 100 microseconds
The subsystem shall close the active log and commit all buffered data within 500 ms of the stop control being activated.	Press the stop control and cut power 500 ms later. Read the memory card and confirm that all events recorded up to the moment of the stop are present and readable.

2.3.6 Data Storage Subsystem

The data storage subsystem holds the record of everything the system has detected. It consists of a microSD card and its socket mounted on the main circuit board, written by the embedded processing and timing subsystem over a dedicated interface. Rather than storing raw sensor data, which would be large and of little use on its own, the subsystem stores one short record per detected road event containing the classification, the severity, the location, the vehicle speed, and the time. This keeps the stored data small enough that a complete history of many trips fits on a single card, and it is what allows the system to build and maintain its own record of road conditions without an external computer. The subsystem is also read back during operation: the embedded processing subsystem queries it to find out whether the vehicle is approaching a previously recorded hazard, and passes that information to the user warning subsystem. It receives regulated power from the power subsystem. This subsystem contributes to the first highlevel requirement by preserving recorded data without loss, and to the third by holding the accumulated record of road conditions from which the campus map is built

Requirement	Verification
The subsystem shall store a complete record for every detected road event, containing its classification, severity, location, vehicle speed, and timestamp	Drive the surveyed test route and read the card afterwards. Confirm that every event the system reported has a stored record and that all five fields are present and populated in each one.
The subsystem shall retain at least 30 minutes of recorded events without corruption, and every stored record shall be verifiable after the fact.	Record a continuous 30-minute trip. Read the card on a computer and confirm that every record passes its checksum and that the record count matches the number of events reported during the drive.
Records written before a power interruption shall remain intact and readable after power is	Interrupt power to the system at random points during recording on at least ten

restored.	separate occasions. After each interruption, read the card and confirm that all records written before the interruption are present and valid.
The subsystem shall return the stored hazards near a given location to the microcontroller within 200 ms, so that a warning can be issued before the vehicle reaches the hazard.	Populate the card with a known set of recorded hazards. Issue a location query from the microcontroller and measure the time until the result is returned, using a toggled output pin and an oscilloscope
The subsystem shall accept a write without blocking the embedded processing subsystem for longer than its available buffer time.	Monitor the write interface with an oscilloscope during normal recording and confirm that no single write operation holds the interface busy for longer than 800 ms

2.3.7 User Warning Subsystem

The user warning subsystem is what turns the recorded data into something useful during a trip rather than only afterwards. When the embedded processing and timing subsystem determines that the vehicle is approaching a location where a hazard was previously recorded, this subsystem produces an audible warning so that the rider or driver knows what is ahead. It consists of a speaker or buzzer and its driver circuit, controlled directly by the microcontroller, and it receives regulated power from the power subsystem. The warning is deliberately audible rather than visual, because a rider on a bicycle or a driver in traffic cannot safely look at a display, and because an audible signal requires no interaction at all while the vehicle is moving. This subsystem is what allows RoadSense to warn users about known poor road conditions before they encounter them, which is the final part of the third high-level requirement.

Requirement	Verification
The subsystem shall produce an audible warning when the vehicle comes within 30 meters of a previously recorded hazard whose severity exceeds a set threshold	Record a hazard at a known location on the test route. Drive the route again and use the logged position data to confirm that the warning is triggered between 25 and 35 meters before reaching the recorded location
The warning shall reach at least 80 dB measured at one meter, so that it remains audible over road and traffic noise	Measure the output with a sound level meter at one meter in a quiet room, then repeat the measurement inside a vehicle traveling at 30 km/h with the windows closed, confirming the warning is clearly distinguishable from background noise.
The warning shall be issued at least 2 seconds before the vehicle reaches the hazard at a speed of 30 km/h	Drive past a recorded hazard at a controlled 30 km/h. Compare the timestamp of the warning against the timestamp at which the vehicle position matched the hazard position and confirm the interval is at least 2 seconds
The subsystem shall produce no more than one warning per kilometer on sections of road where no hazard has been recorded.	Drive at least 5 km of road that contains no recorded hazards. Count the warnings issued and confirm the rate stays below one per kilometer.
The subsystem shall require no interaction from the user while the vehicle is in motion.	Operate the system through a complete trip without touching the device after the trip has started, and confirm that all warnings are delivered without any input.

