Detecting Human Falls with a 3-Axis Digital Accelerometer

By Ning Jia

Foreword

For a human, experiencing a fall unobserved can be doubly dangerous. The obvious possibility of initial injury may be further aggravated by the possible consequences if treatment is not obtained within a short time. For example, many elderly individuals can suffer accidental falls due to weakness or dizziness—or, in general, their diminished self-care and self-protective ability. Since they tend to be fragile, these accidents may possibly have serious consequences if aid is not given in time. Statistics show that the majority of serious consequences are not the direct result of falling, but rather are due to a delay in assistance and treatment. Post-fall consequences can be greatly reduced if relief personnel can be alerted in time.

Besides senior citizens, there are many other conditions and activities for which an immediate alert to a possible fall, especially from substantial height, would be quite helpful—for example mountaineers, construction workers, window washers, painters, and roofers.

In light of this need to warn of falls, the development of devices for detection and prediction of all types of falls has become a hot topic. In recent years, technological advances in *microelectromechanical-system* (MEMS) acceleration sensors have made it possible to design fall detectors based on a 3-axis *integrated MEMS* (*i*MEMS®) accelerometer. The technique is based on the principle of detecting changes in motion and body position of an individual, wearing a sensor, by tracking acceleration changes in three orthogonal directions. The data is continuously analyzed algorithmically to determine whether the individual's body is falling or not. If an individual falls, the device can employ GPS and a wireless transmitter to determine the location and issue an alert in order to get assistance. The core element of fall detection is an effective, reliable detection principle and algorithm to judge the existence of an emergency fall situation.

This article, based on research into the principles of fall detection for an individual body, proposes a new solution for detection of fall situations utilizing the ADXL345,[1] a 3-axis accelerometer from Analog Devices.

The ADXL345 *i*MEMS Accelerometer

*i*MEMS semiconductor technology combines micromechanical structures and electrical circuits on a single silicon chip. Using this technology, *i*MEMS accelerometers sense acceleration on one, two, or even three axes, and provide analog or digital outputs. Depending on the application, the accelerometer may offer different ranges of detection, from several *g* to tens of *g*. Digital versions may even have multiple *interrupt* modes. These features offer the user convenient and flexible solutions.

The recently introduced ADXL345 is an *i*MEMS 3-axis accelerometer with digital output. It features a selectable ±2-*g*, ±4-*g*, ±8-*g*, or ±16-*g* measurement range; resolution of up to 13 bits; fixed 4-m*g*/LSB sensitivity; a tiny 3-mm × 5-mm × 1-mm package; ultralow power consumption (25 µA to 130 µA); standard I^{2}C® and SPI serial digital interfacing; and 32-level FIFO storage. A variety of built-in features, including motion-status detection and flexible interrupts, greatly simplify implementation of the algorithm for fall detection. As you will see, this combination of features makes the ADXL345 an ideal accelerometer for fall-detector applications.

The fall-detection solution proposed here takes full advantage of these internal functions, minimizing the complexity of the algorithm—with little requirement to access the actual acceleration values or perform any other computations.

Interrupt System

Figure 1 shows the system block diagram and pin definitions of the ADXL345.

