Perpetuum Vibration Energy Harvester-Powered Wireless Condition Monitoring Application Note

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Introduction

Using Perpetuum's vibration energy harvesters to power wireless electronic sensor systems can yield significant benefits. Increased reliability, lower life time costs and no battery disposal issues are just some of the benefits offered. In order to fully exploit the benefits levied by vibration energy harvesters it is necessary to consider certain key points during the design of the wireless sensor system. This application note is intended to assist the design engineer in making those decisions.

Whilst many varied applications can utilise Perpetuum's vibration energy harvesters, this application note will describe the steps necessary to design the power supply and energy storage circuit of a wireless condition monitoring sensor node. Please contact Perpetuum for design advice for your application.

What is a Vibration Energy Harvester?

In many applications where process information is required, energy is available in the form of kinetic vibration. A vibration energy harvester, also called a generator, is a device that converts this kinetic energy into useable electrical energy.

What is Condition Monitoring?

Condition monitoring is used extensively across many industries, such as, oil and gas, utilities and chemical industries as a critical part of asset management systems.

Accelerometers are used to monitor the condition of bearings and rotors in rotating equipment such as motors, fans, pumps and compressors. Defects in the bearing surfaces and unbalanced or misaligned shafts give rise to vibrations in the machine, ultimately causing machine failure. The frequency of these vibrations is a function of the bearing or shaft construction and its rotational speed, whilst the amplitude is a function of the severity of the problem.

By observing the changes in the vibration spectra of a machine over time a skilled engineer can interpret its condition and more importantly give prior warning of imminent failure. This facilitates a planned maintenance and repair program and avoids costly down-time.

Historically this condition monitoring has been performed by costly hard-wired sensors or infrequent checks by maintenance personnel equipped with hand held monitoring equipment. Self-powered wireless condition monitoring sensor systems provides on-line monitoring of critical plant and machinery providing major operating cost benefits. It is a low cost way to install such monitoring and therefore provides an excellent return on investment.

Application Description

Figure 1 shows a block diagram of a typical vibration energy harvester-powered wireless sensor node. Kinetic energy is converted into electrical energy by the generator. This energy is then stored in a capacitor until sufficient energy is available to power the sensor, microcontroller and radio. This application note uses the Atmel[1] 128L microcontroller and the Texas Instruments[2] CC2420 radio, using the 802.15.4 protocol.

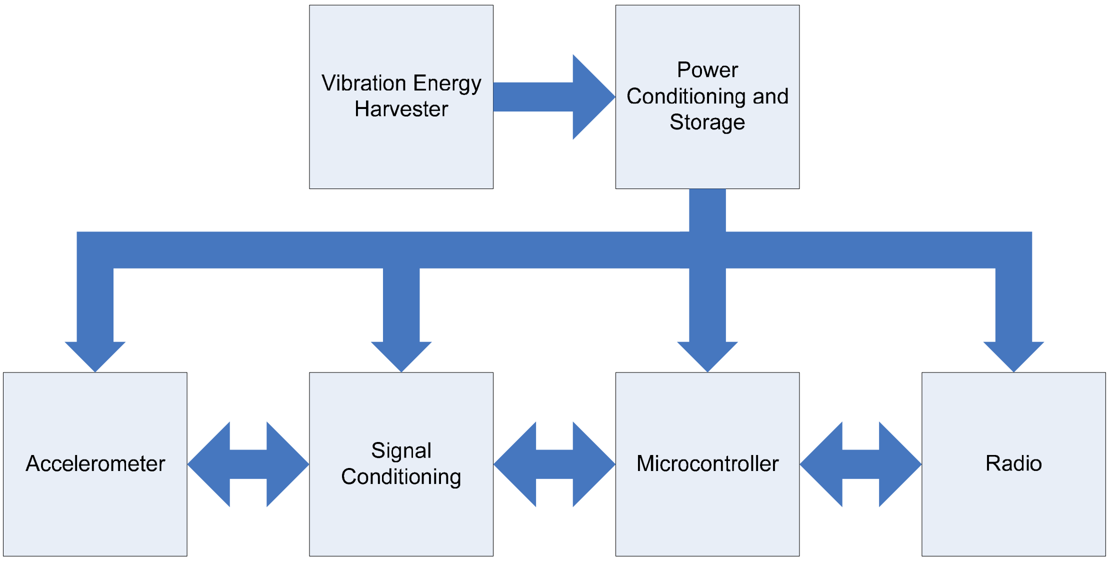

Figure 1 – Vibration Energy Harvester-Powered Wireless Sensor Node

Vibration data will be collected from a piezoelectric accelerometer. The signal conditioning will comprise of a biasing and gain stage for the accelerometer and an 8th order active filter to remove aliasing artefacts and reduce noise. The design will utilise the on-board 10 bit analogue to digital converter of the Atmel 128L. Over sampling will be utilised to reduce noise.

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[1] Atmel Corporation - http://www.atmel.com/

2 Texas Instruments - http://www.ti.com/

Now the key blocks have been defined, the first task is to determine the power budget. This will determine the capacitor size which in turn will define the rate at which readings can be transmitted. Minimising the amount of energy required will minimise the charge time of the capacitor and maximise the data throughput. This is simply a case of calculating the worse case data sheet values for each stage.

