AN13523

带硬件触发的LPC553x/LPC55S3x ADC及ADC计算工具

第1版—2022年4月20日 应用笔记

1 介绍

LPC553x/LPC55S3x MCU系列是EdgeVerse边缘计算平台的一部分，它建立在全球首个基于Cortex-M33的通用微控制器的基础上，由LPC5500系列推出。LPC553x/LPC55S3x使用一个16位模数转换器（ADC），这是一个双逐次逼近的ADC。该ADC允许进行差分16/13位分辨率和单端16/12位分辨率的操作。

本应用笔记介绍了LPC553x/LPC55S3x器件所具备的ADC功能，以及用于计算采样时间或源阻抗的附属工具。此外，还提供了一个示例来解释输入多路复用（INPUTMUX）模块，使用 CTimer 触发ADC转换来实现硬件触发功能。

目录

2 ADC的特性

ADC模块在ADC0和ADC1这两个实体上有以下性能特点：

- 线性逐次逼近算法
- 16位或13位分辨率的差分操作
- 16位或12位分辨率的单端操作
- 支持两个单端转换同时进行

有对于模拟输入通道的通道支持（多达20个通道），用于转换外部引脚和来自内部的输入源。它有可配置的模拟输入采样时间，以及速度选项以适应低功耗模式。它能够拥有多达4个具有不同优先级的触发源。

ADC模块支持三种不同的运行模式。

表1. 不同的运行模式

模式	说明
运行	正常运行
深度睡眠或睡眠	可以继续运行，只要Doze Enable位（CTRL[DOZEN]）被清零，并且模块使用在深度睡眠/睡眠模式下保持运行的外部或内部时钟源。
深度省电模式	Doze Enable（CTRL[DOZEN]）位被忽略，模块在确认进入深度省电模式之前，会等待当前传输完成所有待处理的操作。

3 ADC触发器的互连

ADC命令的执行由多达4个触发器源发起。每个触发器都可以通过向相应的SWTRIG[SWTn]位域写入0b1而由软件生成。或者，硬件触发器可以从模块外围的异步输入源生成。例如，我们可以使用PWM信号，来周期性地触发转换。当一个硬件触发输入被启用时，硬件触发事件在相关硬件触发源的上升沿检测到。每个触发源通过相关的优先级控制字段（TCTRLa[TPRI]）被分配一个优先级。每个触发源通过相关的命令选择字段（TCTRLa[TCMD]）与一个命令缓冲区相关联。

INPUTMUX为内部外设提供信号路由选项。一些外设的输入被多路复用到多个输入源。这些来源可以是外部引脚、中断、其他外设的输出信号或其他内部信号。

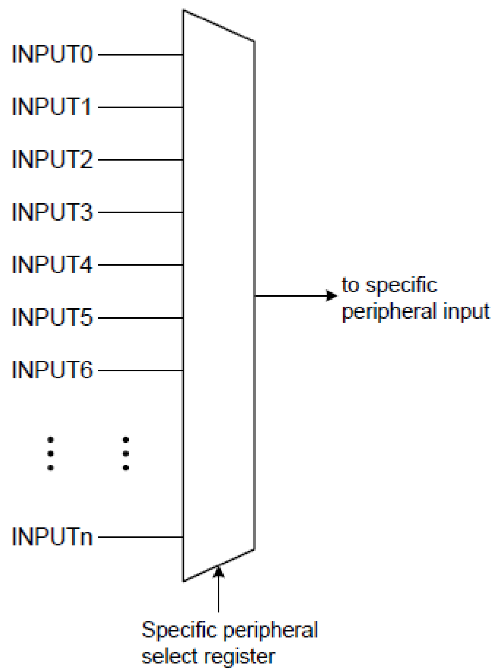

图1. 通用输入多路复用块

ADC在ADC0和ADC1两个实体中都有多种选择，以触发模拟转换。四个ADC0触发器输入连接可以从《LPC553x/LPC55S3x参考手册》的“ADCn触发器输入连接ADCn_TRIG0-ADCn_TRIG3”部分的列表中选择。本文重点讨论如何将CTimer用作触发器。

