Description
This reference design demonstrates the implementation of a capacitive touch button based on TI's CapTIvate™ technology in an ultra-small 3.5-mm width PCB. This button is commonly used as a set button in proximity switches. In combination with the highly integrated IO-Link PHY, a flexible output, either PNP or NPN, is realized. This SIO stage protects against reverse polarity, ESD, EFT, and surge, allowing the design to meet IEC 61000-4 standards. The Hall sensor with an analog output signal enables flexible usage by teaching the distance of the magnetic object with the capacitive teach button. The analog signal is captured by the integrated ADC of the MCU.

Features
• Capacitive Teach Button With CapTIvate Technology:
  – Support for Metal Touch and Water Rejection Designs
  – Self and Mutual Capacitance Electrodes
  – Enables Increased Immunity to Power Line, RF, and Other Environmental Noise
• Highly Integrated Output Driver:
  – NPN, PNP, IO-Link (Optional)
  – 3.3-V or 5.0-V LDO; 20 mA
  – Reverse Polarity Protection
  – ESD, EFT, and Surge Protection According to IEC 61000-4
  – 50- to 350-mA Configurable Output Current Limit
• 3.5-mm Width PCB

Applications
• Factory Automation and Control:
  – Displacement Sensors
  – Proximity Switches

Resources

TIDA-01239  Design Folder
TIOL111  Product Folder
DRV5053  Product Folder
MSP430FR2633  Product Folder

An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.
1 System Description

In Factory Automation and Control systems, proximity switches or displacement sensors are widely used. The output changes once a certain threshold is achieved. This threshold can be set with a teach button. This reference design realizes the teach button with a capacitive touch based on TI's CapTIvate technology as part of the MSP430™ MCU. With only a tiny electrode of 2 mm × 5 mm on the PCB, solutions for very small space constraints can be realized. In this TI Design, the set button and the entire electronics fit onto a 3.5-mm wide PCB. This is achieved by using the 2.3-mm×2.3-mm small MCU including CapTIvate technology, as well as the 2.5-mm×3-mm highly integrated digital sensor output driver. The output can be configured either as NPN, PNP, or even IO-Link output. In addition, the output driver integrates reverse polarity protection and helps designers to meet system compliance with the International Electrotechnical Commission (IEC) 61000-4 standard. The built-in EMC protection allows for the following:

- ±16-kV IEC 61000-4-2 ESD Contact Discharge
- ±4-kV IEC 61000-4-4 Electrical Fast Transient (EFT)
- ±1.2-kV/500-Ω IEC 61000-4-5 Surge

With the capability of using the onboard LDO with either a 3.3-V or 5-V output, the remaining system can be supplied with up to 20 mA. This reference design uses the integrated 3.3-V LDO, which supplies the MCU and the Hall sensor with power from the voltage input that covers a range from 7 to 36 V with a ±65-V tolerant transient.

For object detection, many different methods are available depending on the material and distance of the object. In this reference design, a Hall sensor with an analog output is detecting the magnetic object, and the built-in ADC inside the MCU measures the magnetic field.

1.1 Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWER SUPPLY</strong></td>
<td></td>
</tr>
<tr>
<td>Operating voltage</td>
<td>7- to 36-V DC</td>
</tr>
<tr>
<td></td>
<td>±65-V transients &lt; 100 µs</td>
</tr>
<tr>
<td>LDO</td>
<td>3.3-V output voltage</td>
</tr>
<tr>
<td></td>
<td>20-mA output current</td>
</tr>
<tr>
<td><strong>INTERFACE</strong></td>
<td></td>
</tr>
<tr>
<td>SIO</td>
<td>NPN, PNP</td>
</tr>
<tr>
<td>Communication</td>
<td>50- to 350-mA configurable current limit</td>
</tr>
<tr>
<td><strong>DIAGNOSTICS</strong></td>
<td></td>
</tr>
<tr>
<td>Fault indicator (open drain output)</td>
<td>Overcurrent</td>
</tr>
<tr>
<td></td>
<td>Overtemperature</td>
</tr>
<tr>
<td></td>
<td>Power supply</td>
</tr>
<tr>
<td><strong>HMI</strong></td>
<td></td>
</tr>
<tr>
<td>Indicator</td>
<td>RGB LED</td>
</tr>
<tr>
<td>Teach button</td>
<td>PCB electrode (2 mm × 5 mm)</td>
</tr>
<tr>
<td></td>
<td>Connection for external or remote electrode</td>
</tr>
<tr>
<td><strong>FRONT-END</strong></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>Hall-effect sensor with analog output</td>
</tr>
<tr>
<td>ADC</td>
<td>integrated ADC inside MCU</td>
</tr>
<tr>
<td><strong>MECHANICS</strong></td>
<td></td>
</tr>
<tr>
<td>Form factor</td>
<td>PCB width: 3.5 mm</td>
</tr>
</tbody>
</table>
2 System Overview

