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ULTRA-LOW POWER MOTION-TRIGGERED IMAGE SENSOR FOR DISTRIBUTED WIRELESS SENSOR NETWORK

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Abstract

This paper describes a motion-triggered CMOS image sensor. It uses low resolution photosensor array with an ultra low power data converter in the read out circuit. The analog motion sensor shares the same photosensors using an interleaved structure. The motion sensor triggers the digital imager and RF data transmission to the base station in case there are objects moving in the scene, otherwise, the system remains standby to save power. This design is specially optimized for very low power applications such as distributed wireless sensor network.

Keywords

Low power, CMOS imager, motion sensor

INTRODUCTION

This paper describes the integrated electronic circuits of a generic sensor platform for a distributed wireless sensor network. The device is powered by on-board micro-batteries which are remotely rechargeable via microwave from the base station. Since the radiation regulation limits the maximum microwave power, the available power for the remote sensors is extremely low. In this paper, we focus on an ultra-low power motion triggered image sensor.

Fig. 1 presents the sensor module architecture. The power is provided by microwaves from the base station while a RF signal is used to send data to the base station. A DSP will be used to control the functioning of the whole sensor and the communication with the base station. A power management unit manages the power supply of the chips. The module is intended for any possible plug-in sensor. However, optical sensors are the most challenging elements in terms of power consumption and required transmission bandwidth. The total power budget is $100\mu\text{W}$. By optimizing the pixel and A/D converter design, we obtained a very low power digital 2-D image sensor which dissipates less than $35\mu\text{W}$. However, when the imaging acquisition and transmission is on, the DSP and RF part consume much more power, exceeding $100\mu\text{W}$ when certain data rate is required. Fortunately, for a security camera surveillance system, it is not necessary to keep the camera and RF data transmission on all the time, unless there are movements in the scene. So, when the scene is stationary, it is possible we turn off the digital camera system and go to standby mode. When the system is in acquisition mode, it is easy for the base station to send a command to the re-

mote sensor to enter standby mode when it finds that the scene is quiet. A low power motion sensor could act as a monitor and wake up other parts of the device when there are movements. We designed an analog motion sensor which shares the photo sensors with the digital imager using an interleaved structure. Since most of the time the scene is static the system can remain standby to save large portion of power. The designed motion sensor dissipates only $20\mu\text{W}$, which allows the device to transfer up to 80 percent of the microwave power to micro-battery for later usage. Besides lowering down the power consumption, it also reduces the amount of information to be transmitted, thus, reduces the total bandwidth requirement for RF communication.

Fig. 1. Motion triggered image sensor for distributed wireless sensor network

ARCHITECTURE OF MOTION TRIGGERED IMAGE SENSOR

Fig. 2 shows the interleaved structure for the motion sensing operation. An additional transistor is added into each pixel to set the operation modes. In acquisition mode, we sample each pixel frame by frame using a column/row selection circuit and a single ADC to obtain digitized data. In standby mode, the digital camera is off, and the added transistors are turned on to connect the photo current outputs to the motion sensor cells. We connect every other pixel in the even columns to the x-axis 1-D motion sensor array to detect horizontal motion, and connect every other pixel in the even row to the y-axis 1-D motion sensor array to detect vertical motion, respectively. A decision circuit compares the motion sensor output with a threshold to decide whether to turn on the system or not. Since the digital imager and the motion sensor are integrated on a single chip and share the same set of photosensors, only one set of

optical lenses is required to realize compact design. The picture shows only a 6 x 6 array as an example, but the actual demo image sensor contains a digital imager of 64 x 64 photodiodes and two 16 x 1 analog motion sensor array, with layout on a 2mm by 2mm mini-chip in TSMC 0.18 μ m process.

Fig. 2. Interleaved structure of combined digital imager and analog motion sensor

THE LOW POWER DIGITAL IMAGER

Fig. 3 shows typical structure of a passive pixel image sensor. The pixel array shares one charge amplifier which consume the largest portion of power in this architecture. To minimize the power, the proposed schematic is shown in Fig. 4. The entire array shares one single A/D converter and the charge amplifier is eliminated.