Stage	Potential (V)	Current (A)	Time (s)	Energy (J)
Sensor and bias circuit	5V	175µA	1.2s	1.05mJ
Analogue	3V	250µA	1.2s	0.90mJ
Microcontroller (sleep)	3V	30µA	1.0s	90µJ
Microcontroller (active)	3V	8mA	0.5s	12.0mJ
Radio	3V	20mA	0.1s	6.0mJ
Total				20.04mJ

Table 1 – Power Budget

From Table 1 it can be seen that the total energy requirement is approximately 20mJ. This energy needs to be increased to take account of the power supply inefficiencies. From Graph 1 it can be seen that efficiencies of greater than 75% are possible with a buck switch mode power supply based on Linear Technologies[3] LTC1877. Therefore the total stored energy requirement is 27mJ.

The output impedance of the micro generator is too high to supply the peak power required by the microcontroller and radio in Table 1. A storage capacitor, C26 in Figure 2, is charged by the micro generator until sufficient energy is available. The low output impedance of the capacitor will enable it to supply the power surges.

The generator produces an AC voltage; therefore it is necessary to convert this to DC before it is possible to charge the capacitor. Diodes D1 to D4 in Figure 2 form a bridge rectifier and perform this task. For reliable, efficient operation of the wireless sensor it is essential to select diodes that exhibit low forward voltage drop and low reverse leakage. The BAS16 from On Semiconductor[4] have proved a good choice over the entire industrial temperature range of -40°C to +80°C.

Capacitors C9, C11 and C12 smooth the resultant full wave rectified voltage.

The output impedance of the generator and input capacitance of the energy storage circuit forms a resistor-capacitor network. This gives rise to a time constant which dictates how quickly the voltage on the storage capacitor rises. The output impedance of the generator and the capacitance of the storage

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[3] Linear Technologies - http://www.linear.com/

[4] On Semiconductor - http://www.onsemi.com/

capacitor typically have a time constant of a few tens of seconds. The consequence of this is that when a discharged sensor node is placed on a piece of vibrating equipment with a low vibration it will take several minutes before there is sufficient energy to acquire a vibration spectra and transmit it.

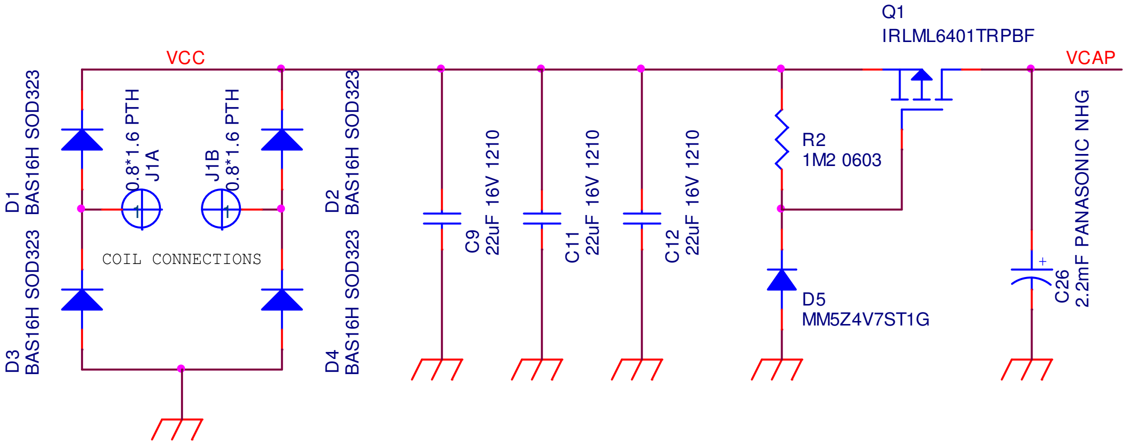

Figure 2 – Bridge Rectifier and Storage Capacitor Circuit

As a solution to this problem; the circuit formed by Resistor R2, Zener diode D5 and transistor Q1 in Figure 2 isolate the large storage capacitor, C26 from the smaller smoothing capacitor mentioned earlier. This allows the voltage, VCC, on this rail to establish itself significantly (approximately 30 times) earlier.

The circuit in Figure 3 uses the rapidly established VCC rail to power a low power LED flashing circuit. U14 is a low quiescent current linear regulator to power the relaxation oscillator formed by R24, R28, R36, R37, C482, and U15.

R24 and C482 determine the pulse period and R30 and C27 determine the pulse width. With the values shown the LED will flash for approximately 10ms every 10s.

The resultant LED flash aids installation and diagnostics greatly and is well worth the few percent increase in charging time experienced by the main storage capacitor.

