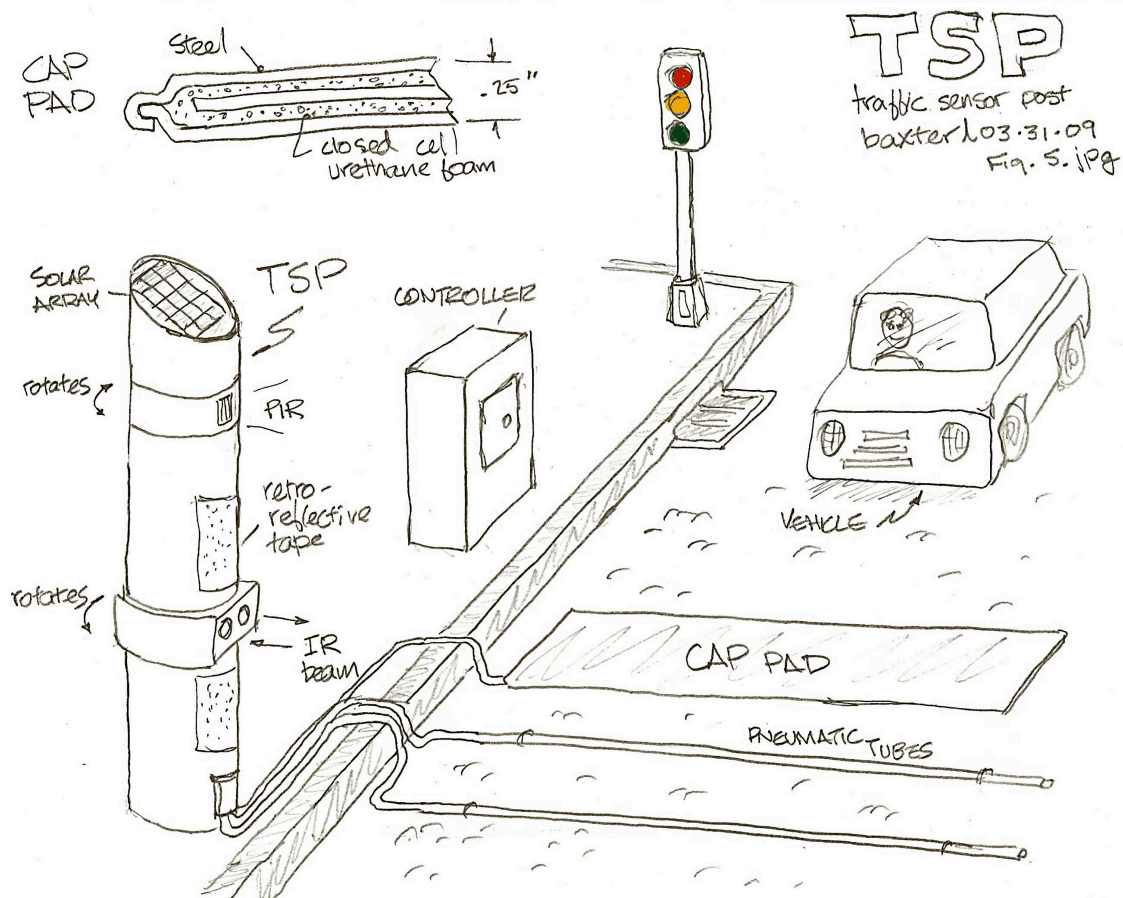


Traffic Sensor Post

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Key words: traffic sensor, capacitive sensor, cap pad, wireless vehicle sensor, traffic network



The Problem

Ever sit in your car waiting interminably for the green light when nobody's using the cross street?

The U.S. Has 330,000 traffic signals, and fewer than 25% are intelligently controlled. \$30B was lost last year due to congestion, 753M gallons of fuel was burned at idle, and air quality suffered from carbon monoxide emission. Intelligent traffic signals can reduce this waste, reduce traffic accidents, and improve enforcement.

