Energy Management in Embedded Systems

Feasibility study

Name： Ziqin Tang , Wen Qi

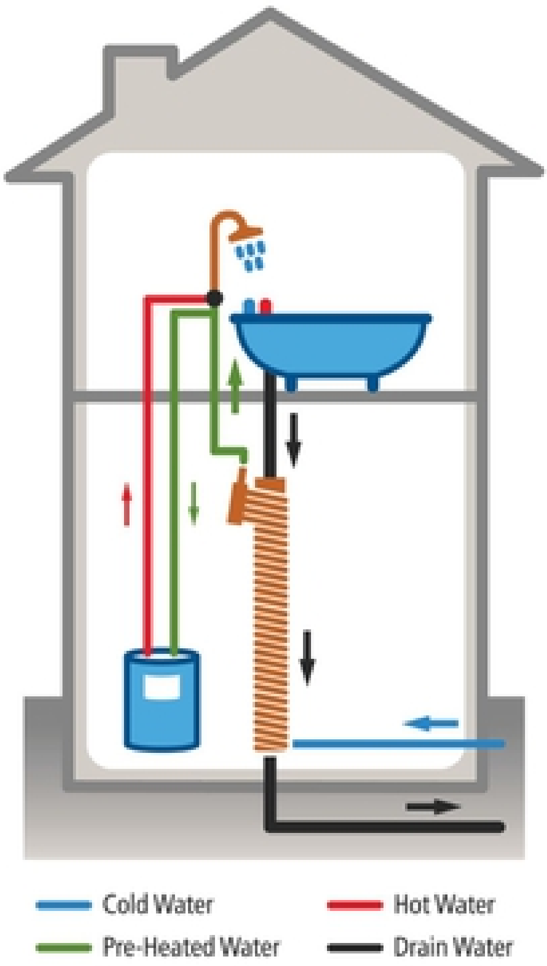
Catalog

Application requirements

In the hot water pipe temperature system, the environmental energy source is the waste heat of hot water. We combined its thermal gradient and ambient temperature for energy harvesting, thereby designing an energy-independent embedded system.

The system should be mobile, real-time and independent.
The temperature of the hot water in the hot water pipe should be kept above a certain temperature. Here, we set the threshold temperature to 80.
The temperature sensor is used to monitor the water temperature, which is maintained by the closed loop control system.

The communication of each component in the embedded system should be wireless so that the water temperature in the hot water pipe can be remotely monitored. The communication unit uses RF1000.
The function of the hot water temperature monitoring system is that the temperature sensor measures the water temperature and communicates wirelessly with the microcontroller unit (MCU), and the MCU processes the data. When the temperature is lower than the preset threshold, the heater heats hot water and raises the water temperature.



Hot water pipe system

Embedded System Architecture

Based on the requirements of the hot water pipe system function, we designed the following embedded system architecture, as shown in Figure 1.
In order to achieve the functions we require, the entire proposed architecture includes a temperature sensor, an MCU and two RF transceivers. The energy harvesting system serves as the energy source for the entire hot water pipe system, converting heat energy into electrical energy, and powering each component in the system.