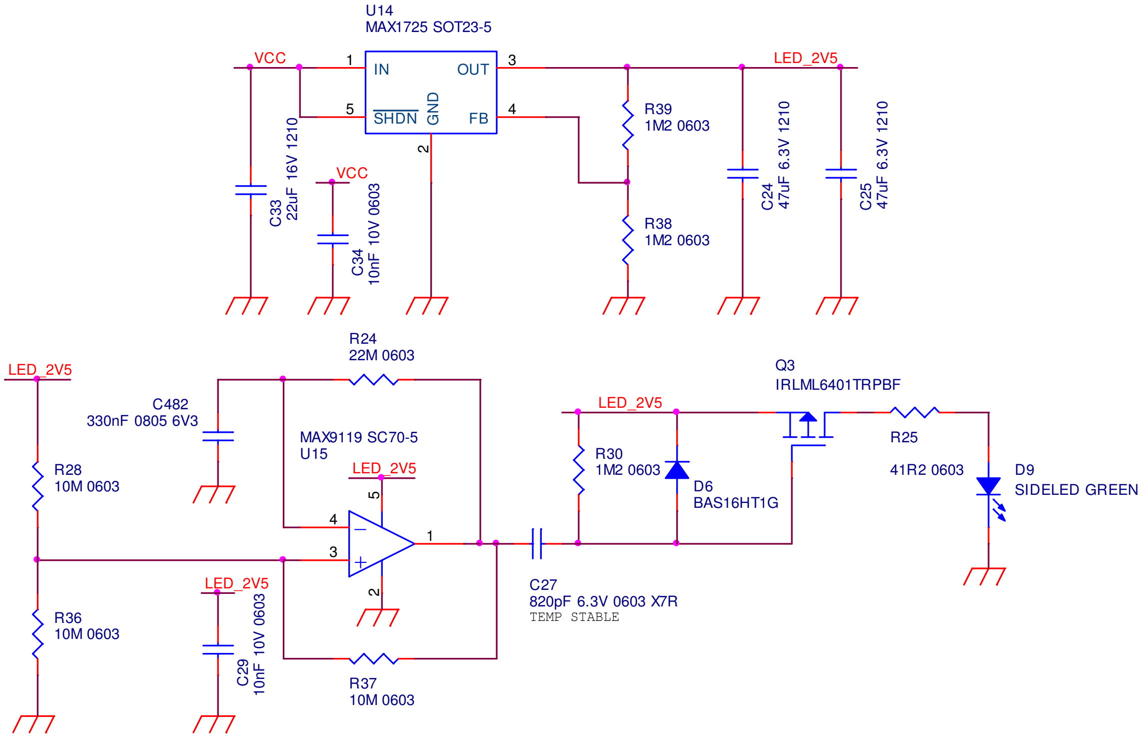

Figure 3 – Charging Diagnostic Flash LED Circuit

In addition to the amount of energy to be stored, two further pieces of information are required before the capacitor, C26, can be sized. These are the initial voltage the capacitor is charged to, V_{initial} and the voltage the capacitor is discharged to, V_{final}. The capacitor size can be determined using Equation 1.

$$\text{Capacitor} := \frac{2 \cdot \text{Energy}}{v_i^2 - v_f^2}$$

Equation 1

The output of the generator is clamped at approximately 11V peak to peak by internal Zener diodes. After rectification the voltage is approximately 10V peak, open circuit. To avoid any problems associated with Zener leakage the upper voltage, V_{initial}, is chosen as 8V. Similarly to avoid any problems with the buck switch mode power supply dropping out of regulation the lower limit, V_{final}, will be set to 3.2V.

Using Equation 1 the capacitor is calculated to be approximately 1mF. To allow for temperature coefficients and manufacturing tolerance this value is increased to either 1.5mF or 2.2mF.

Electrolytic capacitors were chosen due to the low cost, low leakage (0.01CV) and high capacitance per unit volume. Low leakage aluminium electrolytic capacitors are available in this value from several manufacturers.

A switch mode power supply has been chosen due to its increased efficiency over a wide input voltage. Several manufacturers make switch mode power supply control chips including Maxim[5], National Semiconductor[6], Linear, Torex[7] and Micrel[8]. The LTC1877 from Linear Technology was chosen due to its high efficiency even at the low load levels our circuit presents. Efficiencies of 80% are possible at loads as low of 1mW (330μA at 3V), see Graph 1.

Contact the Author

John Parker is a Senior Engineer at Perpetuum Ltd and has worked on several applications with a wide variety of customers. If you would like to contact John Parker to discuss this application note, or any other issues, please do so at:

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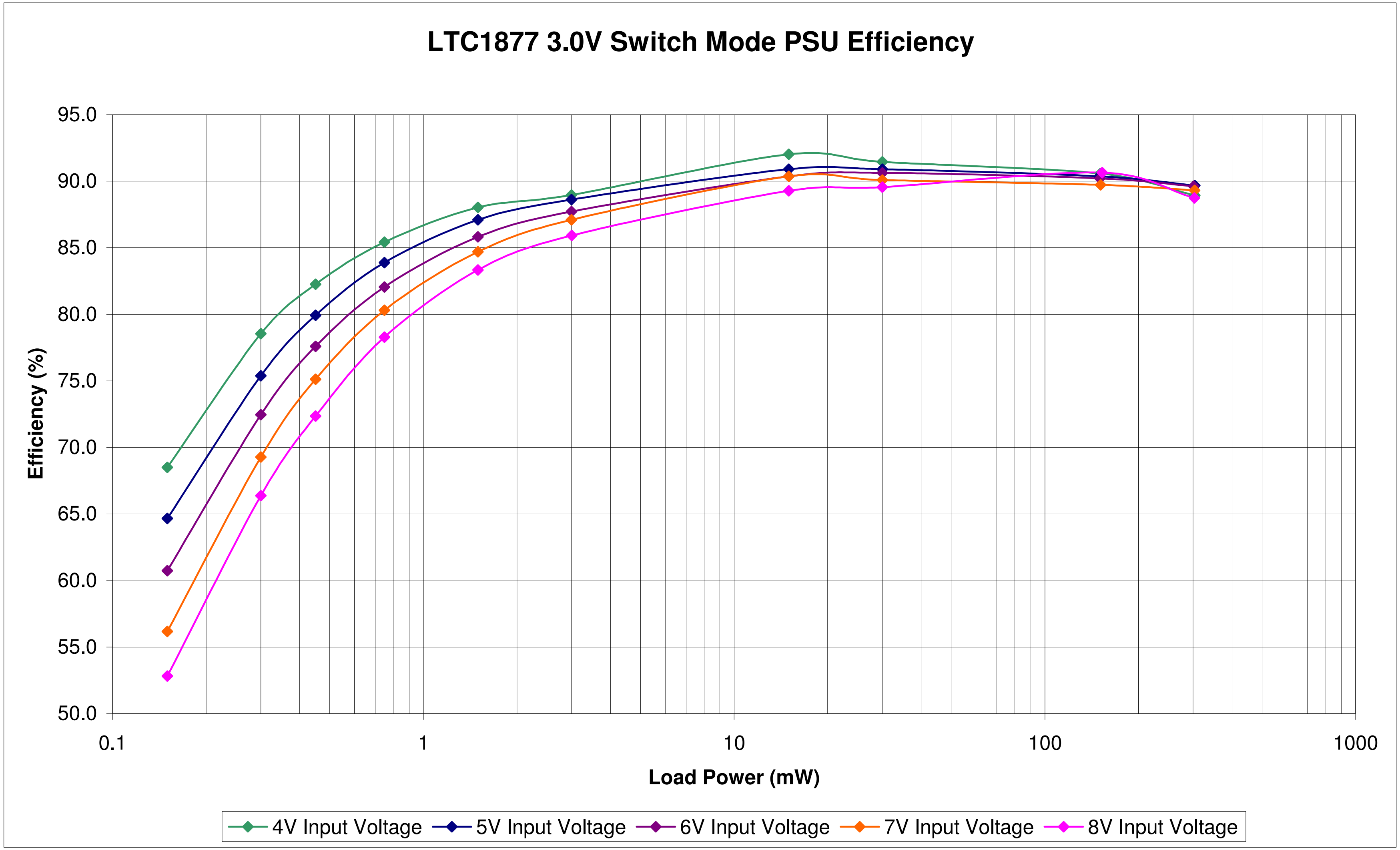
5 Maxim Integrated Products - http://www.maxim-ic.com/
6 National Semiconductor - http://www.national.com/
7 Torex Semiconductor - http://www.torex-europe.com/
8 Micrel Inc. - http://www.micrel.com/


