Topical Review

Micromachined threshold inertial switches: a review

Qiu Xu and Mohammad I Younis*

Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

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Abstract

This paper presents a review of the recent advances on micromachined inertial switches/triggers. The review focuses on their advantages and disadvantages, sensitive directions, mechanisms of contact-enhancement, threshold accuracy, and the tunability of the acceleration threshold. Several applications of these sensors are highlighted including in healthcare, structural health monitoring, internet of things, and military. Recent contemporary research directions are also discussed, such as multi-directions/axis, multi-threshold sensors, and machine learning implementation. The article concludes with discussion on future development trends and performance improvements of inertial switches.

Keywords: MEMS (micro-electromechanical system), inertial switch, acceleration switch, threshold acceleration, triggers, inertial sensors

(Some figures may appear in colour only in the online journal)
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1. Introduction

Micro-electromechanical systems (MEMSs) inertial switches are widely used in many fields, such as wireless structural health monitoring, military, automobiles, arming and firing systems, shipment monitoring, safety, and geriatric healthcare systems. Their advantages include miniaturization, zero-power consumption, low cost, batch production, and resistance to electromagnetic interference.

The inertial switch, also called acceleration switch, G-switch, trigger, is a kind of an electrical switch, which is activated at a predetermined threshold acceleration [1]. Essentially, it functions as both a threshold sensor and an actuator. The basic structure of an inertial switch relies on a proof mass suspended by a spring, working as a movable electrode, and a contact point as a stationary electrode. Such a system can be modeled as a ‘spring-mass-damper’ system, as shown in figure 1, containing a seismic mass \( m \), a suspended spring of elastic coefficient \( k \), and a viscous damping coefficient \( c \). For most inertial switches, electrostatic forces are generally negligible because the overlapped area between a stationary electrode and a movable electrode is very small. Hence, the electrostatic force can be neglected. However, when the contact area is large enough, the electrostatic force may be sufficient to affect the performance of the system. Such switches are commonly called electrostatic force-assisted inertial switches.

For the switch in figure 1, the dynamic equation of the seismic mass is written as [2, 3]:

\[
m \ddot{x}_m + c(\dot{x}_m - \dot{x}_s) + k(x_m - x_s) = 0 \tag{1}
\]

where \( x_s \) is the displacement of the substrate, \( x_m \) is the displacement of the seismic mass, and \( \dot{x}_s \) represents the acceleration.

When the inertial switch is subjected to a sufficient acceleration, the movable electrode rapidly moves forward toward the stationary electrode and contacts it, forming an external electrical path [4–7]. Note here that generally, the moveable and stationary electrodes are not electrically connected to each other. Subsequently, the movable electrode quickly returns back to its original position due to the restoring force of the spring, which turns off the external circuit. When the substrate is regarded as the reference plane, the proof mass is subjected to the inertial acceleration \( a = -\ddot{x}_s \). Referring to the relative displacement between the proof mass and substrate as \( x = x_m - x_s \), equation (1) can be written as:

\[
m \ddot{x} + c \dot{x} + kx = ma. \tag{2}
\]

For the inertial switch with electrostatic force assistance, the dynamic equilibrium equation (2) of the spring mass system can be expressed as follows [3]:

\[
m \ddot{x} + c \dot{x} + kx = \frac{\varepsilon_0 V_{DC}^2}{2(x_0 - x)^2} + ma \tag{3}
\]

where, \( \varepsilon_0 \) is the permittivity of air, \( x_0 \) is the initial gap between the movable electrode and the stationary electrode, and \( V_{DC} \) are the effective overlap electrode area, and potential voltage difference between the parallel plates, respectively.

MEMS inertial switches were firstly proposed in 1972 [1]. Since then, they have been under extensive research and development. They have been optimized and improved in structure design and performance for different application requirements. Before the emergence of the MEMS technology, the development of inertial switches was based on precision machining technology. However, the precision machining technology may not meet the requirement of small size and low-cost batch production compared to MEMS [8]. This limited the application scale of inertial switches. In particular, there was a difficulty to meet the requirements in the fabrication integration. The MEMS technology has resolved this issue and has brought several additional advantages, such as miniaturization, low cost of fabrication, batch production, zero power consumption at the normal state, high sensitivity, and high reliability [9, 10]. The inertial switch fabricated through the MEMS technology (also called micro machined inertial switch) has quickly replaced the inertial switch based on precision machining. At present, the micromachined inertial switch is widely applied, such as in accessories, video games consoles and toys, the transportation of special goods, automotive, defense security, arming and firing systems, shipment monitoring, geriatric healthcare systems, the internet of things (IoT), airbags, and remote monitoring (RMON) [11–20].