2.4 Hardware Design

2.4.1 Power Regulation and Protection

RoadSense is powered from a 5V source and requires a stable 3.3V supply for the microcontroller, sensors, GPS receiver, storage, and supporting circuitry. Before reaching the voltage regulator, the 5V input passes through protection circuitry designed to reduce the risk of damage caused by incorrect connections. The input protection consists of a PTC fuse, reverse

polarity protection, and an input voltage clamp. The protected 5V input is then regulated to 3.3V using an AP 2112K-3.3 linear voltage regulator. The regulated output is designed to remain at $3.3V \pm .1V$ during normal operation.

Because the analog accelerometer and its circuitry are sensitive to electrical noise, the analog circuitry uses an additionally filtered version of the 4.4V supply. A ferrite and capacitor filter reduces noise entering the analog portion of the circuit. The analog front end also requires a 1.65V reference, which is equal to about $\frac{1}{2}$ of the 3.3V analog supply. It allows the bipolar acceleration signal to be represented within the positive voltage range that can be measured by the STM32. The design requires this reference to remain within 1% tolerance and stable as the accelerometer signal changes.

2.4.2 Motion Sensing Hardware

The motion sensing hardware uses the bosch BMI 270, which is an inertial measurement unit used to measure three-axis acceleration and three-axis angular velocity. The sensor is powered by the regulated 3.3V supply and communicates with the STM32F411 through an SPI interface. We are using SPI because it provides sufficient communication speed for the required sensor sampling rate and allows the microcontroller to receive motion measurements with consistent timing. A data-ready signal from the BMI 270 is also connected to the STM32 so that new measurements can be read as soon as they become available.

The BMI270 is mounted to the roadsense PCB, which is rigidly connected to a car or bike so that its measurements represent motion of the vehicle rather than the movement of the sensor itself. The sensor orientation is fixed relative to the PFC so that the sTM32 can use the

gyroscope measurements to determine the orientation of the device and calculate the true vertical acceleration even when the enclosure is mounted at an angle.

2.4.3 Vibration Sensor and Analog Front-End Hardware

The analog sensing hardware for RoadSense uses a LDT0-028K piezoelectric vibration sensor to measure high-frequency vibrations produced by potholes, cracks, and rough pavement. Unlike the BMI 270, which provides digital acceleration and rotation measurements, the piezoelectric sensor produces an analog voltage in response to mechanical vibration. Because this signal cannot be connected directly to the STM32 without conditioning, an analog front-end circuit is used to buffer, bias, filter, and scale the signal before it reaches the microcontroller.

The front end is built around the MCP6002 op-amp powered from the regulated 3.3V analog supply. Since the STM32 can only measure positive voltages between ground and its supply voltage, the vibration signal is biased around a 1.65V reference. This allows positive and negative changes above and below 1.65V while remaining within the STM32 input range. The amplifier stage also isolates the piezoelectric sensor from the STM32 and provides signal conditioning before sampling.

A low-pass filter is included in the front end to reduce high-frequency noise and prevent frequencies above the useful measurement range from aliasing into the sampled data. The STM32 then samples the conditioned analog signals using its ADC and uses the resulting vibration measurements together with the data from the BMI270 to help distinguish sharp road impacts from normal vehicle motion.

2.4.4 Event Classification and Severity

(you guys can choose which ones you want to keep)

2.5 Software Design

2.5.1 Sensor Acquisition & Timing

All three sensors are read by the STM32F411 at the same time but on different schedules, and the first job of the software is to put every reading on one timeline. The BMI270 raises a data-ready signal each time a new sample set is available, which triggers an interrupt that reads the sensor over its serial bus. The analog front end is read by the microcontroller's analog-to-digital converter, which is started by a hardware timer rather than by software, so that the spacing between analog samples is set by the timer and does not drift with processor load. The GPS receiver sends position, speed, and time over a serial port, which is read into memory by direct memory access so the processor is not interrupted on every character.

The timing reference is the one-pulse-per-second output from the GPS receiver, which is captured by a timer input. Each captured edge gives the microcontroller an exact moment of GPS time, and the free-running counter between pulses is used to interpolate

timestamps for every sensor reading in between. This is what allows readings taken on three different schedules to be compared with one another, and it is what the first high-level requirement depends on.