LTC1877 3.0V Switch Mode PSU Efficiency
Efficiency (%)
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0.1
1
10
100
1000
Load Power (mW)
4V Input Voltage
5V Input Voltage
6V Input Voltage
7V Input Voltage
8V Input Voltage

Graph 1

Disclaimer

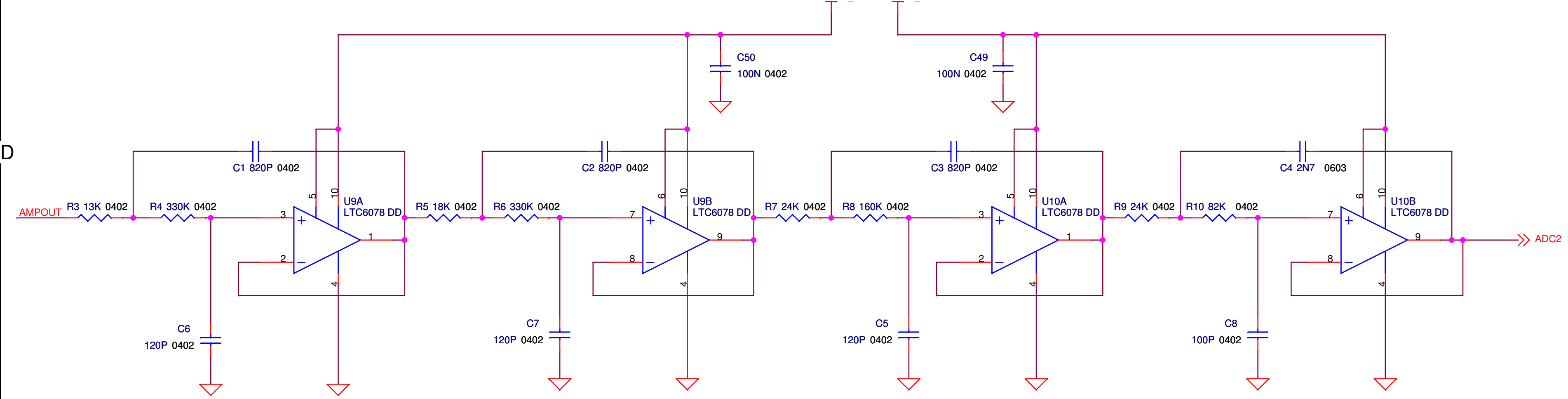
Every reasonable effort has been made in the production of this document to ensure that the information contained in this document is correct; however no responsibility can be taken for losses as a result of errors and omissions.