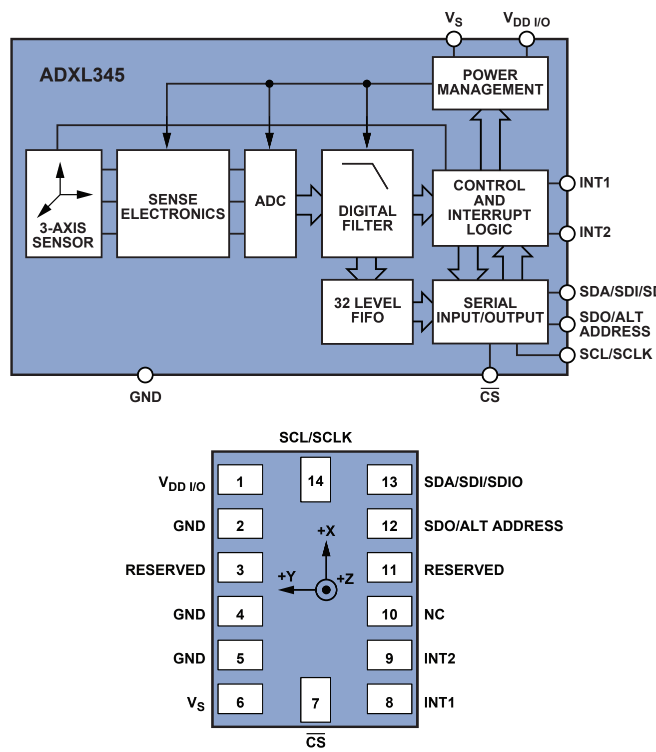


Figure 1. ADXL345 system block diagram and pin designations.

The ADXL345 features two programmable interrupt pins—INT1 and INT2—with a total of eight interrupt functions available. Each interrupt can be enabled or disabled independently, with the option to map to either the INT1 or INT2 pin. All functions can be used simultaneously—the only limiting feature is that some functions may need to share interrupt pins. The eight functions are: DATA_READY, SINGLE_TAP, DOUBLE_TAP, ACTIVITY, INACTIVITY, FREE_FALL, WATERMARK, and OVERRUN. Interrupts are enabled by setting the appropriate bit in the **INT_ENABLE** register and are mapped to either the INT1 or INT2 pins, based on the contents of the **INT_MAP** register. The interrupt functions are defined as follows:

1. DATA_READY is set when new data is available—and cleared when no new data is available.
2. SINGLE_TAP is set when a single acceleration event that is greater than the value in the THRESH_TAP register occurs for a shorter time than specified in the DUR register.
3. DOUBLE_TAP is set when two acceleration events that are greater than the value in the THRESH_TAP register occur and are shorter than the time specified in the DUR register, with the second tap starting after the time specified by the LATENT register and within the time specified in the WINDOW register.

Figure 2 illustrates the valid SINGLE_TAP and DOUBLE_TAP interrupts.

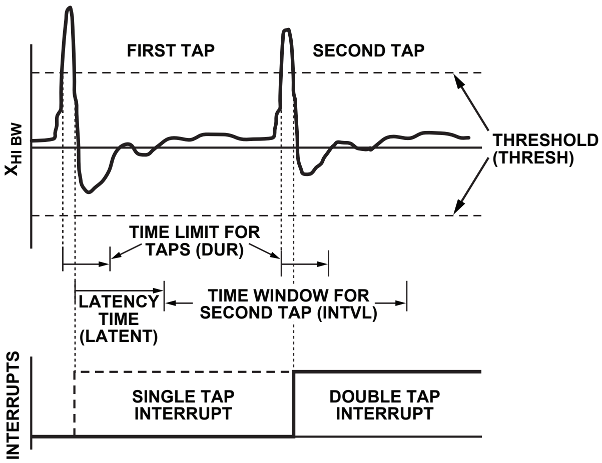


Figure 2. SINGLE_TAP and DOUBLE_TAP interrupts.

4. ACTIVITY is set when acceleration greater than the value stored in the THRESH_ACT register is experienced.
5. INACTIVITY is set when acceleration of less than the value stored in the THRESH_INACT register is experienced for longer than the time specified in the TIME_INACT register. The maximum value for TIME_INACT is 255 s.

   Note: With ACTIVITY and INACTIVITY interrupts, the user can enable or disable each axis individually. For example, the ACTIVITY interrupt for the X-axis can be enabled while disabling the interrupts for the Y-axis and Z-axis.