000101 - T0_MAT3

000110 - T1_MAT3

000111 - T2_MAT3

001000 - T3_MAT3

001001 - T4_MAT3

图2. ADC0的CTimer触发器选项

4 ADC CTimer示例

在这个示例中，设置了以下3个模块：ADC、CTimer和INPUTMUX。本示例是在SDK 2.10.2版本中使用MCUXpresso 11.4.1创建的。

尽管没有必要为CTIMER指定一个外部引脚，但在这个例子中，为了验证CTIMER的行为，使用了PIO1_22。此外，ADC0使用一个外部引脚来测量一个外部模拟源。本示例的简单框图如下所示。

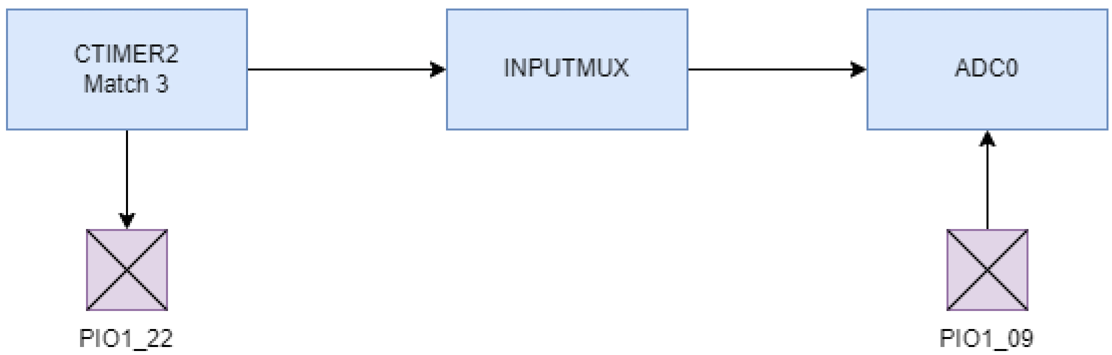

图3. ADC CTimer互连的示例

ADC的配置方式如下。

ADC的输入频率为5.7 MHz，与配置为45.8 MHz 的PLL0时钟相连。建议使用低频率来执行校准流程。选择128个ADC转换，这些转换的平均数用于计算每个校准值。选择更高的平均数可以在完成校准后获得更精确的转换。ADC模拟电路预先启用并准备好执行转换，没有启动延迟（以较高的直流电流消耗为代价）。参考电压是VDDA引脚上的电压。

```
/*Attaching low frequency clock from PLL for calibration purposes: ADC0 Frequency at 5.7MHz*/
CLOCK_SetClkDiv(kCLOCK_DivAdc0Clk, 0U, true);            /*!< Reset ADC0CLKDIV divider counter and halt it */
CLOCK_SetClkDiv(kCLOCK_DivAdc0Clk, 8U, false);           /*!< Set ADC0CLKDIV divider to value 8 */
CLOCK_AttachClk(kPLL0_to_ADC0);                 /*!< Switch ADC0 to PLL0 */

/* Disable VREF power down */
POWER_DisablePD(kPDRUNCFG_PD_VREF);

LPADC_GetDefaultConfig(&mLpadcConfigStruct);
mLpadcConfigStruct.enableAnalogPreliminary = true;
mLpadcConfigStruct.referenceVoltageSource = kLPADC_ReferenceVoltageAlt3;
mLpadcConfigStruct.conversionAverageMode = kLPADC_ConversionAverage128;
LPADC_Init(DEMO_LPADC_BASE, &mLpadcConfigStruct);
```