2.5.2 Signal Filtering & Orientation Compensation

The analog channel is sampled faster than it needs to be and then reduced in software, because sampling quickly and averaging down rejects more noise than sampling slowly. A finite impulse response filter reduces the analog stream to 1000 samples per second, which is the rate the rest of the chain works at.

The acceleration measured by the device is not the acceleration of the road, because the enclosure is not guaranteed to sit level and because gravity appears in every reading. The software therefore estimates the orientation of the device from the accelerometer and gyroscope together, using a complementary filter: the accelerometer gives a long-term reference for which way is down but is disturbed by every bump, while the gyroscope tracks short-term changes accurately but drifts over time. Combining them gives an orientation estimate that is stable in both the short and long term. Gravity is then removed and the remaining acceleration is rotated into the vehicle frame, so that the vertical channel contains vertical motion and nothing else. Without this step, braking on a slope would appear in the vertical channel and be reported as a road event

2.5.3 Road Event Detection

Detection runs continuously on the corrected vertical acceleration. A candidate event is declared when the signal departs from its recent baseline by more than a set

threshold, where the baseline is a slow-moving average of the last several seconds so that the system adapts to a rough road without reporting every metre of it as an event. Once a candidate is declared, the software captures a window of data on either side of it, because the information needed to classify the event includes what happened immediately before and after, not only at the peak.

A minimum separation is enforced between events so that a single defect producing several oscillations is recorded once rather than three times. Events are also rejected at this stage if the motion is dominated by the forward or sideways axes rather than the vertical one, since that pattern indicates braking or cornering rather than a road defect.

2.5.4 Event Classification & Severity

Each captured event is classified using the frequency content of the vertical acceleration. The energy in a slow band from 0.8 to 3 Hz is divided by the energy in a fast band from 8 to 40 Hz to give a ratio R . A speed bump is a long, smooth obstacle that drives the slow suspension motion of the vehicle and produces a large R , while a pothole is a short, sharp impact that drives the fast wheel motion and produces a small R . Section 2.7 shows by simulation that these two values are separated by a factor of roughly four thousand, which is what makes the decision reliable.

Two further checks support the classification. The direction of the first motion separates the two cases independently, because a pothole deflects the wheel downwards before it rises while a speed bump does the opposite. The duration of the event multiplied

by the vehicle speed from the GPS receiver gives the physical length of the defect, which distinguishes a short expansion joint from a long speed bump regardless of how fast the vehicle was travelling.

Severity is calculated from the peak vertical acceleration, scaled by vehicle speed so that the same defect receives a comparable score whether it was crossed quickly or slowly. The result is reduced to a small integer scale so that it can be stored compactly and compared across trips

2.5.5 Data Logging

Detected events are written to the memory card as fixed-length records containing the classification, the severity, the latitude and longitude, the vehicle speed, and the timestamp. Writing happens through two buffers used alternately, so that the system continues collecting data into one buffer while the other is being written. This matters because a memory card can occasionally pause for over a hundred milliseconds while it reorganises itself internally, and without buffering those pauses would cost data.

Every block written carries a sequence number and a checksum. This is what allows the claim of thirty minutes without data loss to be checked after the fact rather than assumed: a missing sequence number shows a gap and a failed checksum shows corruption. If a buffer ever does overflow, the event is counted, written into the log, and shown on the status indicator, so that a failure is reported rather than hidden.

2.5.6 Hazard Lookup & User Warning

The same memory card is read back while driving. As the vehicle moves, the software compares the current position against previously recorded hazards and issues a warning when it comes within a set distance of one whose severity exceeds a threshold. The search is kept fast by storing hazards grouped by geographic area, so that only the entries near the current position are examined rather than the entire history.

The warning is delivered as an audible tone, because a rider on a bicycle or a driver in traffic cannot safely look at a display. A minimum interval is enforced between warnings so that a stretch of road with several recorded defects produces a useful signal rather than a continuous noise that the user learns to ignore.

2.7 Tolerance Analysis

The part of this design that carries the most risk is the one the whole project rests on. RoadSense claims it can tell a pothole apart from a speed bump using motion alone. If those two events do not actually shake the vehicle differently, then no amount of software can separate them, and the second high-level requirement cannot be met no matter how well the rest of the system is built. This section shows, by simulation, that they are separable, and by how much.