The traffic signals in most intersections are now controlled by a large-suitcase-sized box, one per intersection. These controllers are classically dumb, with relays and cams and switches, but now may include software that accepts data from local sensors. Sensors are most often an automobile-sized inductive loop buried in the asphalt.

A second application of this project is a specialized sensor that weighs moving trucks, the weight-in-motion (WIM) sensor.

The first simple traffic signal controller was installed at a Cleveland intersection in 1914. Cost is high, about \$25K per signal, and reliability low: inductive loop sensors fail 20%/year due to asphalt failure and resurfacing. Instrumenting a typical intersection can cost \$100,000, and a single WIM sensor system costs \$150-780K.

Modern controllers have gained some intelligence. They may share data with nearby intersections, respond to radio requests from emergency vehicles, and sometimes take commands from a metro traffic control center (see both *The Italian Job* films).

More intersections will be controlled more accurately if effective, inexpensive, and easy-to-install sensors to monitor traffic flow are available. These sensors measure vehicle location and speed in four or more streets at an intersection, or at a distance from the intersection for early warning.

The Solution

This project, the Traffic Sensor Post (TSP), is a wireless, solar-powered sensor array that handles all the data collection needed at an intersection. TSPs may be installed at each of the four corners of an intersection for full coverage. All TSPs send data to the single controller box over IEEE 802.15.4 in a star network.

This project does not include the controller box, just the traffic sensor posts; the controller will need appropriate wireless transceivers and application software.

Traffic data collection now uses a wide variety of sensors. Besides the old standby inductive loop, there are video cameras, microphones, sonar, pneumatic tubes, radar, etc. But the environment is so varied and unfriendly that none performs well. Inductive loops are unreliable and expensive, stop traffic for installation, and need considerable maintenance. Video cameras are confused if the sun angle is wrong, and need periodic lens cleaning.

The TPS solution is to combine four different sensors in an inexpensive, low maintenance, easy-to-install post, six inches in diameter and six feet tall. It can be built into the post holding traffic signal lights or stand alone. All four sensors are not needed in each TSP, they can be selected based on usage.

TPS is the first wireless solution for this problem, and one of the sensors (Cap Pad) is novel and is a huge advantage over expensive and inaccurate current truck-in-motion sensors.

The sensors used in TPS:

1. A passive IR (PIR) sensor, looking in the 10u deep-infrared band for moving IR sources. This technology is used in inexpensive motion-detecting lamp controls and picks up my car in the driveway every time from 30 feet. The detection range is good, the parts are cheap, and the beam can look through a layer of dirt. It can't measure speed, distance, or direction (a modification would add direction).
2. Conventional pneumatic tubes. Rubber tubes are stapled to the asphalt and feed two pressure sensors. This is accurate and measures speed well, but is not used for permanent installations as it is easily damaged. Pneumatic tubes are often deployed to measure traffic volume in service of road construction.
3. The Cap Pad, an innovative new sensor developed for this report. The Cap Pad is a 10" x 12' sandwich of three 0.05" thick stainless steel sheets separated by

two 0.05" closed-cell urethane foam layers. A truck's axle is weighed by capacitively measuring the small (0.025") deflection of the pad under the tire. One Cap Pad can handle the WIM (weight in motion) requirements, two can add speed and direction information. Multiple pads can handle multilane roads. The Cap Pad can be fastened to the asphalt with adhesive or pavement tape or buried under as much as an inch of asphalt for protection. Its materials cost is only a couple of hundred dollars, a huge saving over the piezoelectric weight-in-motion sensors now used.

4. A near-IR transmitter-receiver using a pulsed LED for transmission and a PIN photodiode for reception. Both need cylindrical lenses to focus the beam to a 2 degree wide 5 degree high ellipse that covers a remote retroreflective screen (as in highway signs), or to the IR sensors on another TSP. The range is further improved with a multilayer optical bandpass filter that removes visible light.