图4. ADC配置

一旦自动校准完成，你可以为ADC选择一个更高的频率时钟。在这个例子中，我们使用 48 MHz。为与A端相关的通道0设置了使用高分辨率转换的命令配置。选择模拟信号ADC0IN0A进行转换，使用引脚PIO1_9作为ADC输入引脚。每个ADC命令独立地进行通道和转换类型选择。在本例中，选择了单端操作。也可以转换为差分模式，但只有有限的“对”可以被设置为差分通道。请参考LPC553x/LPC55S3x参考手册中的可用引脚配对。此外，触发配置被设置为硬件触发，因为我们正在使用另一个模块的信号来触发ADC转换。

```c
/* Set conversion CMD configuration. */
LPADC_GetDefaultConvCommandConfig(&mLpadcCommandConfigStruct);
mLpadcCommandConfigStruct.channelNumber = 0U;
mLpadcCommandConfigStruct.sampleChannelMode = kLPADC_SampleChannelSingleEndSideA;
mLpadcCommandConfigStruct.conversionResolutionMode = kLPADC_ConversionResolutionHigh;

LPADC_SetConvCommandConfig(DEMO_LPADC_BASE, DEMO_LPADC_USER_CMDID, &mLpadcCommandConfigStruct);

/* Set trigger configuration. */
LPADC_GetDefaultConvTriggerConfig(&mLpadcTriggerConfigStruct);
mLpadcTriggerConfigStruct.targetCommandId       = 1U;
mLpadcTriggerConfigStruct.enableHardwareTrigger = true;
LPADC_SetConvTriggerConfig(DEMO_LPADC_BASE, 0U, &mLpadcTriggerConfigStruct); /* Configurate the trigger0. */
```

图5. LPADC CMD和触发器配置

CTimer的配置方式如下：

CTimer的输入频率是 96 MHz。从ADC0实例可用的触发器选项中，我们可以配置任何CTimer0 - CTimer4 Match 3信号，在本例中，使用CTimer 2 Match 3。它被配置为计时器模式，使用每个APB总线时钟向上计数。计数器在每次匹配后被复位，并以1 kHz的频率切换输出。没有必要启用CTimer的中断，因为我们是将信号附加到ADC的触发器上。然而，如果有必要改变CTimer的匹配值或其他设置，你可以为可能需要的额外操作启用一个中断。

```c
/* Use 96MHz clock for CTimer2*/
CLOCK_SetClkDiv(kCLOCK_DivCtimer2Clk, 0u, false);
CLOCK_SetClkDiv(kCLOCK_DivCtimer2Clk, 1u, true);
CLOCK_AttachClk(kFRO_HF_to_CTIMER2);

CTIMER_GetDefaultConfig(&config);

CTIMER_Init(CTIMER, &config);

/* Configuration 0 */
matchConfig0.enableCounterReset = true;
matchConfig0.enableCounterStop  = false;
matchConfig0.matchValue         = CTIMER_CLK_FREQ / 2000;
matchConfig0.outControl         = kCTIMER_Output_Toggle;
matchConfig0.outPinInitState    = false;
matchConfig0.enableInterrupt    = false;

CTIMER_SetupMatch(CTIMER, CTIMER_MAT3_OUT, &matchConfig0);
CTIMER_StartTimer(CTIMER);
```

图6. CTimer配置

INPUTMUX的配置方式如下：

INPUTMUX模块在附加适当的信号之前，需要被初始化。在本例中，我们使用CTIMER2 Match 3信号来触发ADC0实例。

```c
INPUTMUX_Init(INPUTMUX);
INPUTMUX_AttachSignal(INPUTMUX, 0U, kINPUTMUX_Ctimer2M3ToAdc0Trigger);
```

图7. INPUTMUX配置

通过检查CTimer的外部引脚（PIO1_22，位于LPC55S36-EVK的接头J10引脚9处），可以验证信号是否如预期的那样有效工作。它以1 kHz 的速率切换。如前所述，每个ADC转换是在CTimer波形的上升边缘触发的，如下图所示。下图中的三个蓝色箭头表示ADC0被触发的上升边缘。