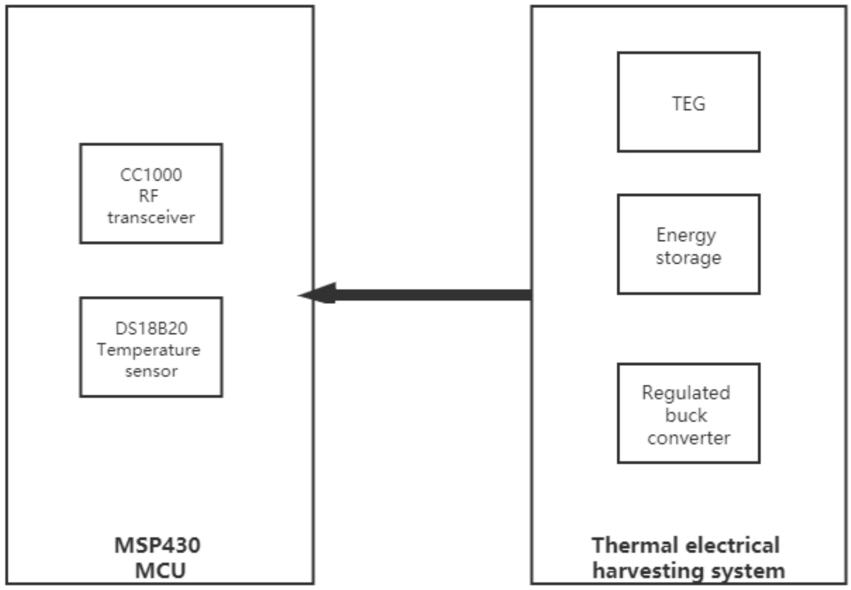


Figure1

Temperature sensor is DS18B20. The motivations of this choice are,

- Measures Temperatures from -55°C to +125°C (-67°F to +257°F) ±0.5°C Accuracy from -10°C to +85°C.
- The typical standby current(I_{DDS}) of DS18B20 is 750nA which means when the sensor is not working the required current is very low.
- When the sensor is working for measuring the temperature the entire active time(T_{active}) is almost 187.5ms with 10-bit resolution of temperature values.
- The DS18B20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. In addition, the DS18B20 can derive power directly from the data line (“parasite power”), eliminating the need for an external power supply.

Micro controller unit is MSP430. The motivations of this choice are,

- Low Supply-Voltage Range: 1.8 V to 3.6 V
- Ultra-Low Power Consumption
  – Active Mode: Approximately 100 µA/MHz;
  – Standby (LPM3 With VLO): 0.4 µA (Typical);
  – Real-Time Clock (LPM3.5): 0.25 µA (Typical);
  – Shutdown (LPM4.5): 0.02 µA (Typical).
- Ultra-Fast Wake-Up From Standby Mode in Less Than 1 µs
- MSP430 MCU offers superior integration and a wide range of high-performance analog and digital peripherals.

RF transceiver is CC1000.The motivations of this choice are,

- Low supply voltage (2.1 V to 3.6 V)
- Very low current consumption
- High sensitivity (typical -110 dBm at 2.4 kBaud)
- No external RF switch / IF filter required

- It is based on Chipcon's SmartRF® technology in 0.35 µm CMOS.
- Single port antenna connection
- It has Wake-on-radio functionality for automatic low-power RX polling.

Energy and power estimation

As we described before, the entire temperature monitoring system consists of a temperature sensor, MCU and RF transceiver.

The working process of the entire embedded system is that the temperature sensor detects the temperature and wirelessly transmits the information containing the temperature value to the MCU for processing. The wireless communication process relies on the wireless transceiver for sending and receiving.

In this hot water pipe temperature monitoring system, we assume that the cycle of the system is 5 minutes or 300 seconds, which means that the entire system works every five minutes. The sleep time indicating that the component is in standby mode is calculated from the cycle and active time.

There is usually an error in the value measured during the duty cycle. In order to reduce this error, we performed multiple sets of measurements on the water temperature and averaged the data through the MCU. Therefore, each duty cycle temperature sensor will test the temperature one hundred times.

I. DS18B20

V_{DD}(V)	I_{DD}(A)	I_{DDS} (A)	T_{active}(s)	T_{sleep}(s)
3	1×10^{-3}	7.5×10^{-7}	0.2	280

The energy consumption of active mode is :

$E_{active} = V_{DD} \cdot I_{DD} \cdot T_{active} = 3 \times 1 \times 10^{-3} \times 0.2 \times 100 = 6 \times 10^{-2}(J)$

The energy consumption of standby mode is :

$E_{standby} = V_{DD} \cdot I_{DDS} \cdot T_{sleep} = 3 \times 7.5 \times 10^{-7} \times 280 = 6.3 \times 10^{-4}(J)$

The total energy consumption of temperature sensor is:

$E_{total} = E_{active} + E_{standby} = 6.063 \times 10^{-2}(J)$

II. MSP430

V_{DD}(V)	I_{DD}(A/MHz)	I_{DDS} (A)	T_{active}(s)	T_{sleep}(s)	$T_{wake\text{-}up}$(s)	$Q_{wake\text{-}up}$ (nAs)
3	1×10^{-4}	4×10^{-7}	3.3×10^{-2}	296.7	7×10^{-6}	16.5

The energy consumption of active mode is :