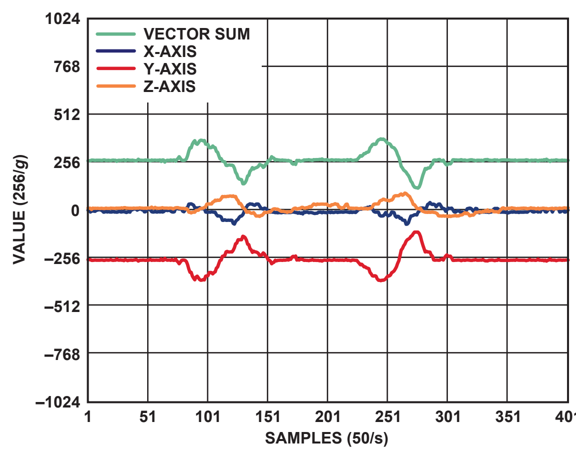
   Furthermore, the user can select between *dc*-coupled or *ac*-coupled operation mode for the ACTIVITY and INACTIVITY interrupts. In dc-coupled operation, the current acceleration is compared with THRESH_ACT and THRESH_INACT directly to determine whether ACTIVITY or INACTIVITY is detected. In ac-coupled operation for activity detection, the acceleration value at the start of activity detection is taken as a reference value. New samples of acceleration are then compared to this reference value; if the magnitude of the difference exceeds THRESH_ACT, the device will trigger an ACTIVITY interrupt. In ac-coupled operation for inactivity detection, a reference value is used for comparison and is updated whenever the device exceeds the inactivity threshold. Once the reference value is selected, the device compares the magnitude of the difference between the reference value and the current acceleration with THRESH_INACT. If the difference is below THRESH_INACT for a total of TIME_INACT, the device is considered inactive and the INACTIVITY interrupt is triggered.
6. FREE_FALL is set when acceleration of less than the value stored in the THRESH_FF register is experienced for longer than the time specified in the TIME_FF register. FREE_FALL interrupt is mainly used in detection of free-falling motion. As a result, the FREE_FALL interrupt differs from the INACTIVITY interrupt in that all axes always participate, the timer period is much shorter (1.28 s maximum), and it is always dc-coupled.
7. WATERMARK is set when the number of samples in the FIFO has filled up to the value stored in the SAMPLES register. It is cleared automatically when the FIFO is read and its content emptied below the value stored in the SAMPLES register.

   Note: the FIFO register in the ADXL345 has four operation modes: Bypass, FIFO, Stream, and Trigger; and can store up to 32 samples (X-, Y-, and Z-axis). The FIFO function is an important and very useful feature; *however, the proposed solution does not use the FIFO function*, so it will not be further discussed.
8. OVERRUN is set when new data has replaced unread data. The precise operation of OVERRUN depends on the operation mode of FIFO. In bypass mode, OVERRUN is set when new data replaces unread data in the DATAX, DATAY, and DATAZ registers. In all other modes, OVERRUN is set when the FIFO is filled with 32 samples. OVERRUN is cleared by reading the FIFO contents and is automatically cleared when the data is read.

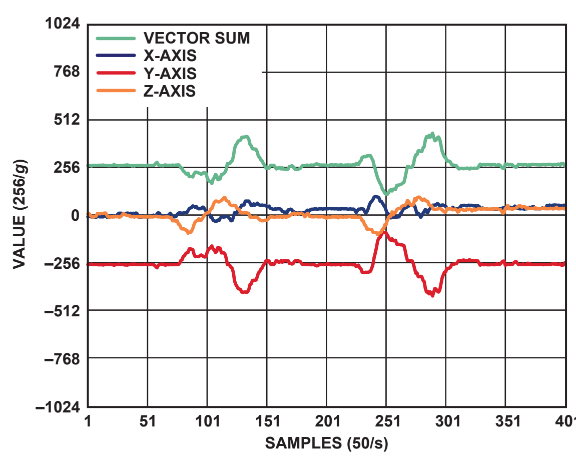
Acceleration-Change Characteristics While Falling

The main research on the principles of fall detection focuses on the changes in acceleration that occur when a human is falling.