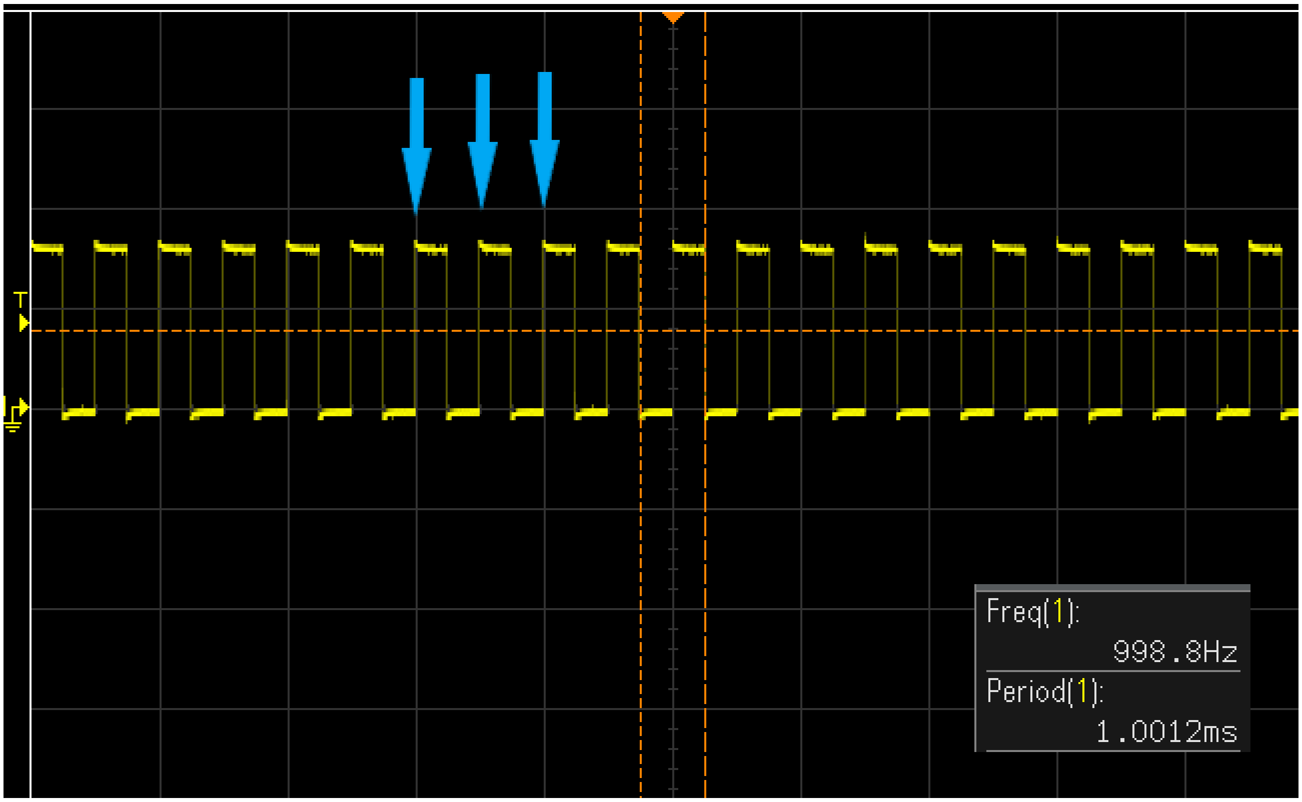

图8. 通过外部引脚显示的CTimer匹配率

下图是测量3.3 V时的ADC结果示例。我们应该期望终端窗口中显示的16位分辨率的最大值，在本例中是65535。要更改转换值，请更改LPC55S36-EVK上的J7接头，引脚PIO1_9上的电压。