The model. We represent one corner of the vehicle using the standard quarter-car model (Gillespie), which treats the car as two masses joined by springs: the body resting on the suspension, and the wheel and hub resting on the tire. The values used are typical for a mid-size passenger car.

Quantity	Symbol	Value
Body mass over one wheel	m_s	300 kg
Wheel and hub mass	m_u	40 kg

Suspension spring rate	k_s	20,000 N/m
Suspension damping	c_s	1,500 N·s/m
Tire vertical stiffness	k_t	200,000 N/m

The system has two natural frequencies:

$$\text{body mode} = (1/2\pi) \cdot \sqrt{(k_s/m_s)} = 1.30 \text{ Hz, damping ratio } 0.31$$

$$\text{wheel-hop mode} = (1/2\pi) \cdot \sqrt{((k_s+k_t)/m_u)} = 11.80 \text{ Hz, damping ratio } 0.25$$

These are a factor of nine apart and both are lightly damped, so the vehicle behaves as two separate mechanical channels: a slow one and a fast one. The question the simulation answers is which channel each road event drives.

The two inputs. A standard speed hump is 3.7 m long and 90 mm high and is designed to be crossed at 15 mph, which puts the tire on it for 0.55 seconds. We model it as a half-sine of that length. A pothole is modelled differently, because at speed the tire never reaches the bottom. Taking a hole 0.5 m long and 60 mm deep struck at 30 mph, the tire is over it for only 37 ms and falls just 6.7 mm under gravity before meeting the far wall. The event is therefore dominated by the climb out of the hole, which takes about 11 ms, set by how quickly the contact patch rises over the exit edge. Both profiles are shown in Figure 3(a).

Method. The two road profiles were applied to the quarter-car equations of motion, which were integrated numerically at 2 kHz. The resulting body acceleration is what the device actually measures, and is plotted in Figure 3(b). The power spectral density of each response was computed, and the energy falling in the slow band (0.8 to 3 Hz) and the fast band (8 to 40 Hz) was integrated to form the ratio used by the classifier:

$$R = (\text{energy from } 0.8 \text{ to } 3 \text{ Hz}) \div (\text{energy from } 8 \text{ to } 40 \text{ Hz})$$

Results.

Event	Slow band energy	Fast band energy	R
Speed bump	3.71×10^{-2}	6.26×10^{-4}	59.3
Pothole	4.94×10^{-6}	3.41×10^{-4}	0.01

The two values of R are separated by a factor of roughly **4,000**. Placing the decision boundary at $R = 1$ leaves the speed bump a factor of 59 above it and the pothole a factor of 68 below it. Every parameter in the model above could be wrong by a factor of ten and the classification would still come out correct. This is the margin that makes the 80 percent classification target in the second high-level requirement achievable rather than optimistic.

Figure 3(c) shows why. The speed bump concentrates its energy below 3 Hz, right on the body mode, and puts almost nothing into the fast band. The pothole peaks near 12 Hz, directly on the wheel-hop mode, and leaves the slow band almost empty. The two events drive different channels of the same mechanical system.

A second, independent clue. Figure 3(b) shows a feature the ratio does not use. The pothole response begins with a downward deflection, because the wheel drops before it climbs, while the speed bump begins upward. The sign of the first motion is therefore a second and completely independent check on the classification, available at no additional cost in computation.

What this requires of the hardware. The useful information extends to about 40 Hz. Sampling at the 100 samples per second floor stated in the first high-level requirement would place the highest observable frequency at 50 Hz, leaving no margin for the anti-aliasing filter to roll off. For this reason the motion sensing subsystem is configured to deliver 400 samples per second, which oversamples the band of interest by a factor of ten and places the filter corner well clear of it.

Known limitation. A bicycle has no suspension, so its frame and wheel resonate between roughly 15 and 40 Hz rather than at 1.3 and 11.8 Hz. The value of R shifts accordingly, and a separate decision boundary must be determined from recorded bicycle data rather than assuming the automotive one carries over.