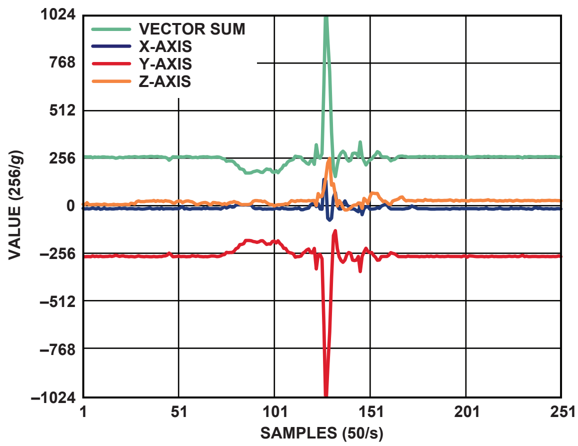
Figure 3 illustrates changes in acceleration that occur when (a) walking downstairs, (b) walking upstairs, (c) sitting down, and (d) standing up from a chair. The fall detector is mounted to a belt on the individual's body. The red trace is the Y-axis (vertical) acceleration; it is –1 *g* at equilibrium. The black and yellow traces are the respective X-axis (forward) and Z-axis (sideways) accelerations. They are both 0 *g* at equilibrium. The green trace is the vector sum magnitude, 1 *g* at equilibrium.



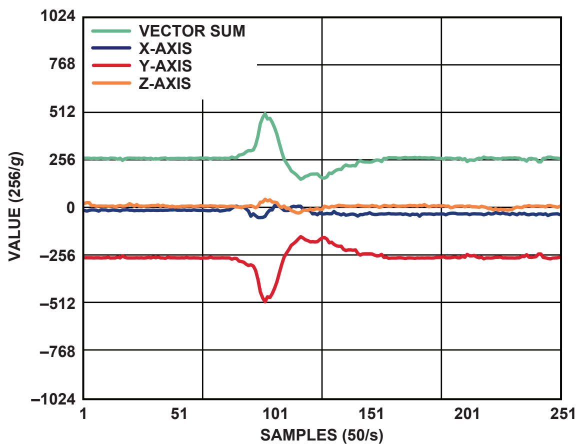
a. Walking downstairs.



b. Walking upstairs.



c. Sitting down.



d. Standing up.

Figure 3. Accelerometer responses to different types of motion.

Because the movement of elderly people is comparatively slow, the acceleration change will not be very conspicuous during the walking motions. The most pronounced acceleration is a 3-*g* spike in Y (and the vector sum) at the instant of sitting down.

The accelerations during falling are completely different. Figure 4 shows the acceleration changes during an accidental fall. By comparing Figure 4 with Figure 3, we can see four critical differences characteristic of a falling event that can serve as the criteria for fall detection. They are marked in the red boxes and explained in detail as follows:

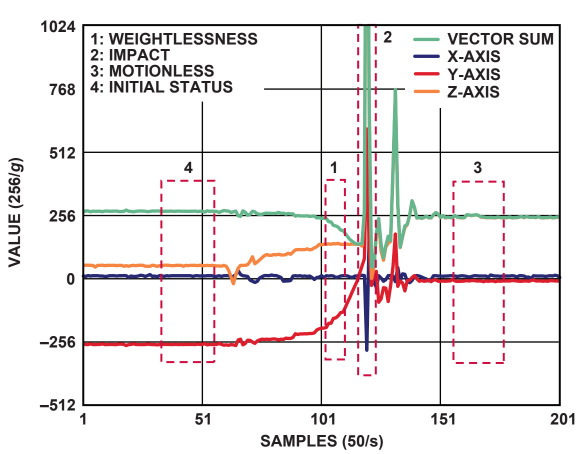


Figure 4. Acceleration change curves during the process of falling.