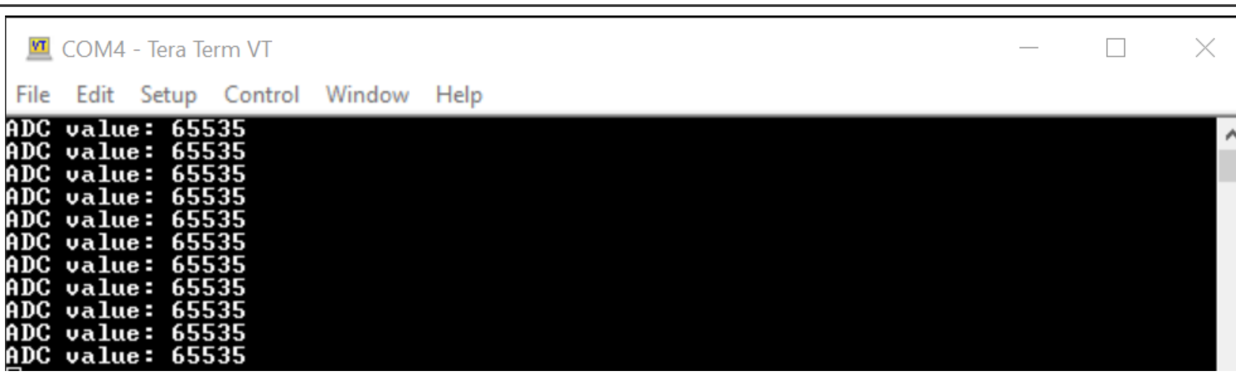

图9. 从测量3.3V源显示的打印结果

5 ADC计算工具

本应用笔记所附工具的目的是根据输入信号的阻抗特性，定义可以实现的最大采样率。为了准确地对输入电压进行采样，必须适当地选择源电阻和ADC采样时间。对于一个固定的源电阻（R_{AS}），所需采样时间为：

$$\min t_{SMP} = B \times [R_{AS} \times (C_{AS} + C_P + C_{ia}) + C_{ia} \times (R_{AS} + R_I)]$$

$$B = -\ln\left(\frac{LSB_{ERR}}{2^N}\right)$$

N - ADC分辨率，即13位和12位模式为12，16位模式为16。

LSB_{ERR} - LSBs中可接受的采样误差值，即在 ¼ LSB精度内采样。

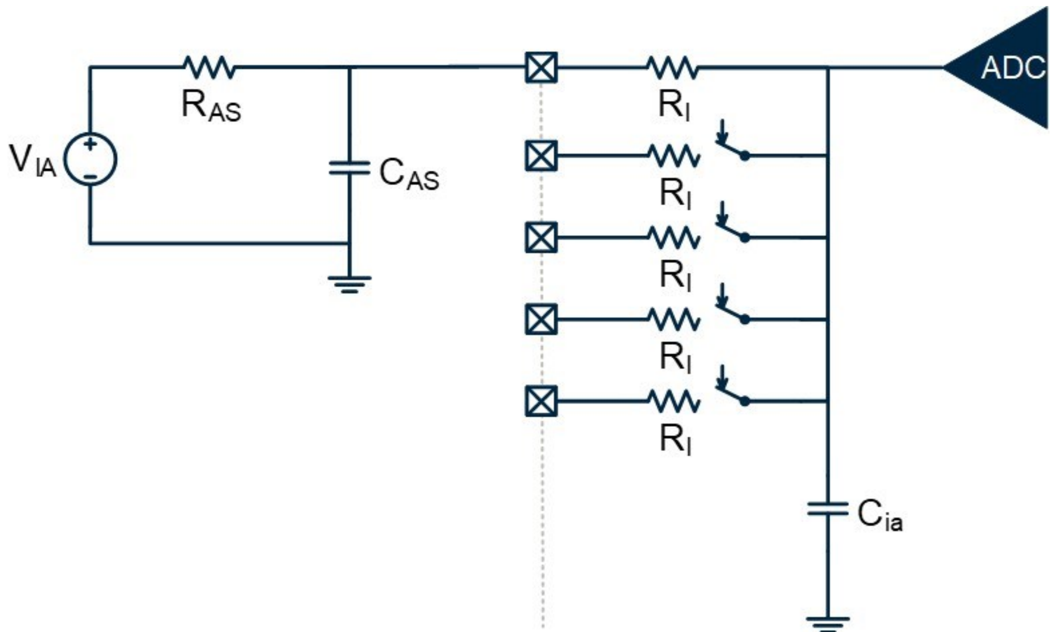

图10. ADC简单电路图

其中B是根据所选采样误差调整后的分辨率。用户配置的采样时间由ADC输入时钟频率（F_{ADCK}）和ADC命令寄存器中的采样时间选择（STS）位决定，后者选择采样周期的数量。当STS被编程为非零值时，采样时间为（3 + 2^{STS}）ADCK周期。最短的采样时间最大限度地提高了低阻抗输入的转换速度。延长采样时间可以对较高阻抗的输入进行精确采样。