Cap Pad Math

An air gap between adjacent metal plates can be measured to sub-nanometer accuracy with precision capacitive sensors. Unfortunately, accuracy in the WIM application requires flat and parallel surfaces, and the Cap Pad has neither.

A force on adjacent flat plates with a restoring spring can also be measured accurately with capacitive sensors, but flat and parallel are still requirements. Maintaining parallelism over a thin 10' pad would be very difficult, and roads are seldom flat.

But if compression of the air pockets in closed-cell foam provides the restoring force, the resulting spring constant, from the ideal gas law $P_1/V_1 = P_2/V_2$, changes from the conventional $F = K \cdot x$ of springs or cantilevered beams to $F = P_0 \cdot H / (H - x)$ where P_0 is atmospheric pressure, H is the starting gap, and x the displacement. The happy result of this new force equation is that the capacitance of the pad varies linearly with applied force, and the surfaces of the Cap Pad no longer need to be parallel or flat. A force is measured accurately regardless of its size. An overloaded skinny-tired motorcycle and a fat-tired sand buggy are both weighted accurately. Deflection of the steel plates under the tires or bends to follow road curves do not affect accuracy. Second-order effects like the spring constant of polyurethane will hurt accuracy, but as the standard WIM accuracy requirement is only $\pm 6\%$, we'll be OK. A patent search revealed no prior disclosure of this method.

Circuit description

Most of the circuit amplifies outputs from the four sensors, digitizes them with the MSP430's 12 bit ADC, does some preprocessing, and messages the controller.

