Enabling noise-tolerant capacitive-touch HMIIs with MSP CapTIvate™ technology

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Introduction

Capacitive touch as a human-machine interface (HMI) technology is finding its way into more and more applications each year. It is rapidly becoming a popular technology for mechanical button replacement in end equipment such as small and large home appliances, industrial control panels and automotive center stacks. While the technology offers designers new freedoms in how they can differentiate their products via the user interface, it also presents new challenges. The challenges arise from the fact that these markets often share two important characteristics: they are high in electrical noise and they have safety-critical functions controlled by the user interface.

Capacitive touch interfaces are inherently susceptible to many different types of noise, posing serious challenges to designers looking to integrate capacitive touch into products that require a high level of reliability. Complicating things further, there are a wide variety of capacitive-touch solutions available on the market from various semiconductor manufacturers. Each manufacturer has a unique approach to measuring changes in capacitance. Evaluating the performance of different capacitive-touch solutions in the presence of noise is difficult because noise immunity is a system-level design challenge. Factors that contribute to the noise performance of a solution include the capacitive measurement technology itself, the hardware design of the system and the software that is used to interpret the raw data and process it into a touch status.

MSP microcontrollers (MCUs) featuring CapTIvate™ technology provide designers with a feature-rich capacitive-sensing peripheral that can be configured for ultra-low-energy battery-powered applications as well as applications that require a high level of noise tolerance. In order to demonstrate system-level design principles for creating a noise-tolerant solution, TI has certified the TIDM-CAPTOUCHEMCREF capacitive touch TI Design for immunity to conducted noise, electrical fast transients and electrostatic discharge per the IEC 61000-4-6, IEC 61000-4-4 and IEC 61000-4-2 system-level standards, respectively. This design provides a reference for schematic, layout and software best practices when designing for noise tolerance with CapTIvate technology.

MSP CapTIvate technology

The CapTIvate technology from Texas Instruments is a capacitance measurement peripheral that is targeted specifically at human-machine interface applications such as buttons, sliders, scroll wheels, proximity detection and more. It supports self- and mutual-capacitance measurement topologies to allow designers to create unique interfaces that leverage the benefits of each topology in the same design using the same MCU.

The CapTIvate technology peripheral (see Figure 1 on the following page) contains numerous analog
components to provide robustness. A dedicated, on-chip low-drop-out (LDO) voltage regulator powers all of the analog measurement circuitry. This enables rejection of differential-mode noise on the MCU VCC supply rail, a common issue that plagues other MCU solutions that are referenced to their own VCC. In addition, there is no variance in sensitivity with changes in supply voltage. This is particularly important for battery-operated systems where the supply voltage dips as the battery discharges over time.

In a given MCU, the peripheral may contain multiple CapTIvate technology measurement blocks. The MSP430FR2633 MCU has four measurement blocks. Measuring electrodes in parallel optimizes the overall conversion time for a system and provides common-mode rejection of noise in slider and scroll-wheel implementations, since noise will effect each element of the sensor proportionally.

The CapTIvate technology measurement block is an integrator-based charge transfer engine that has the capability of applying gain and offset to a charge transfer, allowing for compensation of large parasitic capacitances. This offset capability allows designers to use dense ground-shielding structures in the PCB to limit fringing E-field lines, improving immunity to noise (see Figure 2).

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**Figure 1: Peripheral diagram**

**Figure 2: Measurement block diagram**
To enable designs with noise tolerance, the capacitance-to-digital conversion is clocked by a dedicated oscillator with frequency-hopping capability and spread-spectrum modulation. The ability to move the conversion around in the frequency domain allows for the CapTIvate technology software library to gather more information about a product's current operating environment, preventing false touch detections in the presence of electrical fast transients and ESD events and allowing for accurate touch detection in the presence of conducted noise.

Three-sided approach to immunity

Ultimately, creating a capacitive-touch interface that is robust in the presence of many different possible noise sources requires careful application of a three-sided approach that consists of CapTIvate technology features, hardware design techniques and signal-processing algorithms. All three elements must work together to provide immunity. Only applying signal-processing algorithms while neglecting good hardware design techniques will not lead to a successful design.