Fig.3. Passive pixel image sensor structure

Pixel design and readout circuit

Different from conventional solutions, this design uses a successive approximation A/D converter. As mentioned

before, the system measures the change resulting from the integration of the photo current in a storing capacitor C_s directly and does not require a charge amplifier. When a given pixel is selected, the charge on the storing capacitor is shared with the capacitors array of the successive approximation network. Since the storing capacitor equals the value of the entire SAR array, the signal is divided by two. In reality, if accounting for the parasitic effects, the final read voltage, V_x , is about half of the original voltage, V , stored in C_s . This relationship can be expressed as

$$V_x = V \frac{C_s}{2C_s + C_p},$$

where C_s is 0.4pF and C_p is the sum of the diode capacitance and 64 transistor diffusion-substrate capacitances. In this case, C_p is around 170fF, and the final read out voltage is 0.4 times of the original voltage stored in C_s . To make the ratio close to 0.5, larger C_s can be used.

Fig.4. Proposed sensor structure

The layout area of each pixel is 12 x 12 μ m². The photodiode are Nwell-Psub, single ring structure. This structure is chosen due to its better responsivity (measured from previously fabricated chip) and good isolation between the pixels [1]. Since the average photo current is around 0.7nA, the calculated power consumption of photodiodes of 64 x 64 array is 3.44 μ W.

Low power ADC

A significant fraction of the power consumption of image sensor array comes from the analog to digital interface. This chip as already mentioned does not require a charge pre-amplifier, while using a low power comparator in a conventional successive approximation (SA) converter. Fig. 5 shows the SA architecture. The comparator has zero DC current and uses capacitors instead of active loads. A charging/discharging process enables amplifying the input signal. Simulation shows it has 8-bit resolution, averaged

5.7 μW analog and 4.0 μW digital power consumption at 200 kHz conversion frequency.

Fig.5. Low power charge redistribution successive approximation converter

The schematic of comparator used into the ADC is shown in Fig 6. During Φ_1 , the two switches across C_1 and C_2 discharge the capacitors and bring the differential output to V_{DD} . The transistors controlled by Φ_2 keep the input pair off. During Φ_2 , the voltage V_b enables M3 and M4 to form cascode configurations with M1 and M2. Capacitors C_1 and C_2 are charged and the output voltages go down. M5 and M6 make a common mode feedback and control the quiescent current across the differential input. At a given point, the current goes to zero and the output voltages reach a steady value. A possible unbalancement of the input voltages leads to an amplified steady output difference. The outputs are then used to drive a latch controlled by the phase Φ_L . The power consumption of the pre-amplifier is $P_p = C_1 V_{DD}^2 f$. In our design $C_1=C_2=200\text{fF}$, $V_{DD}=1.5\text{V}$, $f=2\text{MHz}$, therefore, $P_p= 0.9\mu\text{W}$. The power required by the positive-feedback latch is 1.1 μW .

Fig.6. Low power comparator

The control logic is generated through successive approximate register (SAR [3]) by registering the comparator out-

put every bit cycle. Then, the binary weighted capacitor changed the V_A of the comparator.

Fig.7. Structure of SAR

Fig. 8 shows some simulated waveforms for the ADC. The difference between input signal and the common voltage ($V_{dd}/2$ in this architecture) is amplified about ten times by the preamplifier. (a) shows the preamplifier outputs. They dynamically change and they are suitable for controlling a positive feedback latch. (b) shows the latch outputs which are triggered by Φ_L . (c) shows the two inputs signal of the comparator in Fig 5. "B" terminal is kept constant and "A" terminal is changed by SAR according to the comparator output bit. Then the correct output bit is obtained from the SAR through an output buffer.

Fig.8. Simulation results for the ADC (a) output signals of preamplifier (b) output signals of latch (c) input signals of the comparator

Fig. 9 shows the response time of the positive-feedback latch stage. It takes about 4 ns to establish the logic signal with input difference 50mV. However, when the difference of two inputs is 1LSB, i.e. 4mV, the time will increase to 5 ns. And the reason that the latch stage in Fig. 6 is chosen is that the outputs of the pre-amplifier are always high in half time and gradually goes low in another half [4][5]. This schematic ensures that there is no static power consumption when the latch works in hold mode. When the latch is triggered, the logic level is achieved in 4ns, so it

only consumes power during the short switching time. An additional SR latch follows the latch shown in Fig. 6.