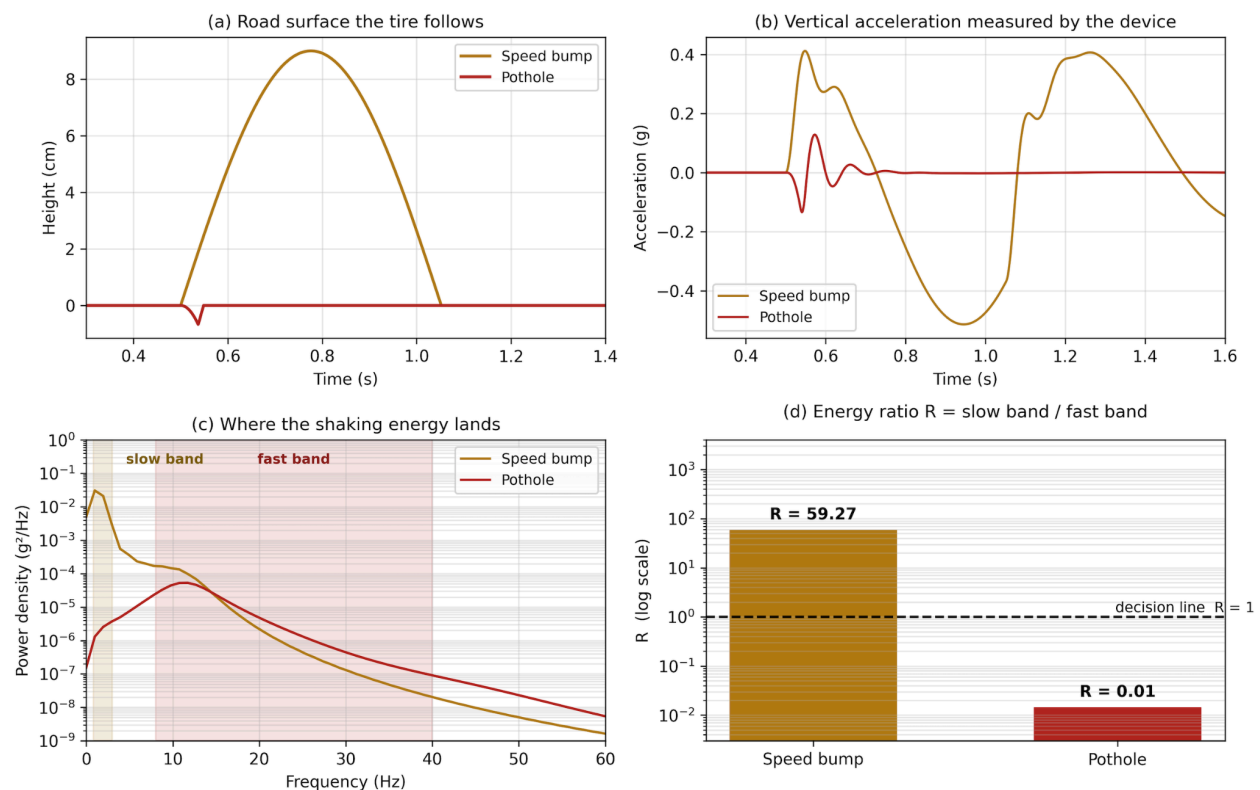


Figure 3. Quarter-car simulation of the two road events. (a) the road profile the tire follows, (b) the vertical acceleration the device measures, (c) where each event places its energy, and (d) the resulting ratio R, separated by a factor of roughly 4,000 across the decision line.

2.10 Risk Analysis

The component that poses the greatest risk to successful completion is the analog front end, together with the analog-to-digital conversion that follows it. Every other block in the design either carries digital data, where a wiring error produces an obvious failure, or delivers power, where a fault is immediately visible on a meter. The analog chain is different: a mistake in it produces data that looks plausible but is wrong, and that error cannot be detected by inspecting the circuit or by reading the log.

The specific failure we are most concerned about is aliasing. The microcontroller samples the analog signal at a fixed rate, and any vibration above half that rate is not discarded but folded down into the measured band, where it appears as a slow signal that was never present on the road. A filter that is built with the wrong component values, or one whose corner frequency drifts because of component tolerance, will let those frequencies through. The resulting data will contain events that did not happen, the classifier will faithfully categorise them, and nothing in the system will indicate that anything is wrong. This failure would directly undermine the second high-level requirement, and it would be difficult to diagnose after the fact because the recorded data would look normal.