2.1 Block Diagram

![Block Diagram of TIDA-01239](image_url)

Figure 1. Block Diagram of TIDA-01239

2.2 Design Considerations

The top layer of this reference design includes the following (see Figure 2):

- Hall sensor
- MSP430 with CapTIvate: The MSP430FR2633 uses the integrated ADC to convert the voltage signal of the Hall sensor. In addition, the capacitive touch button, based on CapTIvate technology, is realized as well as the communication to the TIOL111, which is used in SIO mode. With an IO-Link stack, the system can also be used with IO-Link communication.
- Interface and power: The TIOL111 can be powered from 7 to 36 V and converts with the integrated LDO down to 3.3 V, providing up to 20 mA. With the built-in protection scheme, designers can easily design to meet the IEC 61000-4 standard.
- Output stage: The TIOL111 is used in SIO mode. The user can select if he or she wants to use an NPN or PNP output. The device is also capable to communicate through IO-Link.
- Programming connector: J1 is the programming connector. This connector works in combination with the MSP CapTIvate MCU development kit.

The bottom layer of this reference design includes the following (see Figure 3):

- CapTIvate electrode: This electrode builds the capacitive touch button in combination with the CapTIvate solution.
- RGB LED: This indicator LED shows the status of the system.
- Cut out area: The actual system can be removed once the programming and debugging is finalized. The Hall sensor in the TO-92 package remains on the PCB. Instead, the user can now use the Hall sensor in the SOP package.
Figure 2. Description of Subsystem Blocks in Top Layer

Figure 3. Description of Subsystem Blocks in Bottom Layer
2.3 Highlighted Products

2.3.1 TIOL111

The TIOL111 family of transceivers implements the IO-Link interface for industrial bidirectional, point-to-point communication. When the device is connected to an IO-Link master through a three-wire interface, the master can initiate communication and exchange data with the remote node while the TIOL111 acts as a complete physical layer for the communication.

These devices are capable of withstanding up to 1.2 kV (500 Ω) of IEC 61000-4-5 surge and have integrated protection against reverse polarity. A simple pin-programmable interface allows easy interfacing to the controller circuits. The output current limit can be configured using an external resistor. Fault reporting and internal protection functions are provided for undervoltage, overcurrent, and overtemperature conditions.

Key features of this device include:
- 7- to 36-V supply voltage
- PNP, NPN, or IO-Link configurable output:
  - IEC 61131-9 COM1, COM2, and COM3 data rate support
- Low residual voltage of 1.75 V at 250 mA
- 50- to 350-mA configurable current limit
- Tolerant to ±65-V transients < 100 µs
- Reverse polarity protection of up to 55 V on L+, CQ, and L–
- Integrated EMC protection on L+ and CQ:
  - ±16-kV IEC 61000-4-2 ESD Contact Discharge
  - ±4-kV IEC 61000-4-4 EFT
  - ±1.2-kV/500-Ω IEC 61000-4-5 Surge
- Fast demagnetization of inductive loads up to 1.5 H
- Large capacitive load driving capability
- < 2-µA CQ leakage current
- < 1.5-mA quiescent supply current
- Integrated LDO options for up to 20-mA current:
  - TIOL111: No LDO
  - TIOL111-3: 3.3-V LDO
  - TIOL111-5: 5-V LDO
- Overtemperature warning and thermal protection
- Remote wake-up indicator
- Fault indicator
- Extended ambient temperature: –40°C to 125°C
- 2.5-mm×3-mm 10-pin VSON package
2.3.2 DRV5053

The DRV5053 device is a chopper-stabilized Hall device that offers a magnetic sensing solution with superior sensitivity stability over temperature and integrated protection features.

The 0- to 2-V analog output responds linearly to the applied magnetic flux density and distinguishes the polarity of magnetic field direction. A wide operating voltage range from 2.5 to 38 V with reverse polarity protection up to –22 V makes the device suitable for a wide range of industrial and consumer applications. Internal protection functions are provided for reverse supply conditions, load dump, and output short circuit or overcurrent.