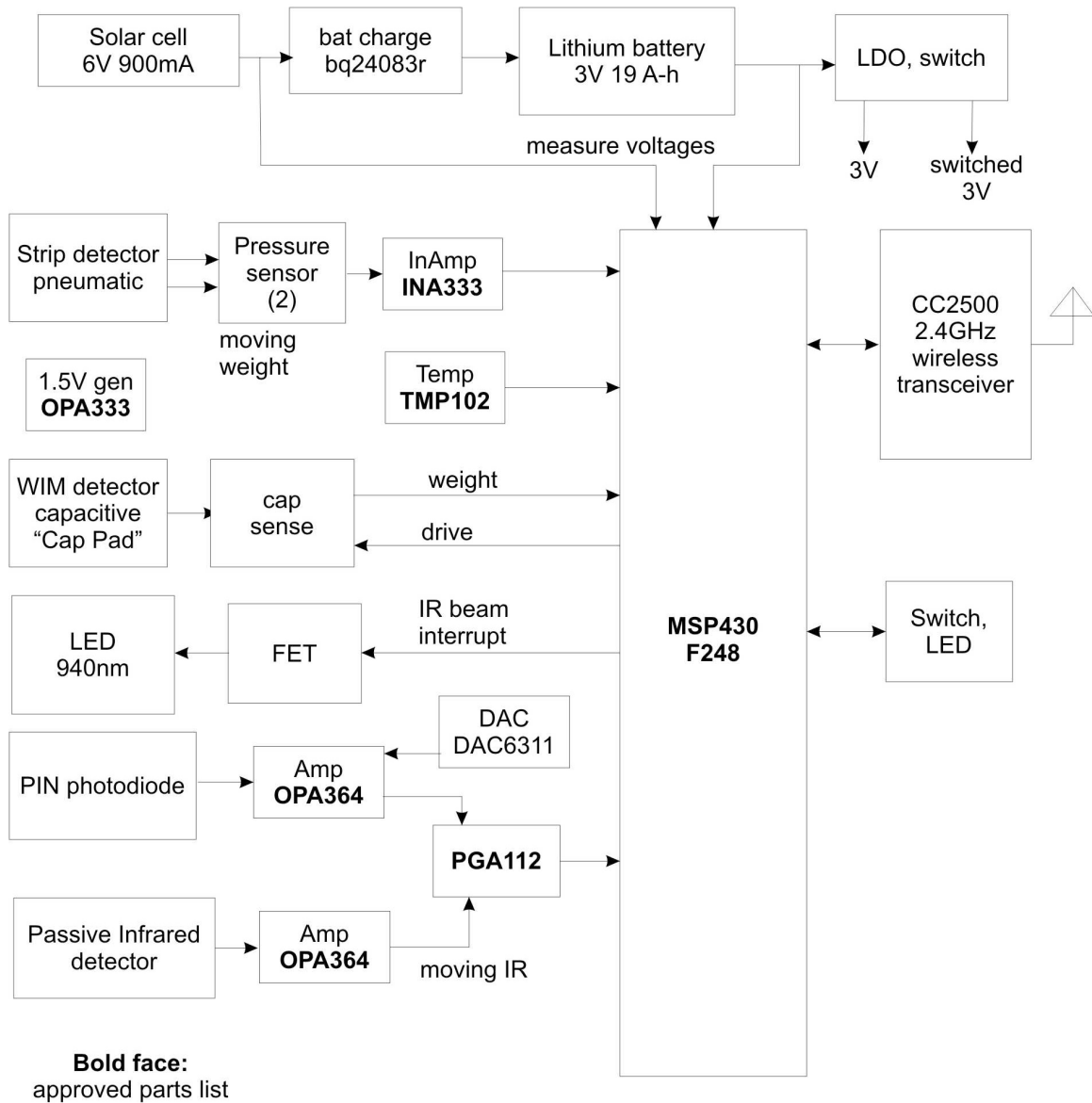


Fig. 1 – Circuit description.

