Tamper Detection Using Low-Memory MSP430™ MCUs

Introduction
Security threats come in many forms and vary widely in their goals. They may include attempting to trick a sensor into collecting incorrect data such as for electronic meters or trying to open a secure location to gain access to proprietary hardware or information. This tampering can take many forms including applying heat or magnetic fields from the outside of a system to alter measurements or physically opening an enclosed container.

Properly enabled physical tamper detection can trigger defensive measures when an attacker is attempting to obtain or modify secure assets for unintended purposes. Some defensive measures after tamper detection include sounding an alarm, deleting sensitive data, or making a unit inoperable until a trusted source can repair it.

This document focuses on detecting when a secured enclosure is opened. The described system provides tamper detection and evidence, and typically is used as the first line of defense in system applications. Use cases could include detecting if a product (for example, meters, thermostats, or e-locks) was opened, and tamper evidence could be used for warranty voidance or further investigation. More information on security threats, physical attacks, and typical measures can be found in System-Level Tamper Protection Using MSP MCUs.

Open/close tamper detection has been implemented using different strategies in the past. Buttons may be placed along the edge of a box opening that are held pressed when the box is closed. However, due to the mechanical nature of the buttons, they may become stuck and fail to trigger when a box is opened.

Inductive sensors placed along the hinge next to a magnet or metal object, can measure a changing inductance when the box is opened, triggering detection. Externally applying a magnetic field may be able to fool the sensor when the box is opened.

The method outlined in this document implements open/close tamper detection by outputting a clock signal from a microcontroller (MCU) pin, reading the outputted signal into a separate input pin of the MCU, and counting the number of edges on the incoming signal over a consistent period of time. A real-time clock (RTC) can be used to set the time interval over which the number of edges is counted. If the signal is disconnected for any extended period of time, tampering has occurred, and the count at the end of a time interval will be incorrect. The value on a separate pin can then be toggled to signal the host processor to take defensive action. Because code does not always execute at the same speed, there will be a small variation to the actual counted value over the time interval that is unrelated to tampering. Therefore, a tolerance should be added when the value is checked to avoid indicating a false tampering event. The RTC and outputted signal should be clocked from the same source so clock inconsistencies will affect both in the same way and reduce the amount of tolerance needed.

The MSP430FR2000 MCU contains an RTC that can be sourced by an auxiliary clock (ACLK) and is able to output the ACLK on a pin. Additionally, the MCU has GPIOs available to count the edges of the clock signal and raise an alert signal to a host processor. The MCU is also able to overwrite persistent variables in FRAM to delete sensitive data in response to a tampering event. This project has been optimized to minimize the likelihood of missing a tampering event or triggering a false warning for the method described as well as fit within the 0.5 KB of memory in the MCU. To get started, download project files and a code example demonstrating this functionality.

More information about MSP security features can be found in Understanding MSP430 MCU Security Features Overview and MSP Code Protection Features.

Implementation
This application uses the MSP430FR2000 MCU with the MSP-TS430PW20 target development board. The MCU firmware implements the tamper detection strategy described in the introduction. It is possible to customize the clock source and count time interval to better suit the system according to the designer’s needs.

Pin P1.1 outputs the ACLK signal and pin P1.0 counts the number of edges. Pin P2.0 is initially set to 0 when the MCU is powered on and, if a tamper event is detected, pin P2.0 is raised from 0 to 1. The value of P2.0 is set to 1 only during the time period after an interval in which the count was incorrect. If the count is correct in a following time period after an incorrect interval count, the value of P2.0 will toggle back from 1 to 0. External oscillator circuitry may be added to P2.6 and P2.7 to improve clock accuracy. Figure 1 shows an example of how the tamper detection hardware could be implemented in a system. The ACLK signal
runs to the edge of the hatch and crosses the boundary with interlaced copper fingers or a similar mechanism. When the box is opened, the copper separates, and the ACLK signal disconnects, triggering detection. Care should be taken when designing the system to ensure the external oscillator and ACLK lines are not easily accessible from the outside of the box.

Figure 1. Hardware Connection Diagram

The MCU RTC is timed by ACLK which is clocked by reference oscillator (REFO) (32.768 kHz) by default. Additionally, an external crystal oscillator can be used by configuring the macros at the top of the source code. If an external oscillator is used, EXT_OSC should be changed to 1 and ACLK_FREQ should equal the external oscillator frequency.

There are also macros defining the time period (in seconds) for which the count is checked. The time interval should be entered as a multiple of a minimum fraction of whole numbers next to CHECK_TIME (for example, 1/2048, 1/8, 3/16, 1, or 75/32). The minimum fraction value is dependent on the RTC prescaler defined in RTC_DIV and RTCCTL. RTC_DIV and the RTC prescaler value should always match each other. RTC_DIV is set at the top of the code in a macro, and the RTC prescaler is set in RTCCTL in the main program. Figure 2 shows where the macros are located at the top of the code, and Figure 3 shows how to set RTCCTL in the main program.