Key features of this device include:

- Linear output Hall sensor
- Superior temperature stability:
  - Sensitivity ±10% over temperature
- High sensitivity options:
  - –11 mV/mT (OA)
  - –23 mV/mT (PA)
  - –45 mV/mT (RA)
  - –90 mV/mT (VA)
  - 23 mV/mT (CA)
  - 45 mV/mT (EA)
- Supports a wide voltage range:
  - 2.5 to 38 V
  - No external regulator required
- Wide operating temperature range:
  - \( T_A = -40 \text{ to } 125^\circ C \) (Q)

- Amplified output stage:
  - 2.3-mA sink, 300-μA source
- Output voltage: 0.2 to 1.8 V
  - \( B = 0 \text{ mT}, \text{ OUT} = 1 \text{ V} \)
- Fast power-on: 35 μs
- Small package and footprint:
  - Surface mount three-pin SOT-23 (DBZ):
    - 2.92 mm × 2.37 mm
  - Through-hole three-pin TO-92 (LPG):
    - 4.00 mm × 3.15 mm
- Protection features:
  - Reverse supply protection (up to –22 V)
  - Supports up to 40-V load dump
  - Output short-circuit protection
  - Output current limitation

Figure 4. Block Diagram of TIOL111 With Integrated Voltage Regulator
2.3.3 MSP430FR2633

The MSP430FR263x and MSP430FR253x are ultra-low-power MSP430 microcontrollers for capacitive touch sensing that feature CapTIvate touch technology for buttons, sliders, wheels, and proximity applications. MSP430 MCUs with CapTIvate technology provide the most integrated and autonomous capacitive-touch solution in the market with high reliability and noise immunity at the lowest power. TI's capacitive touch technology supports concurrent self-capacitance and mutual-capacitance electrodes on the same design for maximum flexibility. MSP430 MCUs with CapTIvate technology operate through thick glass, plastic enclosures, metal and wood with operation in harsh environments including wet, greasy, and dirty environments.

MSP430 MCUs with capacitive touch sensing are supported by an extensive hardware and software ecosystem with reference designs and code examples to get a design started quickly. Development kits include the MSP-CAPT-FR2633 CapTIvate technology development kit. TI also provides free software including the CapTIvate Design Center, where engineers can quickly develop applications with an easy-to-use graphical user interface (GUI) and MSP430Ware™ software and comprehensive documentation with the CapTIvate technology guide.

TI’s MSP430 ultra-low-power FRAM microcontroller platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the non-volatility of flash.

Key features of this device include:

- CapTIvate technology (capacitive touch):
  - Performance:
  - Fast electrode scanning with four simultaneous scans
- Support for high-resolution sliders with > 1024 points
- 30-cm proximity sensing

- Reliability:
  - Increased immunity to power line, RF, and other environmental noise
  - Built-in spread spectrum, automatic tuning, noise filtering, and debouncing algorithms
  - Enables reliable touch solutions with 10-\( V_{\text{RMS}} \) common-mode noise, 4-kV EFT, and 15-kV ESD, allowing for IEC-61000-4-6, IEC-61000-4-4, and IEC-61000-4-2 compliance
  - Reduced RF emissions to simplify electrical designs
  - Support for metal touch and water rejection designs

- Flexibility:
  - Up to 16 self-capacitance and 64 mutual-capacitance electrodes
  - Mix and match self- and mutual-capacitive electrodes in the same design
  - Supports multitouch functionality
  - Wide range of capacitance detection, wide electrode range of 0 to 300 pF

- Low power:
  - <0.9 \( \mu \text{A} \)/button in wake-on-touch mode, where capacitive measurement and touch detection is done by hardware state machine while CPU is asleep
  - Wake-on-touch state machine allows electrode scanning while CPU is asleep
  - Hardware acceleration for environmental compensation, filtering, and threshold detection

- Ease of use:
  - CapTIvate design center, PC GUI lets engineers design and tune capacitive buttons in real time without having to write code
  - CapTIvate software library in ROM provides ample FRAM for customer application

Copyright © 2017, Texas Instruments Incorporated

Figure 6. Block Diagram of MSP430FR2633
3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

- TIDA-01239 reference design
- MSP CapTIvate MCU Development Kit
- MSP CapTIvate Design Center GUI
- Code Composer Studio™
- A magnet

3.2 Testing and Results

The reference design can be used in two different ways:

1. Investigate and evaluate the tiny CapTIvate touch button.
2. Use as a Hall sensor with a digital NPN or PNP output.

The first use case only requires the MSP CapTIvate Design Center and the MSP430 CapTIvate programmer (part of the MSP CapTIvate MCU Development Kit) is required with the GUI.

3.2.1 Test Setup

Figure 7 shows the simple test setup. This is the first step for programming the capacitive touch button.

![Test Setup for Capacitive Touch Optimization](image)

Figure 7. Test Setup for Capacitive Touch Optimization
3.2.2 Capacitive Touch Button

With the CapTivate Design Center, it is very easy to set the touch button (find a detailed description here: ). The reference design has two buttons assigned. Figure 8 and Figure 9 show the two electrodes. BTN1 is a mutual coupling button. The Tx signal is connected to pin CAP3.2 (D4) of the MSP430, and the Rx signal is connected to pin CAP2.2 (D5). The self-coupling electrode on pin CAP2.0 (C4) is on the PCB as a via. The user can solder a remote electrode to it.