Fig.9. Response time of the comparator

Table 1 summarizes the simulated ADC performances. The total power consumption of the 2-D image sensor comes from the pixels (3.5 μ W), the ADC (9.5 μ W), the switching matrix (10 μ W) and the data decoder (10 μ W). Therefore, the estimated power consumption is 33 μ W.

Table 1. Specifications of the low power ADC

Sampling frequency	200kHz
Resolution	8bit
Process	0.18 μ m CMOS
Power supply	1.5V
Power consumption	5.672 μ W analog 4.007 μ W digital
Figure of Merit	0.189pJ/conversion

THE LOW POWER ANALOG MOTION SENSOR

CMOS motion sensor chips have been developed during the past 15 years [6][7][8][9][10]. Many visual chips detect motion by tracking the disappearance of an edge and its subsequent reappearing at neighboring pixel, using an edge detector. Typical design of the edge detector compares the concurrent signal with the temporally delayed version, or spatially smoothed version to find out edges. However, these approaches normally lead to active delay elements or filters, which require some of the transistors working in saturation region. A typical value of the power consumption per pixel of these motion sensors is about 50 μ W, thus, the power consumption for a 32x1 motion sensor array is about 1600 μ W. This is acceptable for most applications, but not for the RF powered distributed wireless sensor system which requires extreme low power operation. One solution to reduce the power is to use fewer pixels. However, very low resolution may decrease the spatial sensitivity, since the small area movements may not

necessarily cause obvious change of luminance for large area. In addition, when the sensor resolution is too low, it cannot distinguish whether a large area light density change is caused by the change of the environment luminance such as adjusting the brightness of a lamp or by motion.

To overcome these difficulties while keep the power consumption very low, a new motion detection method is proposed by detecting a moving edge. A static edge in the image is defined sufficient light density contrast between neighboring pixels; the moving of the edge is detected based on the change of the contrast between neighboring pixels. In this approach, the moving edge is detected by directly comparing the outputs of the neighboring pixels without using active delay elements or filter circuits to generate a second version of signal to compare with. As a result, this design largely reduces the power consumption by using simple static logic circuit.

Fig. 10 shows the architecture of the 1-D motion sensor. The edge detectors use the outputs from neighbor pixels to detect the moving edge. The detected moving edge pulses from different locations are then added up together by a pulse fusing circuit. The output of the fusing circuit drives the decision circuit to count the pulses by charging a capacitor. Then, the voltage on this capacitor is compared with a threshold voltage pre-set by the user. Once it reaches a certain voltage level, it means there are substantial movements in the scene so the motion sensor will output an 'enable' signal to trigger the digital image acquisition to start. A 1.5V power supply is used for all parts of the motion sensor.

Fig. 10. Motion detection and trigger circuit.

Motion edge detector

Fig. 11 shows the schematic of the edge detector. The photocurrent is applied to two cascaded diode-mode P-type MOSFETs to obtain log scale current-voltage mapping. Simulation shows it has 6 decades or 120dB of linear re-

sponse range (from 1pA to 1 μ A) with 205mV voltage drop per decade. A Hysteresis comparator is used to compare the neighboring pixel outputs. The Hysteresis shift voltage is $V_{sh}=\pm 10$ mV.

Fig. 11. Edge detector

If the output of the neighboring pixels as marked as 'a' and 'b', and the output of the comparator is marked as 'c', the motion detection algorithm is shown as Table 2.

Table 2. Motion detection algorithm

Previous inputs	Previous output	Current inputs	Current output	Motion edge
$a \leq b + V_{sh}$	C=low	$a > b + V_{sh}$	c=high	Yes
$a \geq b + V_{sh}$	C=high	$a < b + V_{sh}$	c=low	Yes
$a \leq b + V_{sh}$	C=low	$a \leq b + V_{sh}$	c=low	No
$a \geq b + V_{sh}$	c=high	$a \geq b + V_{sh}$	c=high	No