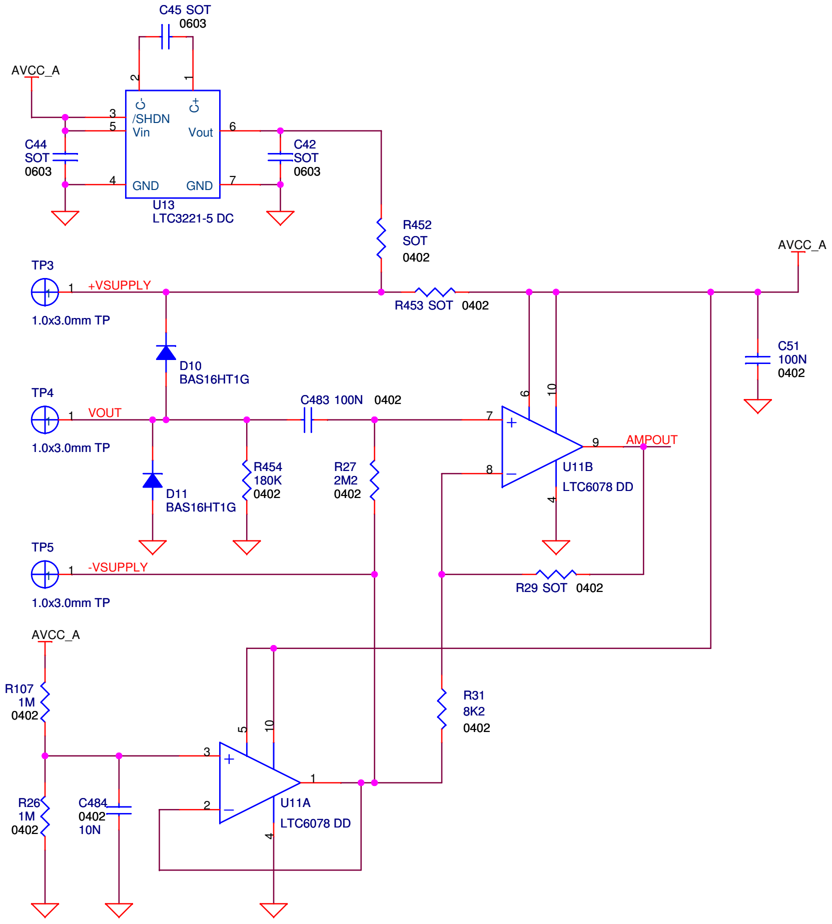
Appendix A

Many engineers are used to dealing with electrical potential (V), current (I) and their product, power (W). However, when working with vibration generators it is often useful to consider energy in addition to power. The energy converted in a process is simply the product of the power and the time taken for the process. If a graph of power consumed (W) is plotted against time (s) the area under the trace is the energy in Joules (J).

Appendix B

The following schematics and bill of material for a complete wireless condition monitoring sensor node follows to assist in the design of your Perpetuum powered wireless sensor node.

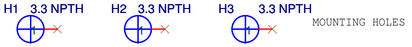




Power plane layer 2 (AVCC_A and DVCC)
GND plane layer 3 (AGND and DGND)
Analog routing + components layer 4 (Analog page)
AGND below AVCC, DGND below DVCC

Applicable to all traces on ANALOG page:
All routing over Analog GND plane,
Extend AGND by at least 3mm beyond Layer 4 routing,
Fill unrouted area on Layer 4 above this AGND with copper with regular vias to AGND.
Through holes and op amps close to board edge,
Keep traces as short as possible, minimal vias,
Minimise coupling between input and output stages - layout in straight line,
Minimise Power and Layer1 routing above AGND - no SPI routing,

1mm 4 layer FR4
35um Copper Thickness



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Southampton
SO16 7NS

Accelerometer Reference Design - Sensor Bias and Filtering

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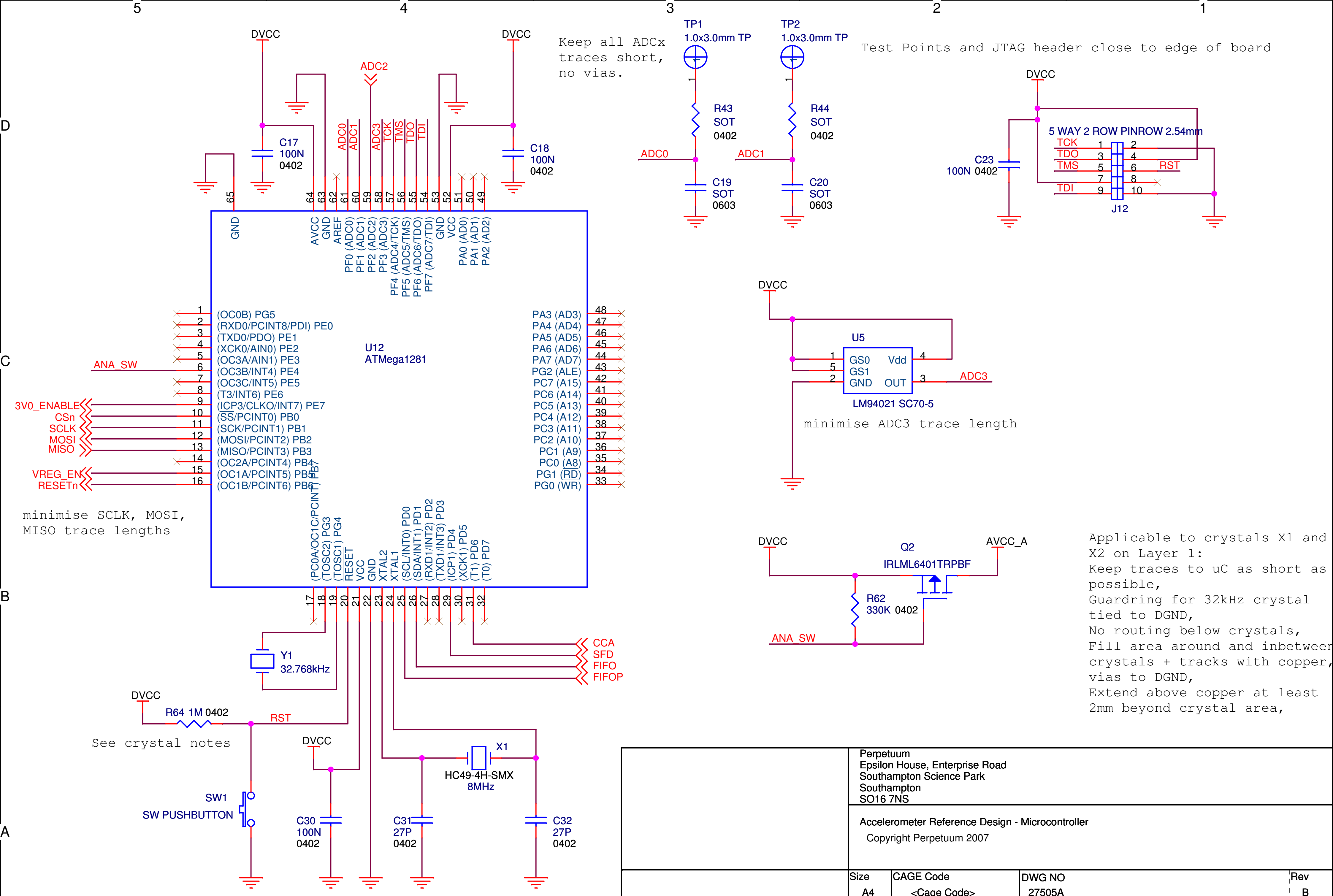
Size	CAGE Code	DWG NO	Rev
A3	<Cage Code>	27505A	B

Wednesday, May 09, 2007

Scale

Sheet 1 of 4



Keep all ADCx traces short, no vias.