![Figure 8. TIDA-01239 MCU Circuitry](image1)

![Figure 9. TIDA-01239 Mutual and Self-Coupling Electrodes](image2)
According to Figure 10, a project can be set up in the CapTivate Design Center. A mutual button is connected to the MSP430FR2633 with Tx to CAP3.2 and Rx to CAP2.2.

Figure 10. CapTivate Design Center: Setup of One Mutual Button
Once the project is setup, the connection between the Design Center and the reference design can be established by clicking "Connect" in the Communications menu. By double-clicking the BTN00 icon, the window shown in Figure 11 appears. Once the button specific parameters are set in the tabs Conversion Control and Tuning (see ), the sensitivity of the touch button can be observed, for example, in the tab Channel Bar Count (see Figure 11 and Figure 12) or Channel Oscilloscope Plot (see Figure 13).

![Figure 11. CapTIvate Design Center: No Touch](image-url)
Figure 12 shows an example of a touch event. In the Tuning tab and Conversion Control tab, the proximity threshold, touch threshold, and other parameters for increasing robustness can be set.

Figure 12. CapTIvate Design Center: Touch on Button Recognized
Figure 13. CapTlivate Design Center: Time Plot With Several Touch Events

Figure 14. CapTlivate Design Center: Code Generation
Once all settings are realized, the GUI can generate C-code to implement in the application code. By double-clicking on the MSP430, the Controller property window opens. The Generate Source Code button creates the code either for a new project or for an existing project (see Figure 14).

### 3.2.3 Test Application

To showcase the functionality of the set button in combination with the SIO mode, the reference design has a Hall sensor with an analog output voltage depending on the magnetic field strength.

The ADC is implemented as a window comparator. It uses two threshold values: the high and low threshold. The ADC continuously receives values from the Hall sensor, which are sampled and sent to the MCU. If the magnetic field sensed by the Hall sensor is smaller than the lower threshold, the LED blinks green. If the value sensed is greater than the higher threshold, the LED blinks red. These threshold values are flexible and can be set during the runtime.

The values received by the Hall sensor in between the higher and lower threshold are ignored and no post processing is done by the MCU. When the Hall sensor measures values greater than the higher threshold, it provides a signal to the IO-Link to open the high-side switch, thus preventing any current to pass through. When the magnet is in the zone of the lower threshold, the MCU signals the IO-Link to close the high-side switch to allow current to pass through.

The MSP430FR2633 has CapTIvate technology integrated in it. Using this technology, there is a capacitive sense button implemented in this reference design. The button triggers the MCU to glow a blue LED once it senses a touch. The thresholds of the ADC are modified when the capacitive button is touched.

The difference between the higher and the lower threshold can be set using software. As shown in Figure 15, once the capacitive button is pressed, depending on the position of the magnet, the new values of the lower and higher thresholds are set. This is done in runtime.

![Figure 15. Application Example](image-url)
4 Design Files

4.1 Schematics
To download the schematics, see the design files at TIDA-01239.

4.2 Bill of Materials
To download the bill of materials (BOM), see the design files at TIDA-01239.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints
To download the layer plots, see the design files at TIDA-01239.

4.4 Altium Project
To download the Altium project files, see the design files at TIDA-01239.

4.5 Gerber Files
To download the Gerber files, see the design files at TIDA-01239.

4.6 Assembly Drawings
To download the assembly drawings, see the design files at TIDA-01239.

5 Related Documentation

2. Texas Instruments, *MSP430™ FRAM microcontrollers with CapTivate™ technology*, Marketing White Paper (SLAY044)

5.1 Trademarks
CapTivate, MSP430, MSP430Ware, Code Composer Studio are trademarks of Texas Instruments. All other trademarks are the property of their respective owners.

6 About the Author
ALEXANDER WEILER is a systems engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Alexander brings to this role his extensive experience in high-speed digital, low-noise analog, and RF system-level design expertise. Alexander earned his diploma in electrical engineering (Dipl.-Ing.(FH)) from the University of Applied Science in Karlsruhe, Germany.
IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated (‘TI’) technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, “TI Resources”) are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI’s provision of TI Resources does not expand or otherwise alter TI’s applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT. AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED “AS IS” AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include, without limitation, TI's standard terms for semiconductor products (http://www.ti.com/sc/docs/stdterms.htm), evaluation modules, and samples (http://www.ti.com/sc/docs/sampterms.htm).

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2017, Texas Instruments Incorporated