In this design with 205mv/decade current/voltage mapping and ± 10 mv hysteresis, the theoretical sensible contrast change for the detection of moving edges is 12%. However, the mismatch of the fabrication may cause the actual sensible contrast to increase. For example, assume that the maximum mismatch causes 10mv offset in pixel output, the worst case sensible contrast then increases to 25%. But since the mismatches are normally randomly distributed, some of the pixel sensitivities will drop while some others may even increase. Motion with contrast change lower than the hysteresis plus mismatch will not be detected. Looking into the algorithm in Table 2, we can also see that there will be possible edge missing in some conditions. For example, when 'a' is already larger than 'b'+ V_{sh} , and later on 'a' becomes even larger because of object moving, this motion will not be detected by the circuit because it causes no transient change at the comparator output. However, this is tolerable since the motion sensor has two 1-D arrays, and the motion is very likely to be caught at other points with different backgrounds. More complex algorithm could be developed to reduce the edge missing rate, however, tradeoffs with power consumption needs to be considered.

After the comparator, an NXOR based digital edge detector is used to convert each rising and falling edges of the comparator output to a single narrow pulse. The pulse width is tuned by adjusting the output impedance of the inverter and the load capacitor; in this design, it is 20ns.

Pulse fusion circuit and decision circuit

Fig. 12 shows the schematic of the pulse fusion and decision circuit. Most of the time the N-MOSFETs $m_1 \sim m_k$ controlled by the detected edge pulses are turned off so that the voltage on C_3 remains high. When a moving edge occurs, one of the N-MOSFETs $m_1 \sim m_k$ is turned on to discharge C_3 . C_3 will be recharged to high voltage when all m_1 to m_k are off. Since all the drain nodes of m_1 to m_k are connected together to C_3 , the pulses are fused into one pulse. However, since the charging process of C_3 is much slower than the discharging process, the pulse width on C_3 will be expanded compared with the original pulses. Then, a second digital pulse extractor is used to obtain a fixed width narrow pulse. This pulse extractor is similar to the one used previously, but, a NAND gate is used instead of NXOR gate for extracting the falling edges only. The obtained short pulse is fixed at 17ns pulse width. We use this pulse to control the step-by-step charging process of C_1 . C_1 can also be discharged by 'Clear' signal from the DSP to reinitiate the motion detection process. The PMOSFET and NMOSFET connected to C_1 are in cascode structure in order to reduce the leakage current when both the P-type and N-type MOSFETs are off and the charge on C_1 will be maintained for some time. The decision whether to wake up the digital imager is based on the comparison of the voltage on C_1 with a threshold voltage. The threshold voltage, V_{th} , is adjustable by user externally. It can be configured to ignore certain level of non-continuous or small scale motion by setting V_{th} higher than quiescent voltage across C_1 when no edges occur.

Fig. 12. Pulse fusion and decision circuit

Simulation results

Fig. 13 shows the simulation results. The first two plots of I_{01} and I_{02} are the light density of neighboring pixels. The time offset of the two inputs indicates movement of objects, which is detected as shown in the third plot of short

pulses named as 'MvEdge'. All the short pulses are added together by the fusing circuit. The fused pulses are used to charge the capacitor C_1 , the voltage across which is shown in the fourth plot, named 'storage'. It increases step by step. After the 'storage' voltage on the capacitor reaches the threshold, V_{th} , the output 'En' becomes high and trigger the digital camera, the DSP chip, and the RF driver to begin sampling and transmitting data.

The simulated average power consumption for two 16×1 motion sensor arrays is $0.506\mu\text{W}$ per cell at 100pA background photo current per pixel. And the pulse fusion/decision circuit cost $2.946\mu\text{W}$. Thus, the total power for the two 16×1 sensor is only $19.138\mu\text{W}$.

Fig. 13. Simulation results for the motion sensor

SUMMARY

This paper has presented a motion triggered ultra-low power CMOS image sensor containing two parts: digital imager and analog motion sensor. They share the same set of photosensors by an interleaved structure. Both the digital imager and the motion sensor are optimized for very low power consumption. The 64×64 pixel digital imager consumes less than $35\mu\text{W}$ at 200k sampling frequency, including a very low power AD converter which only needs $10\mu\text{W}$. The two 16×1 motion sensor arrays consume less than $20\mu\text{W}$ totally, which is much less than the typical work in the literature. The motion sensors act as a monitor when the system is standby and trigger the image acquisition and RF transmission when motion is detected.

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