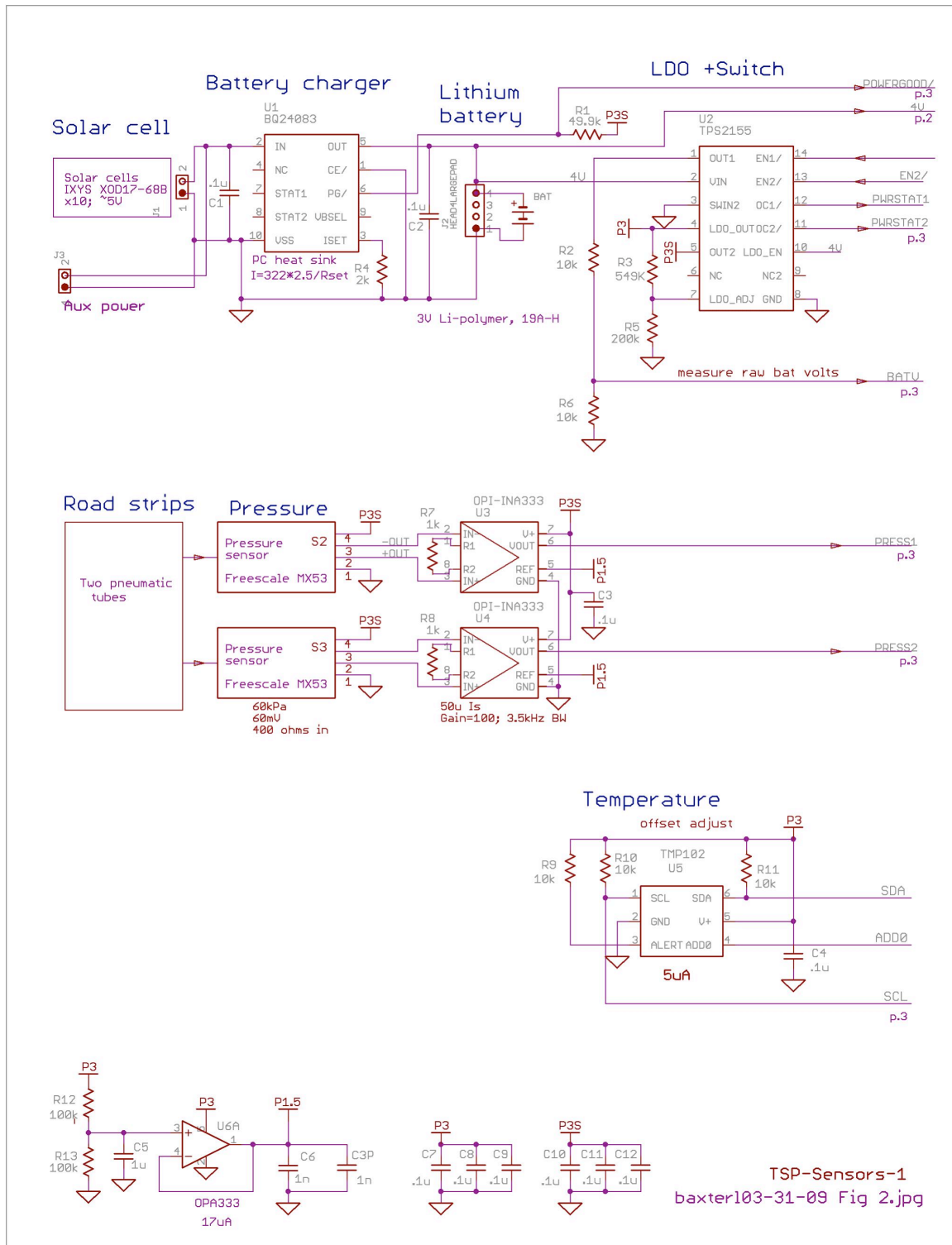


Fig. 2 - The 6V solar panel, 40 IXYS solar cells in series-parallel, charges a 19A-h lithium-polymer 3V battery through U1. Battery output is regulated at 3V by LDO/Switch U2, with decent margins as the battery is over 4V at full charge and 3.2V at end of charge, and the LDO dropout at 42mA is only about 50mV. U2 also switches active-mode 3V power, P3S.

The road strip sensor senses the 0.1-1psi pulse when a car drives over the pneumatic tubes. A silicon 400-ohm bridge sensor outputs about 50mV differentially. The instrumentation amplifiers U3, U4 boost the output to a few volts.

The pressure sensor, as well as the cap pad and the PIN sensor, have a quiescent level with no traffic. The MSP430 detects the no-traffic state and stores this level in RAM, updating every second to follow slow offset drifts from environmental factors. So sensor offset accuracy is not critical. The pressure sensor scale accuracy is relatively uncritical, maybe 30%, but the Cap Pad scale accuracy should be a few percent or less. Resolution needs to be good for all sensors.

An accurate temperature measurement (U5) is needed to handle the Cap Pad's temperature dependence caused by the the elastic modulus change of polyurethane.