1. CapTIvate technology features
   - Integrator-based charge transfer engine
   - Parasitic capacitance offset subtraction
   - Frequency-hopping oscillator
   - Spread-spectrum clock modulation in self mode

2. Hardware design techniques
   - Ground shielding of electrodes in layout
   - 68pF filter capacitors on receive sensing lines in mutual mode

3. Signal-processing algorithms
   - Multi-frequency processing (MFP) algorithm
   - IIR filtering + de-bounce
   - Dynamic threshold adjustment (DTA) algorithm in self mode

TIDM-CAPTOUCHEMCREF TI Design

The TIDM-CAPTOUCHEMCREF is a TI Design that serves as a reference for how to properly design a capacitive-touch user interface for noise immunity using the self-capacitance and mutual-capacitance topologies. This design was used for the system...
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The TIDM-CAPTOUCHEMCREF consists of a polycarbonate enclosure that is 9.5 inches long, 6.3 inches wide and 2.5 inches tall. The enclosure itself serves as the overlay material for the capacitive-touch interface. It is 2.54 mm (0.1 in) in thickness. Internally there are two printed circuit boards (PCBs): a power-supply module (PSM) and a capacitive-sensing module (CSM) (see Figure 4). These two PCBs are connected to each other internally via a 4-node wire harness. The complete assembly is considered to be a single functional unit during electromagnetic compatibility (EMC) testing. The design is modular to allow for different PSM and CSM combinations.

The self-capacitance-sensing module (CSM-SELF) has 12 touch buttons and a 6-inch touch slider composed of four electrodes, requiring a total of 16 touch-sensing pins. The mutual-capacitance-sensing module (CSM-MUTUAL) has 32 touch buttons in two 4×4 matrices (4 Rx lines and 4 Tx lines per 16 buttons, requiring a total of 16 touch-sensing pins). Both modules have backfiring LED indicators to visually indicate the status of each sensor and the system as a whole. Both modules utilize the MSP430FR2633 CapTIvate MCU for capacitive-touch sensing, as well as two TCA9535 I²C IO expander ICs for driving the status LEDs.

The reference design as configured for testing is powered by a universal AC mains input (90 VAC–265 VAC, 50/60 Hz). This universal AC supply (PSM-UACTO3.3VDC) consists of a primary side-regulation flyback stage that generates a 12-VDC supply rail, which is then stepped down to a 3.3-VDC rail by a linear regulator. The flyback converter utilizes TI’s UCC28910 700-V flyback switcher. The 12-VDC to 3.3-VDC stage is provided by the TPS7A4533 linear regulator.

Noise-testing methodology

The International Electrotechnical Commission (IEC) 61000-4 international standard for electromagnetic compatibility was utilized as the foundation for certification. This is a system-level test standard that defines test procedures and pass/fail criteria for
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EMC as it relates to immunity. The following tests were applied to the TIDM-CAPTOUCHEMCREF reference design:

- Conducted RF Noise Immunity (IEC 61000-4-6)
- Electrical Fast Transient/Burst Immunity (IEC 61000-4-4)
- Electrostatic Discharge (ESD) Immunity (IEC61000-4-2)

During testing the reference design was interacted with via a simulated finger that consisted of a copper square sized to represent a human finger. The simulated finger was terminated to reference ground during the test through a 220 pF ±20% capacitor in series with a 510Ω ±10% resistor, per the International Special Committee on Radio Interference (CISPR) standard.

The reference design was powered from a 230 VAC/50 Hz two-wire (line and neutral) supply during testing.

**TI pass/fail criteria for capacitive-touch interfaces**

The following capacitive-touch specific pass/fail criteria were used for testing:

- **Class A:** The equipment under test (EUT) operates as intended with no degradation of performance during the test or after the test. In the context of a capacitive-sensing interface, **Class A** requires the following:
  - The EUT shall not exhibit any false touch detections during or after the test.
  - The EUT shall always detect valid touches during and after the test.
  - If the EUT contains slider or wheel sensors, their position shall be reported accurately to within an acceptable limit during and after the test.
  - The EUT shall not exhibit any integrated circuit (IC) device resets or faults during the test. No non-recoverable IC errors such as FRAM memory corruption, I^2^C bus errors or I^2^C bus glitches are allowed.

- **Class B:** The EUT experiences a temporary loss of function or degradation of performance during the test. This degradation of performance ceases after the test, after which the EUT recovers on its own without operator intervention. In the context of a capacitive-sensing interface, **Class B** requires the following:
  - The EUT shall not exhibit any false touch detections during or after the test.
  - The EUT is allowed to miss (not detect and report) a valid touch during the test, so long as it recovers on its own to full functionality after the test is complete.
  - The EUT shall not exhibit any IC device resets or faults during the test. No non-recoverable IC errors such as FRAM memory corruption, I^2^C bus errors or I^2^C bus glitches are allowed.

