TN1483

Technical note

SR5E1Ex line - ADC accuracy improvement

Introduction

This document describes the usage of the temperature sensor and of the bandgap voltage reference for monitoring and calibration purposes.

This design is intended for applications using the SR5E1Ex line products listed in the following table.

Table 1. **Device list**

Device	Part number
SR5E1Ex	SR5E1E3, SR5E1E7

1 Temperature sensor

1.1 Overview

The SR5E1Ex line products include an onboard temperature sensor (TSENS) that monitors device temperature and delivers two analog output signals and three digital output signals.

The analog outputs consist of two voltage signals:

- A voltage signal PTAT that is linearly increasing with the internal junction temperature, and it is proportional to absolute temperature.
- A voltage signal CTAT that is linearly decreasing with the internal junction temperature, and it is complementary proportional to absolute temperature.

The analog outputs CTAT and PTAT are respectively connected to the channels 13 and 14 of ADC1 and ADC5.

The three digital outputs, connected to the power management controller (PMC), are used to signal under- and overtemperature operating conditions. These signals notify the device to act to appropriately adjust the device temperature in response to an out-of-specification low- or high-temperature operating condition. The under and overtemperature thresholds are trimmed through calibration parameters determined during the factory test by sampling the two analog voltage signals PTAT and CTAT at predefined high and low temperatures.

The calibration parameters, listed in the Table 2, are stored during the production test in the UTEST flash memory.

For further details see the device’s reference manual (see the Appendix A.1 Reference documents).

Table 2. **Calibration constants**

Constant	Description
P1	PTAT output voltage code (converted by ADC) at 150 °C
P2	PTAT output voltage code (converted by ADC) at -40 °C
C1	CTAT output voltage code (converted by ADC) at 150 °C
C2	CTAT output voltage code (converted by ADC) at -40 °C

By converting the two analog outputs of the temperature sensor through the ADC1 or ADC5, the user can find out a constant reference code REFCODE, called digital bandgap voltage, which does not change with temperature.

1.2 Using TSENS voltages to measure the junction temperature

The junction temperature of the device can be calculated by the following formulas:

$$A = (P_X \times C2) - (C_X \times P2) \tag{1}$$

$$B = (C_X \times P1) - (P_X \times C1) \tag{2}$$

$$T = T2 + (A \times (T1 - T2)) \div (A + B) \tag{3}$$

Where $P1$, $P2$, $C1$, and $C2$ are the calibration constants listed in the Table 2, $T1$ = 150 °C, $T2$ = -40 °C, P_X and C_X are the PTAT and CTAT voltages codes (converted by ADC) at the junction temperature T.

This measure assumes that the device’s junction temperature T and the ADC voltage reference are constants during the conversions of PTAT and CTAT voltages.

1.3 Using TSENS voltages to measure the digital bandgap voltage

By converting the two analog outputs of the temperature sensor, the $REFCODE$ can be calculated by the following formula:

$$REFCODE = P_X + C_X \times (P2 - P1) \div (C1 - C2) \tag{4}$$

Where $P1$, $P2$, $C1$, and $C2$ are the calibration constants listed in the Table 2, P_X and C_X are the PTAT and CTAT voltages codes (converted by ADC). This measure assumes that the device's junction temperature T and the ADC voltage reference are constants during the conversions of PTAT and CTAT voltages.

Obviously, the $REFCODE$ is a function of the ADC voltage reference in-field (for the dependence of the P_X and C_X) and in production (for the dependence of the $P1$, $P2$, $C1$, and $C2$).

Moreover, the production $REFCODE_P$ is equal to the in-field $REFCODE$ and can be calculated using only the calibration parameters by the following formula:

$$REFCODE_P = P1 + C1 \times (P2 - P1) \div (C1 - C2) = P2 + C2 \times (P2 - P1) \div (C1 - C2) \tag{5}$$

1.4 Digital bandgap voltage accuracy

The accuracy of the digital bandgap voltage $REFCODE$ depends on the accuracy of the ADC and the accuracy of its voltage reference. In the same way, the accuracy of the calibration constants depends on the accuracy of the ADC and on the accuracy of its voltage reference during production testing.

Moreover, as mentioned before, the $REFCODE$ is temperature independent with the assumption that CTAT and PTAT voltages are converted at the same temperature. As a result, the CTAT and PTAT voltages must be converted one right after the other.

The typical accuracy of the bandgap voltage reference is A_{BGAP} = ±1.5% and the accuracy of the ADC is A_{TUE} = ±7LSB, that is, A_{TUE} = ±0.171%.

For further details see the device's datasheet (see the Appendix A.1 Reference documents).

The accuracy of the ADC voltage reference during production testing is typically A_{VREF} = ±0.025% with a production ADC voltage reference ADC_{VREFP} = 5 V.

As a result, the total error of the production $REFCODE_P$ can be calculated as:

$$ERR_{\pm} = ((100 \pm A_{BGAP}) \times (100 \pm A_{TUE})) \div (100 \pm A_{VREF}) - 100 = \pm 1.699\,\% \tag{6}$$

The accuracy could depend on the device as well as on configuration, so the following calculation is just an example. The final accuracy shall be calculated based on datasheet values for the specific device.