$E_{active} = V_{DD} \cdot I_{DD} \cdot T_{active} = 3 \times 1 \times 10^{-4} \times 3.3 \times 10^{-2} \times 100 = 9.9 \times 10^{-4}(J)$

The energy consumption of standby mode is :

$E_{standby} = V_{DD} \cdot I_{DDS} \cdot T_{sleep} = 3 \times 4 \times 10^{-7} \times 296.7 = 3.56 \times 10^{-4}(J)$

The energy consumption of wake-up mode is :

$E_{wake-up} = V_{DD} \cdot Q_{wake-up} = 3 \times 1.65 \times 10^{-8} = 4.95 \times 10^{-8}(J)$

The total energy consumption of MCU is:

$E_{total} = E_{active} + E_{standby} + E_{wake-up} + E_{shut-down} = 1.346 \times 10^{-3}(J)$

III. CC1000

V_{DD}(V)	I_{DDS}(A)	I_{RX}(A)	I_{TX}(A)	T_{sleep}(s)	T_{RX}(s)	T_{TX}(s)
3	4×10^{-7}	5×10^{-3}	6×10^{-3}	299.9744	1.28×10^{-4}	1.28×10^{-4}

The energy consumption of transmitting is:

$E_{TX} = V_{DD} \cdot I_{TX} \cdot R_{TX} = 3\times6\times10^{-3}\times1.28\times10^{-4} = 2.304\times10^{-6}(J)$

The energy consumption of receiving is:

$E_{RX} = V_{DD} \cdot I_{RX} \cdot T_{RX} = 3 \times 5 \times 10^{-3} \times 1.28 \times 10^{-4} = 1.92 \times 10^{-6} (J)$

The energy consumption of standby mode is:

$E_{s\tan dby} = V_{DD} \cdot I_{DDS} \cdot T_{Sleep} = 3 \times 4 \times 10^{-7} \times 299.97 = 3.5996 \times 10^{-4} (J)$

The total energy consumption of CC1000 is:

$E_{total} = E_{TX} + E_{RX} + E_{s\tan dby} = 3.6418 \times 10^{-4} (J)$

This time we should know how much energy consumption for each component in the active time so that in this time the power of the system is supplied by capacitor.

$\mathrm{E} = E_{sensor} + E_{MCU} + E_{RF-transceiver} = 0.0626(J)$

- ## Energy Harvesting analysis

Thermal energy collection is the process of capturing thermal energy, which is waste energy that is emitted by engines, machines, and other sources or can be obtained and used for free from the environment. This thermal energy can then be converted into mechanical energy or electrical energy, or it can be used as a heat source to pre-heat water used in domestic or industrial processes.

Thermoelectric power generation relies on the Seebeck effect. Since the effect of semiconductor thermoelectric materials is much higher than that of metals, thermoelectric materials with practical value are all made of semiconductor materials.

The Seebeck effect means that different metal conductors have different free electron densities. When two different metal conductors are in contact with each other, the electrons on the contact surface will change from high concentration to Low concentration diffusion. The diffusion rate of electrons is proportional to the temperature of the contact area, so as long as the temperature difference between the two metals is maintained, the electrons can continue to diffuse and a stable voltage is formed at the other two ends of the two metals.

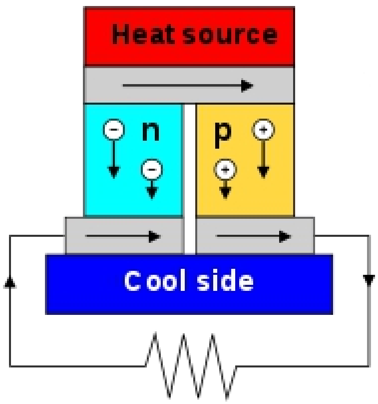


Figure 2

In the system of hot water pipe temperature detection, we use a small-sized sensor to detect the water temperature, which is powered by a small thermal energy harvester (TEH). TEH converts thermal energy into electrical energy by using a thermoelectric generator (TEG) made of thermocouples. In this case, we selected TG12-6-02 as the thermoelectric generation, which specification is 44mm × 40mm × 3.3mm and the resistance is 3.8Ω, Seebeck coefficience is 0.061V/K.