- **Class C:** The EUT experiences a loss of function or degradation of performance during the test which it does not recover from after the test stimulus is removed. The full functionality can be recovered by disconnecting and reconnecting power to the EUT.

**Conducted noise immunity**

Generally speaking, conducted RF noise is the most difficult test for capacitive-touch interfaces to pass. This is a result of the fact that most capacitance measurement solutions operate by charging and discharging sensing electrodes at a frequency that usually falls within the conducted RF range of 100s of kilohertz to 10s of megahertz. The conducted noise immunity test simulates the effect of radio
frequency noise coupling into power cables leading to a product. The cables are used as the coupling medium because the wavelengths of the frequencies being tested are very large. A radiated immunity test would not be feasible because the antennae involved would be prohibitively large. As an example, the TIDM-CAPTOUCHEMCREF drives electrodes in the range of 1.4 MHz to 2 MHz. At 1.4 MHz, a half-wavelength is still over 100 meters. Conducted noise creates problems for capacitive touch because it leads to injected currents during sampling, corrupting conversion results.

The conducted noise immunity test is also valuable for systems that may be powered from a variety of switching-power supplies. Low-cost switching power supplies tend to be great sources of common-mode emissions around their switching frequency. This common-mode interference is very similar to the stress applied during a conducted noise test.

Class A immunity to conducted RF noise was tested for by applying the IEC 61000-4-6 standard in three different ways:

1. The standard noise frequency sweep (150 kHz to 80 MHz, amplitude modulated on a 1 kHz carrier at 80% depth) was applied with no simulated finger present, to ensure that no false detections occur during the duration of the test.

2. The standard noise frequency sweep (150 kHz to 80 MHz, amplitude modulated on a 1-kHz carrier at 80% depth) was applied with a simulated finger affixed to a touch button to ensure that the button remains correctly in touch detect throughout the duration of the test.

3. Eight specific noise frequencies were dwelled at. At each frequency, every touch sensor on the reference design was verified to be functioning correctly with no variations in sensitivity. The specific stress frequencies were chosen based on the worst-case noise situations for capacitive sensing. The worst-case noise frequencies are a function of the conversion clock frequency used in the capacitance-to-digital conversion. For both the CSM-SELF and CSM-MUTUAL panel, the eight stress frequencies are 1.4 MHz, 1.6375 MHz, 1.8375 MHz, 2.0 MHz, 9.87 MHz, 14.77 MHz, 18.055 MHz and 28.05 MHz.

Electrical fast transient / Burst immunity

It is very likely that a line-powered product with a capacitive-touch interface will see electrical fast transients at some point in its life. These transients, typically in the 100s of volts to a few kilovolts, are usually created by the switching of high-current inductive loads. This type of stress is seen more frequently in harsh industrial environments, but it is also present in residential environments.

Fast transients tend to create a disturbance similar to that of conducted noise, but the effect is more broadband in frequency. In addition, transients are short events that do not last for extended periods of time. For this reason, the best defense against fast transients is a well-designed power supply to protect the sensitive ICs in the product, and the application of de-bounce logic to prevent false detections from a sample that was effected by a transient.

Class B immunity to electrical fast transients was tested for by applying the IEC 61000-4-4 standard. Transients were coupled onto the AC mains supply feeding the reference design. Line (L), neutral (N) and line + neutral (L+N) coupling modes were tested. Burst rates of 5 kHz and 100 kHz were applied.
**Electrostatic discharge immunity**

When it comes to ESD, first line of defense for any capacitive-touch interface is the overlay material and mechanical design. Plastic overlays such as acrylic, polycarbonate and ABS have high breakdown voltages that often provide all of the necessary protection. Care should be taken in enclosure design to ensure that off-board connectors are protected and that there are no unshielded gaps where a discharge might spread into a product.

Designs that have exposed electrodes or extremely thin overlays should utilize low-capacitance transient voltage suppression (TVS) diodes to provide a low-impedance path for discharge current, which can be on the order of several amps in a system-level ESD test.

IC protection aside, the strong electric fields that result from electrostatic discharges can disrupt capacitive touch measurements. The same de-bounce methods that are applied for fast transient protection work well for preventing false-touch detections due to an electrostatic discharge near the product, since discharges are momentary and not continuous.