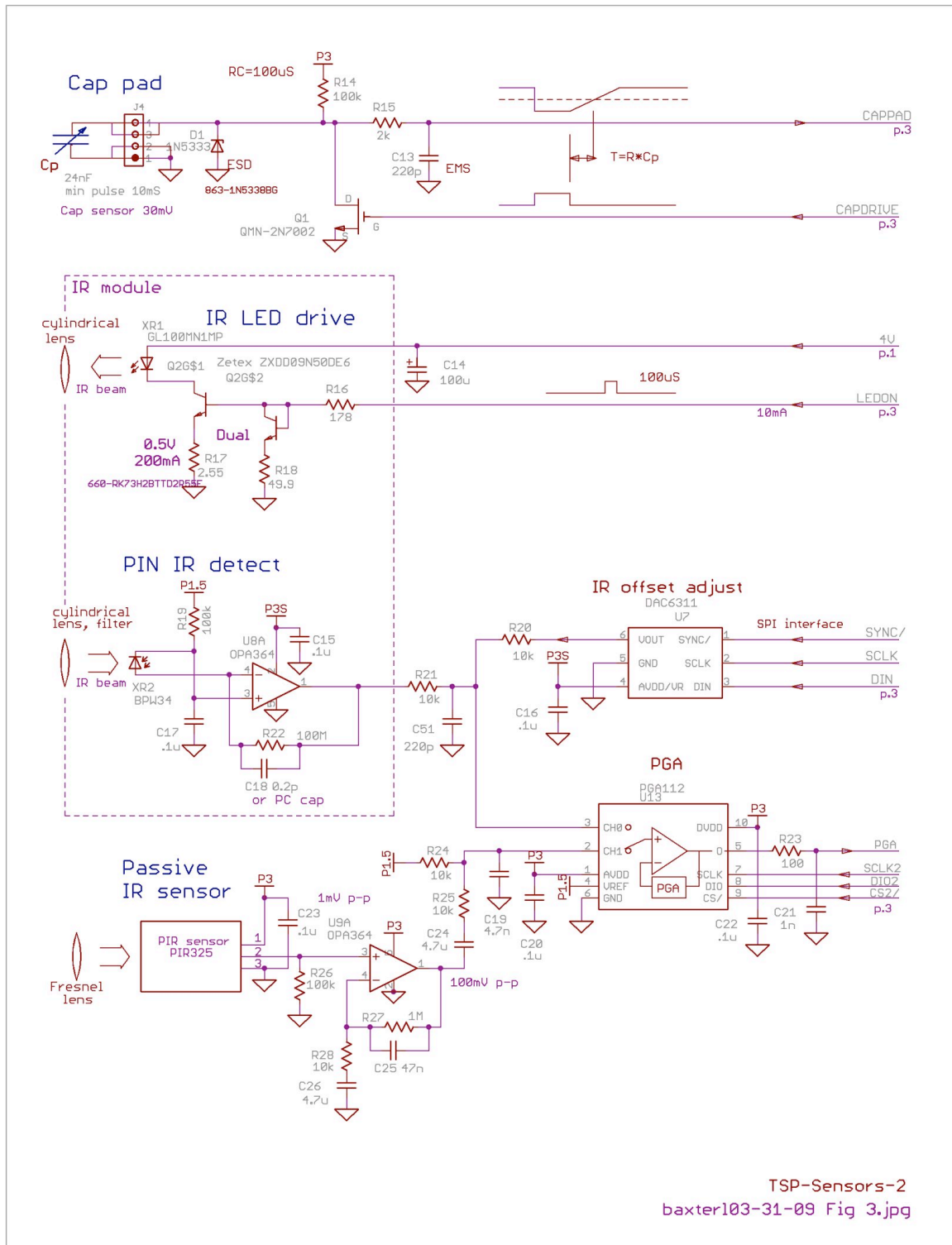


Fig. 3 - The Cap Pad has a nominal capacitance of about 24nF at rest, with a change of about 7% full scale when a truck passes. The CAPDRIVE pulse discharges this capacitance at a 700Hz rate, then a 100K resistor charges it to 3V with a 240uS time constant. A MSP430 timer times the pulse takes to cross the MSP's internal Vdd/2 reference using the internal comparator, and as the timer can be clocked at 12MHz the

resolution is 1%. Increased resolution could be had by timing out the nominal quiescent pulse width and capturing the pulse's level at that point with the 12-bit ADC.

The Cap Pad's sandwich construction shields the active element from electromagnetic interference, but 3W Zener D1 cleans up any remnant lightning strokes.

The IR LED drive is a 20:1 current mirror to handle LED voltage variation.

The PIN photodetector offset is handled with DAC U7, as the extreme night-day dynamic range would overrange the 12-bit DAC.

The passive IR (PIR) sensor turns moving deep-infrared targets into bipolar mV voltage pulses with its special segmented lens and dual-element pyroelectric detector. Its signal and the PIN signal are selected and variably amplified with the PGA.

Power budget

A mosaic of 40 IXYS solar cells connected for 6V output covers the sloped 250 sq. cm. top of the post, generating about 875mA at full sun. With an average current consumption of 7mA, the TPS can run on 1% full sun. The 19A-h battery can provide power with complete darkness for about 14 weeks. This allows operation even in shaded installations, except that extremely sun-challenged places like Seattle in the winter may need auxiliary power. An aux power jack is provided.