In figure 3 is showing equivalent electrical circuit of the thermal energy harvest.In this case, our assumed ambient temperature is about 25 °C (298K).

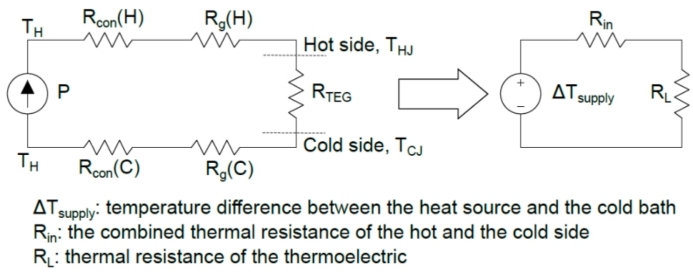


Figure 3

Electrical energy can be generated by the Seebeck effect, and thermocouples made of two different conductors are maintained at different temperatures, namely T_{CJ} and T_{HJ}, which produces a voltage proportional to the temperature difference (gradient) ΔT_{TEG}. Since the TEG is composed of n thermocouples, the open circuit voltage V_{oc} of the TEG is given as

$$V_{oc} = n\times S\times\Delta T_{TEG}= n\alpha(T_{HJ}-T_{CJ})$$

It can be observed that the TEG is connected to the hot water and cold ambient through the thermal contact and thermal grease resistances which are given by $R_{con(H)}$, $R_{g(H)}$and $R_{g(C)}$, $Rc_{on(C)}$respectively. Considering the relationship between all thermal resistances R_{Total} in the structure of the TEG and its own thermal resistance R_{TEG},

The actual temperature drops across the thermoelectric generator, ΔT_{TEG}, may then be expressed as

$$\Delta T_{TEG}=\Delta T\times \frac{R_{TEG}}{R_{Total}}$$

Then we can compute the voltage V_{oc} of the TEG.

$$V_{ocmax} = \alpha(T_{HJ}-T_{CJ}) =0.061\times (100-25)=4.575V$$

$$V_{ocmin} = \alpha(T_{HJ}-T_{CJ}) =0.061\times (25-25)=0V$$

Energy computation of the TEG :

$$E_{TEG}= E\times\frac{4}{3}=0.0626\times\frac{4}{3}=0.0835(J)$$

Storage Requirements

Capacitor with energy harvesting

In hot water pipe temperature detection system, we need the TEH wireless sensor node can long term deployment, to do that we select capacitor as an energy storage device to accumulate the input energy to sustain the operation of sensor throughout the lifetime and suitable for energy storage purpose.

When the energy-consuming module (sensor, MCU, RF) is in standby, the energy consumption is small, and the TEH supplies power to the storage capacitor at the same time. When the energy module works, there is a capacitor to supply power to it.

We need a voltage detection. When the voltage Uc across the capacitor is infinitely close to the voltage Voc of TEH, TEH stops supplying power to the capacitor, so a fully controlled device (such as IGBT) and a diode are needed. When Uc is less than Voc, TEH supplies power to both the capacitor and the energy consuming module.

We assume that DC-DC conversion has a very high efficient.

The entire system the total energy consumption of active in one period is 0.0626J, which is supplied by capacitor.

And the energy consumption of standby in one period is 34.23μJ which is supplied by TEH.

$W=P\times t=V_{DD}\times I\times t=V_{DD}\times Q_{consumption}$

$Q_{consuption}=0.0626J/3V\approx 0.021C$

- ## Conclusion

As mentioned earlier, we use the TEH system and related energy management circuits to convert the thermal energy of hot water waste heat into electrical energy, thereby powering the entire temperature monitoring system. TEG converts thermal energy into electrical energy and stores it in a capacitor, and then connects it to a boost circuit to provide a stable 3V voltage throughout the system.
The selection of components is very suitable for this system in terms of efficiency, power consumption and price.

In terms of energy consumption, through calculation, the energy consumption of the entire system is less than the energy collection of the energy harvesting system in a sampling period. The super capacitor can be stably charged when the system is in standby mode, and will continue to discharge while the system is running.

Therefore, in the hot water pipe water temperature monitoring system, by converting thermal energy into electrical energy, the entire system can be continuously operated without relying on an external power source.
The system design is feasible.