Class B immunity to ESD events was tested for by applying the IEC 61000-4-2 standard. Because the reference design utilizes an insulating polycarbonate enclosure, contact discharge was applied to horizontal and vertical coupling planes, and air discharge was applied to the sensor area, power connector and side of the enclosure.

**Test results**

The TIDM-CAPTOUCHEMCREF TI Design was internally and externally tested. It demonstrates that by applying the three-sided approach to system design, it is possible to achieve a high level of immunity to conducted noise, EFT and ESD with CapTIvate™ technology, as shown in Table 1.

**External test reports**

Northwest EMC provided external testing services to verify many of the internal tests performed on the TIDM-CAPTOUCHEMCREF. The test reports are appended to this document. Please see Table 2 on the following page.

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**Table 1. Noise testing for MSP MCUs with CapTIvate technology**

<table>
<thead>
<tr>
<th>Test</th>
<th>Pass criteria</th>
<th>TIDM-CAPTOUCHEMCREF (CSM-SELF REV. PSM-UACTO3.3VDC)</th>
<th>TIDM-CAPTOUCHEMCREF (CSM-MUTUAL REV. PSM-UACTO3.3VDC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducted immunity (IEC 61000-4-6) sweep for touch detection</td>
<td>Class A</td>
<td>10 $V_{rms}$</td>
<td>3 $V_{rms}$</td>
</tr>
<tr>
<td>Conducted immunity (IEC 61000-4-6) dwell at vulnerable frequencies for touch detection</td>
<td>Class A</td>
<td>10 $V_{rms}$</td>
<td>3 $V_{rms}$</td>
</tr>
<tr>
<td>Conducted immunity (IEC 61000-4-6) sweep for no false detects</td>
<td>Class B</td>
<td>10 $V_{rms}$</td>
<td></td>
</tr>
<tr>
<td>Electrical fast transient/burst immunity (IEC 61000-4-4)</td>
<td>Class B</td>
<td></td>
<td>± 4 kV</td>
</tr>
<tr>
<td>Electrostatic discharge immunity (IEC 61000-4-2)</td>
<td>Class B</td>
<td></td>
<td>± 8 kV / 15 kV contact / air</td>
</tr>
</tbody>
</table>
### Table 2. External testing performed by Northwest EMC

<table>
<thead>
<tr>
<th>Equipment under test</th>
<th>Test applied</th>
<th>Stress level</th>
<th>Pass criteria</th>
<th>Test report</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIDM-CAPTOUCHEMCREF (CSM-SELF REV B, PSM-UACTO3.3VDC)</td>
<td>Conducted immunity (IEC 61000-4-6) sweep for touch detection</td>
<td>3 V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>Class A</td>
<td>TEXI0035, page 23</td>
</tr>
<tr>
<td></td>
<td>Conducted immunity (IEC 61000-4-6) dwell at vulnerable frequencies for touch detection</td>
<td>3 V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>Class A</td>
<td>TEXI0035, page 22</td>
</tr>
<tr>
<td></td>
<td>Conducted immunity (IEC 61000-4-6) sweep for no false detects</td>
<td>10 V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>Class B</td>
<td>TEXI0035, page 19</td>
</tr>
<tr>
<td></td>
<td>Electrical fast transient/Burst immunity (IEC 61000-4-4)</td>
<td>± 4 kV</td>
<td>Class B</td>
<td>TEXI0035, page 16</td>
</tr>
<tr>
<td></td>
<td>Electrostatic discharge immunity (IEC 61000-4-2)</td>
<td>± 4 kV / 8 kV contact / air</td>
<td>Class B</td>
<td>TEXI0035, page 11</td>
</tr>
<tr>
<td>TIDM-CAPTOUCHEMCREF (CSM-MUTUAL REV B, PSM-UACTO3.3VDC)</td>
<td>Conducted immunity (IEC 61000-4-6) sweep for touch detection</td>
<td>3 V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>Class A</td>
<td>TEXI0035, page 18</td>
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<td></td>
<td>Conducted immunity (IEC 61000-4-6) dwell at vulnerable frequencies for touch detection</td>
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<td>TEXI0035, page 17</td>
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<td>Class B</td>
<td>TEXI0035, page 16</td>
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<td>TEXI0035, page 27</td>
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<tr>
<td></td>
<td>Electrostatic discharge immunity (IEC 61000-4-2)</td>
<td>± 8 kV / 15 kV contact / air</td>
<td>Class B</td>
<td>TEXI0035, page 11</td>
</tr>
</tbody>
</table>

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