1. *Start of the fall*: The phenomenon of weightlessness will always occur at the start of a fall. It will become more significant during free fall, and the vector sum of acceleration will tend toward 0 *g*; the duration of that condition will depend on the height of freefall. Even though weightlessness during an ordinary fall is not as significant as that during a freefall, the vector sum of acceleration will still be substantially less than 1 *g* (while it is generally greater than 1 *g* under normal conditions). Therefore, this is the first basis for determining the fall status that could be detected by the ADXL345's FREE_FALL interrupt.
2. *Impact*: After experiencing weightlessness, the human body will impact the ground or other objects; the acceleration curve shows this as a large shock. This shock is detected by the ACTIVITY interrupt of ADXL345. Therefore, the second basis for determining a fall is the ACTIVITY interrupt right after the FREE_FALL interrupt.
3. *Aftermath*: Generally speaking, the human body, after falling and making impact, can not rise immediately; rather it remains in a motionless position for a short period (or longer as a possible sign of unconsciousness). On the acceleration curve, this presents as an interval of flat line, and is detected by the INACTIVITY interrupt of ADXL345. Therefore, the third basis for determining a fall situation is the INACTIVITY interrupt after the ACTIVITY interrupt.
4. *Comparing before and after*: After a fall, the individual's body will be in a different orientation than before, so the static acceleration in three axes will be different from the initial status before the fall (Figure 4). Suppose that the fall detector is belt-wired on the individual's body, to provide the entire history of acceleration, including the initial status. We can read the acceleration data in all three axes after the INACTIVITY interrupt and compare those sampling data with the initial status. In Figure 4, it is evident that the body fell on its side, since the static acceleration has changed from –1 *g* on the Y axis to +1 *g* on the Z-axis. So the fourth basis for determining a fall is if the difference between sampling data and initial status exceeds a certain threshold, for example, 0.7 *g*.

The combination of these qualifications forms the entire fall-detection algorithm, which, when exercised, can cause the system to raise an appropriate alert that a fall has occurred. Of course, the time interval between interrupts has to be within a reasonable range. Normally, the time interval between FREE_FALL interrupt (weightlessness) and ACTIVITY interrupt (impact) is not very long unless one is falling from the top of a very high building! Similarly, the time interval between ACTIVITY interrupt (impact) and INACTIVITY interrupt (essentially motionless) should not be very long. A practical example will be given in the next section with a set of reasonable values. The related interrupt detection threshold and time parameters can be flexibly set as needed.

If a fall results in serious consequences, such as unconsciousness, the human body will remain motionless for an even longer period of time, a status that can still be detected by the INACTIVITY interrupt, so a second critical alert could be sent out if the inactive state was detected to continue for a defined long period of time after a fall.

Typical Circuit Connection

The circuit connection between the ADXL345 and a microcontroller is very simple. For this article, the test platform uses the ADXL345 and an ADuC7026 analog microcontroller—which features 12-bit analog I/O and an ARM7TDMI® MCU. Figure 5 shows the typical connection between ADXL345 and ADuC7026.[2] With the $\overline{CS}$ pin of ADXL345 tied high, the ADXL345 works in I^2C mode. The SDA and SCL, the data and clock of the I^2C bus, are connected to the corresponding pins of ADuC7026. A GPIO of ADuC7026 is connected to the ADXL345's ALT pin to select the I^2C address of the ADXL345, and the INT1 pin of ADXL345 is connected to an IRQ input of the ADuC7026 to generate the interrupt signal.

Other MCU or processor types could be used to access the ADXL345, with similar circuit connections to Figure 5, but the ADuC7026 also provides a data-acquisition facility including multichannel analog-to-digital and digital-to-analog conversion. The ADXL345 data sheet describes SPI-mode applications to achieve higher data rates.

Using the ADXL345 to Simplify Fall Detection

Table 1 and Figure 5 define the realization of the algorithm for the solution mentioned above. The function of each register is included in the table, and the values used in the present algorithm are as indicated. Please refer to the ADXL345 data sheet for the detailed definition of each register bit.

Some of the registers in Table 1 will have two values. This indicates that the algorithm switches between these values for different aspects of detection.

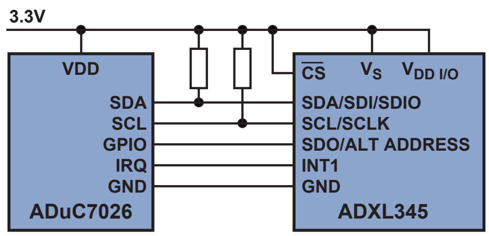


Figure 5. Typical circuit connection between the ADXL345 and microcontroller.