Test Points and JTAG header close to edge of board

minimise ADC3 trace length

minimise SCLK, MOSI, MISO trace lengths

See crystal notes

Applicable to crystals X1 and X2 on Layer 1:
Keep traces to uC as short as possible,
Guarding for 32kHz crystal tied to DGND,
No routing below crystals,
Fill area around and inbetween crystals + tracks with copper, vias to DGND,
Extend above copper at least 2mm beyond crystal area,

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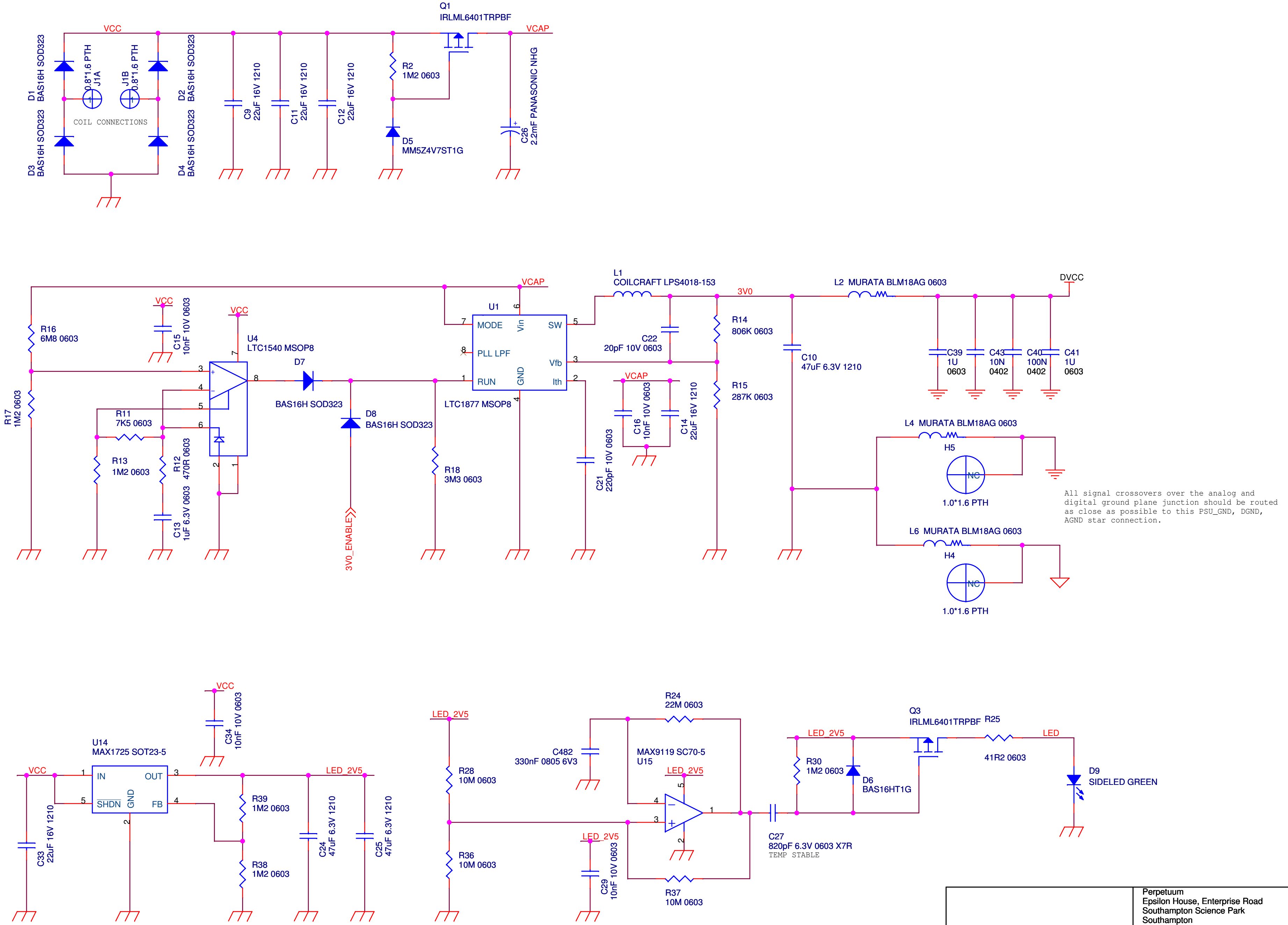
Accelerometer Reference Design - Microcontroller

Size	CAGE Code	DWG NO	Rev
A4	<Cage Code>	27505A	B

Tuesday, May 08, 2007

Scale

Sheet 2 of 4



All signal crossovers over the analog and
digital ground plane junction should be routed
as close as possible to this PSU_GND, DGND,
AGND star connection.