We reduce this risk in three ways. First, the filter is measured rather than assumed: before the board is used to collect any road data, a swept sine wave of known amplitude is injected at the front end input and the output is recorded, confirming the corner frequencies and the attenuation above them against the design values. Second, the system samples faster than it needs to and

reduces the rate in software, which places the folding frequency well above the band of interest and leaves room for the analog filter to roll off. Third, the motion sensing subsystem provides an independent measurement of the same physical event over an overlapping frequency range, so a road event reported by the analog channel that does not appear in the inertial channel can be identified as suspect during testing.

A second risk, lower in likelihood but higher in consequence, is the loss of recorded data through storage failure or power interruption. This is mitigated by writing short records rather than continuous raw data, by double buffering so that a storage delay does not stall acquisition, and by tagging every block with a sequence number and checksum so that any loss is visible rather than silent.

3 Ethics and Safety

This project collects measurements of public roads and reports them to the people who use those roads, and both the collection and the reporting raise issues we have to address deliberately.

The clearest ethical concern is the privacy of the person carrying the device. RoadSense records position continuously while it is operating, and a record of where someone travels is among the most identifying information that can be collected about them. Research on mobility data has shown that only four time-and-place points are enough to uniquely identify ninety-five percent of individuals within a set of one and a half million people [1]. A record of a student's daily travel around campus would reveal where they live, where they study, and when they do so. The IEEE Code of Ethics requires us "to respect the privacy of others" [2], and the ACM Code devotes a full principle to the same obligation [3]. We address this by design rather than by policy. The device contains no wireless transmitter, so recorded data cannot leave it without the owner

physically removing the memory card. The first and last two hundred metres of every trip are discarded automatically, so that a record does not begin at the owner's residence. If data is ever shared beyond the team, it will contain only road segment identifiers, defect classifications, severities, and coarse timestamps, and never a continuous position trail or any device identifier.

A related concern is what the same data could be used for. The measurements that describe a road also describe the person driving over it, including how hard they brake and how fast they take corners. We will not implement any feature that scores or reports on an individual operator, and we state that boundary explicitly because the step from monitoring a road to monitoring a driver is a small one.

The second ethical concern is honesty about what the system can do. Our design targets detecting ninety percent of potholes and correctly classifying eighty percent of detected events, which means that one defect in ten will be missed and one event in five will be labelled incorrectly. A user who trusts a warning that never comes has been misled by our claims rather than only by the road. IEEE Code of Ethics Section I.5 requires engineers "to be honest and realistic in stating claims or estimates based on available data" [2]. We will therefore report our measured accuracy with its uncertainty rather than as a single figure, we will present the system as advisory rather than as a safety device, and we will not describe it as capable of preventing accidents.

On safety, the principal hazard is not electrical but vehicular. Validating the system requires driving and riding over real road defects on public roads. All vehicle testing will be carried out with at least two people, one operating the vehicle with full attention and one operating the device, and no team member will configure or read the device while driving. Illinois law

prohibits the use of handheld electronic devices while operating a motor vehicle [4], and the single-button interface exists so that no interaction is ever required in motion. We will not deliberately strike defects at speeds above thirty-five miles per hour, and every defect on the test route will be measured on foot before it is driven over. Bicycle testing will take place on low-traffic campus routes in daylight with helmets worn. The enclosure will be positively secured in all cases, since an unrestrained device can roll beneath a brake pedal in a car or enter the spokes on a bicycle.

The electrical hazards are modest. The entire system operates from a five volt supply at low current, well below any shock hazard. The significant electrical risk is the lithium battery, which we address by using only a commercially manufactured pack certified to UL 2054 and IEC 62133 [5] rather than assembling cells ourselves, by never charging a pack while it is connected to the device, and by retiring any pack that shows swelling or damage. The board includes a resettable fuse, reverse polarity protection, and a transient voltage suppressor on its input so that an incorrect connection damages nothing.

The device contains no intentional radio transmitter. The GPS receiver only listens, so the rules governing radio transmitters do not apply, and the board falls under FCC Part 15 Subpart B as an unintentional radiator, which is the ordinary status for a student project not offered for sale [6]. Our severity scores are referenced to ISO 2631-1 [7], which defines how human beings perceive vibration at different frequencies, and our continuous roughness ratings are referenced to the road surface classes defined in ISO 8608 [8]. We use these existing standards rather than inventing our own scale so that our measurements are comparable with road condition data collected anywhere else.

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