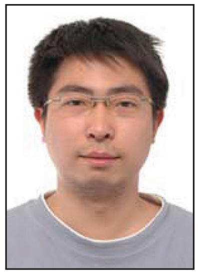
Table 1. ADXL345 Registers Function Descriptions

Hex Address	Register Name	Type	Reset Value	Description	Settings in Algorithm	Function of the Settings in Algorithm
0	DEVID	Read-only	0xE5	Device ID	Read-only	
1-1C	Reserved			Reserved, do not access	Reserved	
1D	THRESH_TAP	Read/write	0x00	Tap threshold	Not used	
1E	OFSX	Read/write	0x00	X-axis offset	0x06	X-axis, offset compensation get from initialization calibration
1F	OFSY	Read/write	0x00	Y-axis offset	0xF9	Y-axis offset compensation, get from initialization calibration
20	OFSZ	Read/write	0x00	Z-axis offset	0xFC	Z-axis offset compensation, get from initialization calibration
21	DUR	Read/write	0x00	Tap duration	Not used	
22	LATENT	Read/write	0x00	Tap latency	Not used	
23	WINDOW	Read/write	0x00	Tap window	Not used	
24	THRESH_ACT	Read/write	0x00	Activity threshold	0x20/0x08	Set Activity threshold as 2 *g*/0.5 *g*
25	THRESH_INACT	Read/write	0x00	Inactivity threshold	0x03	Set Inactivity threshold as 0.1875 *g*
26	TIME_INACT	Read/write	0x00	Inactivity time	0x02/0x0A	Set Inactivity time as 2 s or 10 s
27	ACT_INACT_CTL	Read/write	0x00	Axis enable control for Activity/Inactivity	0x7F/0xFF	Enable Activity and Inactivity of X-,Y-, Z-axis, wherein Inactivity is ac-coupled mode, Activity is dc-coupled/ac-coupled mode
28	THRESH_FF	Read/write	0x00	Free-Fall threshold	0x0C	Set Free-Fall threshold as 0.75 *g*
29	TIME_FF	Read/write	0x00	Free-Fall time	0x06	Set Free-Fall time as 30 ms
2A	TAP_AXES	Read/write	0x00	Axis control for Tap/Double Tap	Not used	
2B	ACT_TAP_STATUS	Read-only	0x00	Source of Activity/Tap	Read-only	
2C	BW_RATE	Read/write	0x0A	Data rate and power mode control	0x0A	Set sample rate as 100 Hz
2D	POWER_CTL	Read/write	0x00	Power save features control	0x00	Set as normal working mode
2E	INT_ENABLE	Read/write	0x00	Interrupt enable control	0x1C	Enable Activity, Inactivity, Free-Fall interrupts
2F	INT_MAP	Read/write	0x00	Interrupt mapping control	0x00	Map all interrupts to Int1 pin
30	INT_SOURCE	Read-only	0x00	Source of interrupts	Read-only	
31	DATA_FORMAT	Read/write	0x00	Data format control	0x0B	Set as ±16 *g* measurement range, 13-bit right alignment, high level interrupt trigger, I^2C interface
32	DATAX0	Read-only	0x00	X-axis data	Read-only	
33	DATAX1	Read-only	0x00		Read-only	
34	DATAY0	Read-only	0x00	Y-axis data	Read-only	
35	DATAY1	Read-only	0x00		Read-only	
36	DATAZ0	Read-only	0x00	Z-axis data	Read-only	
37	DATAZ1	Read-only	0x00		Read-only	
38	FIFO_CTL	Read/write	0x00	FIFO control	Not used	
39	FIFO_STATUS	Read/write	0x00	FIFO status	Not used	

Conclusion

The ADXL345 is a powerful and full-featured accelerometer. We have described a proposed new solution for the fall-detection problem that takes advantage of the various built-in motion-status detection features and flexible interrupts. Tests have shown that it combines low algorithm complexity and high detection accuracy.

The Author



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References

[1] Information on all ADI components can be found at www.analog.com.

[2] www.analog.com/en/analog-microcontrollers/ADuC7026/products/product.html.