$$user\ t_{SMP} = \frac{user\ STS}{f_{ADCK}}$$

用户$_{STS}$ 是采样时间内的ADC时钟周期数，可编程为3、5、7、11、19、35、67或131个ADCK周期（用户$_{STS}$ ≥ min $_{STS}$），它取决于在寄存器CMDHn[STS]中选择的值。用户 t_{SMP} 必须被配置为大于或等于min t_{SMP} 。如果我们设置用户t_{SMP} > min t_{SMP}，并求解R_{AS}，我们可以找到最大的源电阻，使我们能够以期望的精度进行采样：

$$R_{AS} < \frac{\frac{user\ STS}{f_{ADCK} x B} - (R_I x C_{ia})}{C_{AS} + C_P + 2C_{ia}}$$

表2. ADC采样时间计算器

ADC min Sample Time t_{SMP}		
min sample time based on a fixed R_{AS}		
Input... enter yellow highlighted cells		
Resolution	16	bits
C_{AS}	100E-12	F
R_{AS}	5.0E+3	Ω
LSB_{ERR}	1/8	LSB
C_P	3E-12	F
Cia	4E-12	F
B	13.17	

	$R_I(\Omega)$	min t_{SMP}
High Speed		
V_{REFP} = 1.8V	1.6E+3	7.39E-6
V_{REFP} = 3.0V	1.1E+3	7.37E-6
Standard Muxed		
V_{REFP} = 1.8V	3.2E+3	7.48E-6
V_{REFP} = 3.0V	1.8E+3	7.40E-6
Standard Dedicated		
V_{REFP} = 1.8V	300	7.33E-6
V_{REFP} = 3.0V	300	7.33E-6
Internal		
V_{REFP} = 1.8V	1.9E+3	7.41E-6
V_{REFP} = 3.0V	1.1E+3	7.37E-6

这个工具的第一部分如左图所示，该表规定了固定的R_{AS}所需采样时间。

用户可以输入源电阻、源电容（均为外部元件）、分辨率和ADC的LSB中可接受的采样误差值（LSBERR）。

LPC553x/LPC55S3x 数据表中提供以下数值：

C_P – 焊盘/封装的寄生电容

C_{ia} – 输入电容

R_I – 输入电阻

表3. ADC采样频率和R_{AS}计算器

ADC Conversion Time CT and R_{AS} Calculator					
To calculate maximum R_{AS} with given sample time and ADC input clock frequency					
Input... enter yellow highlighted cells					
Resolution	12	bits	Sample Time Select	131	ADCK
C_{AS}	1E-9	F	Hardware Average	1	
ADC Source CLK	100E+6	Hz	Power Select	high power	
ADCnCLKDIV[DIV]	3				
LSB_{ERR}	1/2	LSB			
C_P	3E-12	F			
C_{ia}	4E-12	F			
B	9.01				
f_{ADCK}	33E+6	MHz	max f_{ADCK}	60.0E+6	MHz

	R_I (Ω)	min STS	user STS	user t_{SMP}	max R_{AS}	CT	Msps
High Speed							
V_{REFP} = 1.8V	1.6E+3	5	131	3.9E-6	426.7E+0	4.4E-6	0.23
V_{REFP} = 3.0V	1.1E+3	5	131	3.9E-6	428.7E+0	4.4E-6	0.23
Standard Muxed							
V_{REFP} = 1.8V	3.2E+3	5	131	3.9E-6	420.4E+0	4.4E-6	0.23
V_{REFP} = 3.0V	1.8E+3	5	131	3.9E-6	425.9E+0	4.4E-6	0.23
Standard							
V_{REFP} = 1.8V	300	5	131	3.9E-6	431.9E+0	4.4E-6	0.23
V_{REFP} = 3.0V	300	5	131	3.9E-6	431.9E+0	4.4E-6	0.23
Internal							
V_{REFP} = 1.8V	1.9E+3	5	131	3.9E-6	425.6E+0	4.4E-6	0.23
V_{REFP} = 3.0V	1.1E+3	5	131	3.9E-6	428.7E+0	4.4E-6	0.23