2 Usage of the digital bandgap voltage

2.1 Monitoring the ADC voltage reference

The voltage reference is common to all ADCs and it can be monitored by measuring the $REFCODE$ and comparing it with the expected one.

If the measured $REFCODE$ is not in the range $REFCODE_{EXP}$ ± TOL where $REFCODE_{EXP}$ is the expected $REFCODE$ and TOL is the accepted tolerance, the user can assume an issue with the ADC voltage reference.

Other types of ADC issues affecting the accuracy of the conversion can be detected by other mechanisms.

The expected $REFCODE_{EXP}$ could be calculated as:

$$REFCODE_{EXP} = REFCODE_P \times ADC_{VREFP} \div ADC_{VREFF} \tag{7}$$

Where ADC_{VREFP} is the production ADC voltage reference (typically 5 V ±0.025%) and ADC_{VREFF} is the in-field nominal ADC voltage reference.

For example, with the calibration constants $P1$ = 1780, $P2$ = 983, $C1$ = 741, and $C2$ = 1317, and the in-field nominal ADC voltage reference ADC_{VREFF} = 3.3 V ±5%, using the Eq. (5) and Eq. (7) user can calculate $REFCODE_P$, $REFCODE_{EXP\_MIN}$ and $REFCODE_{EXP\_MAX}$ as:

$$REFCODE_P = 1780 + ((983 - 1780) \div (741 - 1317)) \times 741 = 2805$$

$$REFCODE_{EXP\_MIN} = 2805 \times ((100 - 1699) \times (5 \div 3.3) \div (100 + 5)) = 3979$$

$$REFCODE_{EXP\_MAX} = 2805 \times ((100 + 1699) \times (5 \div 3.3) \div (100 - 5)) = 4550$$

As a result, the measured $REFCODE$ must be greater than the $REFCODE_{EXP\_MIN}$ = 3979 and lower than the $REFCODE_{EXP\_MAX}$ = 4550 otherwise the user can assume an issue with the ADC voltage reference.

2.2 Increasing the ADC accuracy

The accuracy of the converted values depends on the accuracy of the whole conversion path. In case the accuracy of the ADC voltage reference is lower than the accuracy of the bandgap voltage reference, a more accurate converted value can be calculated using the digital bandgap voltage.

Assuming the channel CH is converted, the proper CH_{VBGAP} code of the converted value can be calculated as:

$$CH_{VBGAP} = CH_V \times ADC_{VREFP} \div 2^{12} \times (REFCODE_P \div REFCODE) \tag{8}$$

Where CH_V is the code returned by the ADC conversion.

For example, with the calibration parameters $P1$ = 1780, $P2$ = 983, $C1$ = 741, and $C2$ = 1317, and the in-field voltage reference $\mathrm{ADC}_{\mathrm{VREFF}}$ = 3.3 V ±5%, assuming that the channel CH is connected to 1,65 V and that the ADC voltage reference has a negative error of 2%, the code returned by the ADC conversion CH_V and the measured voltage CH will be:

$$CH_V = 1.5 \times 2^{12} \div (3.3 \times (1 - 0.02)) = 2090 \tag{9}$$

$$CH = CH_V \times ADC_{VREFF} \div 2^{12} = 2090 \times 3.3 \div 4096 = 1.68484\,V \tag{10}$$

The error can be corrected using THE Eq. (8) as follow:

$$CH_{VBGAP} = 2090 \times 5 \div 3.3 \times 2805 \div 4337 = 2048 \tag{11}$$

$$CH_{BGAP} = 2090 \times 5 \div 2^{12} \times 2805 \div 4337 = 1.65006\,V \tag{12}$$

Where $REFCODE_P$ = 2805 is calculated using the Eq. (5) and $REFCODE$ = 4337 is calculated using the Eq. (4) with measured P_X = 1909 and C_X = 1755.

The accuracy of the measures depends on many factors, and this is an example assuming only an ADC voltage reference error.

3 Conclusion

The analog outputs (PTAT and CTAT) of the temperature sensor can be used to measure the junction temperature of the device and the bandgap voltage reference which can be used for multiple purposes as monitoring of the ADC voltage reference or increasing the accuracy of the ADC conversion results.

Appendix A Other information

A.1 Reference documents

Table 3. **Reference documents**

Doc name	ID	Title
DS13808	035656	SR5 E1 line of Stellar electrification MCUs — 32-bit Arm® Cortex®-M7 automotive MCU 2x cores, 300 MHz, 2 MB flash, rich analog, 104 ps 24 ch high-resolution timer, HSM, ASIL-D
RM0483	034781	SR5E1x 32-bit Arm® Cortex®-M7 architecture microcontroller for electrical vehicle applications

Revision history

Table 4. **Document revision history**

Date	Version	Changes
10-Aug-2023	1	Initial release.

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