As the uP can monitor battery charge and solar energy, it could include a low-battery mode with the higher-power sensors sampled less often, surviving even Seattle winters. Assuming no sun, the power budget is

Ref	Device	Low power, mA	Active, mA	Duty cycle	Avg. current, mA	Notes
Page 1						
U1	Batt charge					From solar cells, not battery
U2	LDO/switch					
S2,S3	Pressure					
U3, U4	Press amp					
U6, R	1.5V gen					
U5	TMP102					
	Misc					
Page 2						
Q1, R	Cap pad					
XR1	IR LED					200mA pulse x 100uS, 70Hz
U8	IR amp					
U7	IR DAC					
S1	PIR sensor					
U9	PIR amp					
U13	PGA amp					
Page 3						
U10	MSP430					
U11	Radio					21mA Tx; Assume Rx <1Hz
LED1	LED					
Total			44			IR LED supplied from local cap; radio and pressure are not used together, so peak I ~ 20mA

Peak current

The lithium battery does not like to supply high peak currents, so the 200mA LED has a local 100uF capacitor to smooth its peak. The radio and the pressure transducers are scheduled not to overlap to reduce peak current.

Radio

The network does not require mesh topology, as data flow is almost all from TSP to controller box and all TSPs are close to the controller. The star network further saves power: at a 1 per second rate the TSP pings the controller for a real time update and any other messages, and only then turns its receiver on briefly.

Power, duty cycle, and noise

The IR LED sensor outputs nearly ten times the light level with a 10x higher current drive. As we're power limited, we can increase current 10x and cut down the duty cycle 10x so power isn't changed. As noise power increases only as the square root of the time ratio, the signal to noise ratio (SNR) improves by $\sqrt{10}$, or for the same SNR we save $\sqrt{10}$ in power. Hence the LED is driven by a short pulse.

Unfortunately, this duty cycle trick doesn't work on resistive bridge sensors like the pressure sensors: 10x voltage causes 100x power. For constant power, signal improves $\sqrt{10}$ as noise increases $\sqrt{10}$, there's no advantage.

The passive IR sensor can't easily respond to a 700kHz sample rate, as the analog time constants are too long to settle in time, so it remains powered.

The Cap Pad takes almost no power and could easily run at >3kHz for more accurate sampling.

The IR sensor takes the most power, but can run at 70Hz and easily detect any vehicle longer than 20" traveling at 60mph.

MSP430, software

The MSP 430F248 is the perfect part for this application, as it is low power and it includes the Flash RAM, clock, comparator, ADC, and timer features we need. This model has enough serial IO and plenty of ports. It's plenty fast, and the 16 bit data handles our 12 bit math without roundoff errors.

In low power mode the MSP430 runs from the 32kHz crystal, keeping time. It's interrupted at a 700Hz rate. At this rate, a 60mph vehicle travels about 2". During 700Hz interrupts, it runs from the 12MHz crystal.

700Hz tasks are

- Turn on P3S voltage
- Read PIR sensor, pressure sensor, and cap pad WIM sensor.
- Process sensor data with offset and scale normalization. Compare to threshold to see if a vehicle was sensed. If so, add time stamp and send to controller box.

At a 70Hz rate, its tasks are

- Pulse IR LED drive and read IR detect voltage. Process, threshold, send to controller.
- If all sensors report no traffic, refresh sensor offset voltages in RAM.

At 1Hz rate, its tasks are

- Ping controller for real time update, turn on receiver, update internal clock and handle any other diagnostic messages.
- Reset watchdog timer
- Check data error rate and adjust radio transmitter to lowest power output that gives low error.

The controller box will do the heavy lifting: determine optimal signal timing as an artificial-intelligence function of historical data, time of day, day of week, nearby intersection traffic, holiday/workday, local stadium events, sun angle, traffic queue length, etc.