工具的下一部分，可以根据所使用的采样时间和ADC频率提供最大源电阻。

和上部分一样，用户可以根据他们正在处理的参数改变黄色单元格。

以下是计算器工具中给出的一些其他参数。

F_{ADCK} – 输入时钟频率

CYC_{SMP_MIN} – 所需的最小采样周期 T_{SMP} > T_{SMP_REQ}

CYC_{SMP_USER} – 用户使用CMDHn[STS]设置的采样周期

T_{SMP} – 用户设置的采样时间

6 ADC的基本概念

分辨率：ADC数字输出中代表模拟输入信号的位数。对于LPC553x/LPC55S3x，分辨率可以配置为12、13和16位分辨率。

参考电压：ADC需要一个参考电压，用于与模拟输入进行逐次逼近比较，以产生一个数字输出。数字输出是模拟输入相对于该参考电压的比率。

$V_{REF} = V_{REFH} – V_{REFL}$

其中：V_{REFH} = 高参考电压 V_{REFL} = 低参考电压

ADC的输出公式：ADC的转换公式用于计算对应于特定模拟输入电压的数字输出。这个公式假设了一个理想的A/D转换，没有引入误差。

ADC数字输出 = 2^N 模拟输入电压/参考电压

*N = ADC 分辨率 。对于LPC553x，分辨率可以是*12/13/16

最小有效位（LSB）：最小有效位（LSB）是一个电压单位，等于ADC的最小分辨率，即导致数字输出变化的最小增量电压。LSB等于参考电压除以ADC的最大计数:

$LSB = V_{REF} / 2^N$

N = ADC分辨率

V_{REF} = 模拟参考电压

ADC的实际转换功能：ADC将输入电压转换为相应的数字代码。描述这一行为的曲线是实际转换功能所形成的曲线，包括ADC模块本身固有的所有误差。

ADC的理想转换功能：在ADC理想的转换功能情况下，假设它是完全线性的，或者说，无论输入电压的初始水平如何，给定的输入电压变化都会在转换代码中产生相同的变化。

7 ADC测量的误差来源

本节介绍一些妨碍ADC进行准确A/D测量的典型因素。

参考电压噪声：ADC的输出与模拟输入电压和参考电压成正比。不稳定的参考电压（例如，由供电电压引起的噪声）会导致转换后的数字输出的变化。例如，参考电压为5V，输入电压为1V，使用ADC输出公式，12位的分辨率可以得到819。随着绝对参考电压增加50 mV（即 V_{REF} = 5.05 V），同样的1 V输入电压的新转换值是811。由此产生的参考电压噪声误差为811-819 = - 8 LSB。

模拟输入信号的噪声：模拟输入信号中微小但高频的变化有可能在ADC采样时间内造成大的转换误差。噪声可能是由周围电气设备的电磁辐射引起的（EMI噪声）。因此，转换精度会受到负面的影响。如果输入信号中存在的噪声高于1LSB，这就实际上减少了转换结果中的可靠位数，因为最小有效位会因信号变化而不断变化。

模拟信号源电阻：模拟信号源的阻抗或信号源与输入引脚之间的串联电阻（RIN），由于流入引脚的电流，会导致电压下降。

温度影响：系统温度对ADC精度影响较大，主要是造成偏移误差漂移和增益误差漂移。ADC参考电压也会随着温度的变化而变化。这些误差可以通过调整微控制器固件来补偿，如监测内部带隙电压以验证参考电压没有变化，或当超出应用的温度范围时对系统进行特性分析以说明误差。

8 参考资料

- LPC553x/LPC55S3x 参考手册

- LPC553x/LPC55S3x 数据表
- LPC553x/LPC55S3x 勘误表
- LPC55(S)xx微控制器的硬件设计指南（文件AN13033）

9 修订历史

表4是修订历史表。

表4. 修订历史

版本号	日期	实质性变更
1	2022年4月20日	更新的ADC 计算工具
0	2022年2月2日	初版发布

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