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Accelerometer Reference Design - Power Conditioning and Storage
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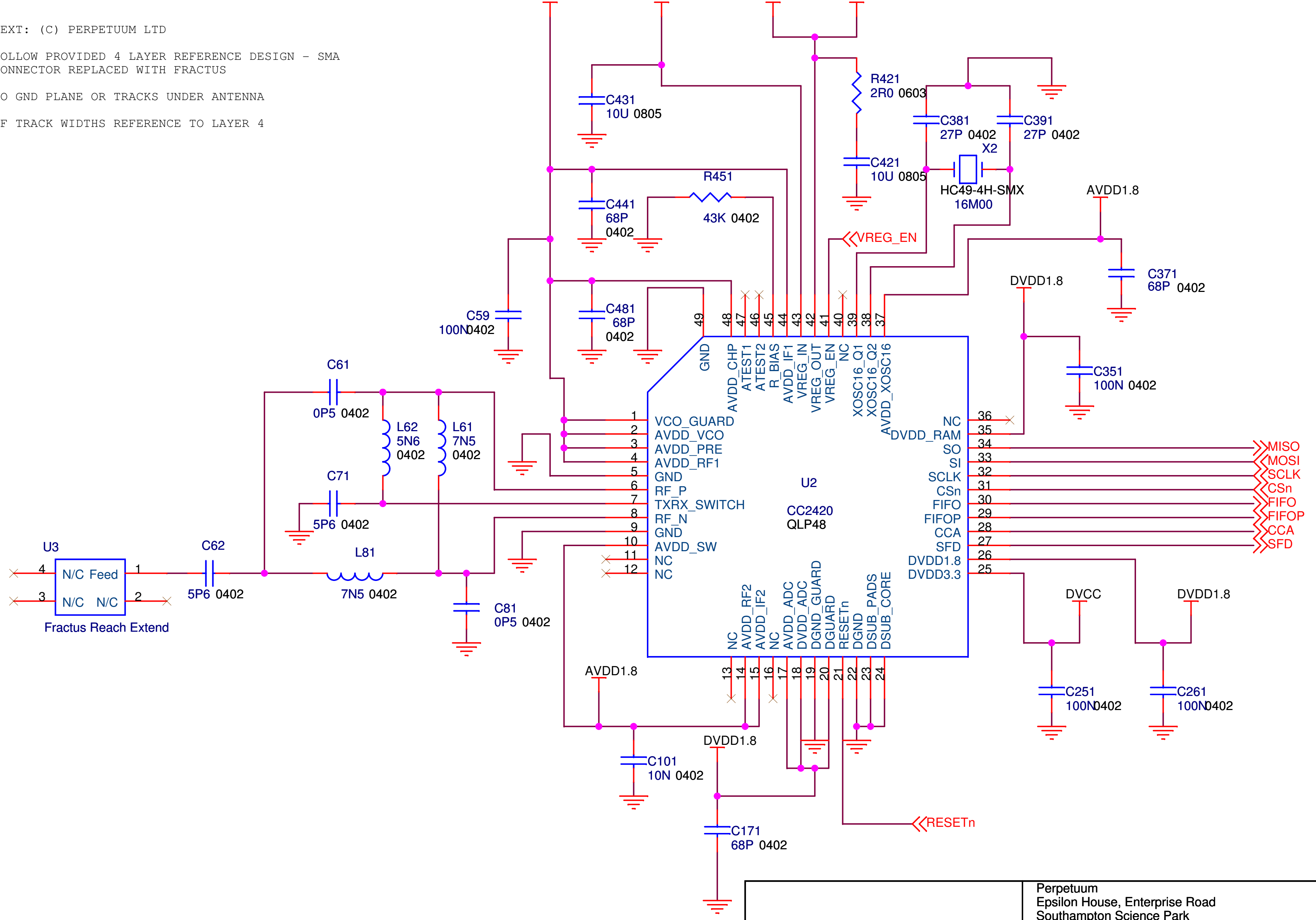
Sheet 3 of 4

TEXT: (C) PERPETUUM LTD

FOLLOW PROVIDED 4 LAYER REFERENCE DESIGN - SMA CONNECTOR REPLACED WITH FRACTUS

NO GND PLANE OR TRACKS UNDER ANTENNA

RF TRACK WIDTHS REFERENCE TO LAYER 4



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Accelerometer Reference Design - Radio
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A4	<Cage Code>	27505A	B

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Sheet 4 of 4

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REFERENCE DESIGN - BILL OF MATERIALS