Figure 2. Macro Configuration

CHECK_CYCLES is the calculated number of clock cycles the RTC should count down to match the time period set in CHECK_TIME. CHECK_COUNT is the ideal value that the count for each time interval should match and depends on ACLK_FREQ and CHECK_TIME.

Table 1 summarizes the macro values for each RTC prescaler choice. System designers interested in responding quickly to a tamper event can choose to set the macros to correspond to the values in the row for RTCPS__16.

Table 1. Standard Macro Values for Different RTC Prescalers

<table>
<thead>
<tr>
<th>RTCCTL</th>
<th>RTC_DIV</th>
<th>Minimum Time Interval</th>
<th>Maximum Time Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fraction</td>
<td></td>
</tr>
<tr>
<td>RTCPS__1024</td>
<td>1024</td>
<td>1/32 s (31.25 ms)</td>
<td>2048 s (≈34 minutes)</td>
</tr>
<tr>
<td>RTCPS__256</td>
<td>256</td>
<td>1/128 s (7.81 ms)</td>
<td>512 s (≈8.5 minutes)</td>
</tr>
<tr>
<td>RTCPS__64</td>
<td>64</td>
<td>1/512 s (1.95 ms)</td>
<td>128 s (≈2 minutes)</td>
</tr>
<tr>
<td>RTCPS__16</td>
<td>16</td>
<td>1/2048 s (0.49 ms)</td>
<td>32 s</td>
</tr>
</tbody>
</table>

The value of UPPER_TOL and LOWER_TOL sets how much the count may differ from the ideal value and can also be adjusted, as needed, to avoid triggering false tamper warnings.

The system clock is set to 16 MHz so that the firmware can respond to the RTC and port interrupts as quickly as possible.
When the firmware is loaded onto the MCU, the persistent variable called secureData is loaded with value 0xC0DE4B1D into FRAM to act as sensitive data. The first time a tamper warning occurs, the firmware erases the stored value, and the value remains erased even after device reset until the firmware is reloaded onto the MCU. Figure 4 and Figure 5 show the MCU memory before and after the erase occurs.

![Figure 4. Protected Data Stored in FRAM](image1)

![Figure 5. Protected Data Erased From FRAM](image2)

**Performance**

The feature uses an MSP430FR2000 MCU. To run the demo, connect the hardware as previously described, load the code into the device, allow the device to run, and end the debug session. For demonstration purposes, the Warn signal was connected to an LED so that it would light up when a tamper event is detected.

For the host processor to respond quickly to a tamper event, the RTC prescaler was set to 16 and the time interval was set to 1/2048 s. During testing, it was discovered that the count variable was very consistent except for the first time interval. This is reasonable behavior because during initialization the RTC and GPIO input interrupts must be enabled in different commands, making the count differ from subsequent time intervals after both are enabled. Therefore, a flag variable was created to ignore the first time interval. The subsequent time intervals had the following range:

\[
\text{CHECK\_COUNT} - 1 \leq \text{count} \leq \text{CHECK\_COUNT} + 1
\]

UPPER\_TOL and LOWER\_TOL were set to 1 and the above inequality was implemented in the firmware count check. Because the count signal is sourced by a clock with a frequency of 32.768 kHz and the tolerance allows for a discrepancy of up to 3 counts, the firmware is able to detect if the signal is disconnected for more than 46 µs and alert the host processor with a delay of no more than 490 µs. The maximum delay to the host processor will match the CHECK\_TIME interval.

Tamper detection can be further improved by outputting randomly generated sequence on P1.1, instead of the ACLK. Additionally, the outputted signal could be read on more pins than P1.0 to allow for more crossings along the box hatch. Testing should be performed by system designers to ensure that the interrupts can respond quickly enough to changing input on multiple pins and no false tampering events are triggered. Using the RTC, timestamps could be generated and written to FRAM each time a tampering event is detected to indicate when they occurred.

**Device Recommendations**

The device used in this example is part of the MSP430 Value Line Sensing portfolio of low-cost MCUs, designed for sensing and measurement applications. This example can be used with the devices shown in Table 2 with minimal code changes. For more information on the entire Value Line Sensing MCU portfolio, visit [www.ti.com/MSP430ValueLine](http://www.ti.com/MSP430ValueLine).

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Key Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSP430FR2000</td>
<td>0.5KB FRAM, 0.5KB RAM, eComp</td>
</tr>
<tr>
<td>MSP430FR2100</td>
<td>1KB FRAM, 0.5KB RAM, 10-bit ADC, eComp</td>
</tr>
<tr>
<td>MSP430FR2110</td>
<td>2KB FRAM, 1KB RAM, 10-bit ADC, eComp</td>
</tr>
<tr>
<td>MSP430FR2111</td>
<td>3.75KB FRAM, 1KB RAM, 10-bit ADC, eComp</td>
</tr>
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