27505A   Issue: B

Revised: Tuesday, May 01, 2007

ITEM	QUANTITY	REFERENCE	DESCRIPTION	MANUFACTURER	PART NUMBER
1	2	C61, C81	0.5pF 0402 ± 0.25pF 50V COG -55 +125	MURATA	GRM1555C1HR50BZ01D
2	2	C62, C71	5.6pF 0402 ± 0.25pF 50V COG -55 +125	MURATA	GRM1555C1H5R6BZ01D
3	1	C22	20pF 10V 0603	MURATA	GRM1885C1H220JA01D
4	4	C31, C32, C381, C391	27pF 5% 0402 50V COG -55 +85degC	MURATA	GRM1555C1H270JA01
5	4	C171, C371, C441, C481	68pF 0402 5% 50V COG -55 +125	MURATA	GRM1555C1H680JZ01D
6	1	C8	100pF 5% 0402 50V COG -55 +85degC	MURATA	GRM1555C1H101JA01
7	3	C5, C6, C7	120pF 5% 0402 50V COG -55 +85degC	MURATA	GRM1555C1H121JA01
8	1	C21	220pF 10V 0603	MURATA	GRM1885C1H221JA01D
9	3	C1, C2, C3	820pF 5% 0402 50V COG -55 +85degC	MURATA	GRM1555C1H821JA01
10	1	C27	820pF 6.3V 0603 X7R	PHYCOMP	2238 586 15622
11	1	C4	2N7 5% 0603 50V COG -55 +85degC	MURATA	GRM1885C1H272JA01
12	3	C43, C101, C484	10N 10% 0402 50V X7R -55 +85degC	MURATA	GRM155R71E103KA01
13	4	C15, C16, C29, C34	10nF 10V 0603	MURATA	GRM188R71H103KA01D
14	13	C17, C18, C23, C30, C40, C49, C50, C51, C59, C251, C261, C351, C483	100N 10% 0402 16V X7R -55 +125degC	MURATA	GRM155R71C1D4KA
15	1	C482	330nF 6.3V 0805 X7R	EPCOS	B37941K0334K60
16	3	C13, C39, C41	1U 10% 0603 6V3 X5R -55 +85degC	MURATA	GRM188R60J105KA01D
17	2	C421, C431	10uF 0805 10% 10V X5R -55 +85	PHYCOMP	222224013676
18	5	C9, C11, C12, C14, C33	22uF 16V 1210	MURATA	GRM32ER61C226KE20L
19	3	C10, C24, C25	47uF 6.3V 1210	MURATA	GRM32ER60J476ME20L
20	1	C26	2.2mF PANASONIC NHG	PANASONIC	ECA1CHG222
21	9	D1, D2, D3, D4, D6, D7, D8, D10, D11	BAS16H SOD323	ON SEMI	BAS16HT1G
22	1	D5	MM5Z4V7ST1G	ON SEMI	MM5Z4V7ST1G
23	1	D9	SIDELED	OSRAM	LG-A670-KIM2
24	1	J12	SMD 2.54mm PINROW 10W	RS	
25	1	L1	COILCRAFT LPS4018-153	COILCRAFT	LPS4018-153MLB
26	3	L2, L4, L6	0603 FERRITE BEAD	FAIR-RITE	2506036017Y0
27	1	L62	5.6nH 0402 5% 300mA -55 +125	MURATA	LQG15HS5N6J02D
28	2	L61, L81	7.5nH 0402 5% 300mA -55 +125	MURATA	LQG15HN7N5J02D
29	3	Q1, Q2, Q3	P CHANNEL MOSFET	IRL	IRLML6401TRPBF
30	10	C19, C20, C42, C44, C45, R29, R43, R44, R452, R453	SOT	TBC	TBC
31	1	R421	2R2 0603 5% 1/16W		TBC
32	1	R25	41R2 0603 1%	MULTICOMP	MC 0.063W 0603 1% 41R2
33	1	R12	470R 0603 1%		
34	1	R11	7K5 0603 1%		
35	1	R31	8K2 THICK FILM 0402 1% 0.063W		
36	1	R3	13K THICK FILM 0402 1% 0.063W	TYCO	TBC
37	1	R5	18k THICK FILM 0402 1% 0.063W	TYCO	TBC
38	2	R7, R9	24K3 THICK FILM 0402 1% 0.063W	TYCO	TBC
39	1	R451	43K 0402 1% 1/16W		TBC
40	1	R10	82K THICK FILM 0402 1% 0.063W	TYCO	TBC
41	1	R8	160K THICK FILM 0402 1% 0.063W	TYCO	TBC
42	1	R454	180K THICK FILM 0402 1% 0.063W	PHYCOMP	232270671804
43	1	R15	287K 0603 1%		
44	3	R4, R6, R62	330K THICK FILM 0402 1% 0.063W	PHYCOMP	232270673304
45	1	R14	806K 0603 1%		
46	3	R26, R64, R107	1M0 THICK FILM 0402 1% 0.063W	PHYCOMP	232270671005
47	6	R2, R13, R17, R30, R38, R39	1M2 0603 1%		
48	1	R27	2M2 THICK FILM 0402 1% 0.063W		
49	1	R18	3M3 0603 1%		
50	1	R16	6M8 0603 1%		
51	3	R28, R36, R37	10M 0603 1%	PHYCOMP	232270461006
52	1	R24	22M 0603 5%	PHYCOMP	235052210226
53	1	SW1	6mm*3mm TACTILE SWITCH	TYCO	
54	1	U1	LTC1877 MSOP8	LINEAR TECHNOLOGY	LTC1877EMS8#PBF
55	1	U4	LTC1540 MSOP8	LINEAR TECHNOLOGY	LTC1540IMS8#PBF
56	3	U9, U10, U11	Vos 25uV, LOW NOISE OP AMP 3V/5V RAIL	LINEAR	LTC6078IDD
57	1	U14	MAX1725 SOT23-5	MAXIM	
58	1	U15	MAX9119 SC70-5	MAXIM	
59	1	U12	1.8V-5.5V AVR uC 8K RAM	ATMEL	Atmega 128L-8MU
60	1	U13	LTC3221-5 DC CHARGE PUMP	LINEAR TECHNOLOGY	LTC3221EDC-5
61	1	U5	ANALOGUE TEMPERATURE SENSOR	NATIONAL	LM94021BIMG
62	1	U2	CC2420 802.15.4 TRX	CHIPCON	CC2420
63	1	U3	FRACTUS SM ANTENNA	FRACTUS	UM_FR05_S1_N_0_001
64	1	Y1	32.768KWATCH CRYSTAL	C-MAC	XTAL002997
65	1	X1	8M QUARTZ CRYSTAL	C-MAC	XTAL003071
66	1	X2	16MHz QUARTZ CRYSTAL	C-MAC	XTAL003237
67	1	SEN1	ACCELEROMETER	MEASUREMENT SPECIA	ACH-01-04