IoT has been an inevitable tendency in the current quickly developing information and technology field, which has attracted great attention from the scientific and industrial communities in the recent years. At its core, numerous sensors are utilized to sense complicated effects and parameters from the environment while being wireless, low-power, and multifunctional. The micromachined inertial switch is applied more and more extensively because of its no-power consumption feature under the normal off state. For example, in remote areas where it is inconvenient for the power supply to recharge and re-change, the low power consumption performance of the micromachined inertial switch is of prominent advantage. Although accelerometers systems can be used to realize the same function of inertial switches; such systems usually are more complicated requiring, in addition to the accelerometers, actuators and a decision unit/microcontroller. Also, the inertial switch has zero power consumption in its more often off-state while the accelerometer always needs a continuous power supply even when it senses no acceleration or inertial signals. Hence, power consumption and maintenance cost are much higher for accelerometers compared to inertial switches especially for IoT applications. Therefore, the inertial micro switch is promising to be widely used in RMON systems [11, 21]. Furthermore, these switches and triggers have more immunity to electromagnetic interference compared to accelerometers [18].

This review paper complements recent review papers [7, 20, 22] and, in addition, adds a different perspective, contemporary applications, and new future directions. Some of the main highlights of this review papers can be summarized as follows:
First, the paper will review tunable inertial switches using the combination of electrostatic and acceleration forces and also highlights that this class of smart devices can have great potential to save energy and data in the IoT era. Here, we provide details on this class of smart devices and discuss future needs and research directions. Second, new important applications of inertial switches are covered here, which received less attention before, such as safety and arming devices, application of free-fall laptop fall, healthcare, structural health monitoring, IoTs, and goods vibration monitoring. For example, a novel inertial switch with a specially designed filtering mechanism can realize acceleration band-pass characteristics. It plays a critical role in fuze applications. Third, we discuss the future potential research of the inertial switch using machine learning techniques. Inertial switches can play key role here since they can work with accelerometers and other inertial sensors to reduce the amount of data that need to be transmitted and processed by machine learning.

2. Key performance parameters of micromachined inertial switches

The working principle of inertial switches is as follows: when the acceleration signal is applied to the micromachined inertial switch, the movable electrode moves in the sensing direction toward the stationary electrode. Then, if the acceleration exceeds a critical value, the movable electrode and the stationary electrode contact each other closing an external circuit. This critical acceleration value is defined as the threshold acceleration ($a_{th}$). It is usually designed according to the required practical application. Therefore, micromachined inertial switches are designed for variety of different threshold levels, which can be applied to various applications. We can classify two main categories according to the threshold levels [23–26]: the relatively high-g (i.e. 100 g, 1000 g) switch and the low-g switch (i.e. 1 g, 10 g) as shown in table 1.

![Figure 1. Schematic of the basic model of an inertial switch. In the figure, $R$ is a current-limiting resistor.](image-url)
3. Basic category of micromachined inertial switches

Different MEMS inertial switches are categorized according to contact mechanism, actuation direction, and acceleration threshold. Table 2 summarizes the performances of some basic MEMS inertial switches. Table 2 shows mainly three categories of typical switches according to directional sensitivity: unidirectional, triaxial, and multi-directional switches. The actuation direction refers to the sensing direction of the inertia switch (the motion direction of the proof mass). Depending on the different sensing directions, the inertial switches can be categorized into the vertical direction, the horizontal direction, and the vertical and horizontal direction switches. The vertical and horizontal direction switch means that the proof mass can move along the horizontal sensing direction or the vertical sensing direction. The acceleration threshold sensitivity refers to the magnitude of the threshold acceleration. For the inertial switches with multiple thresholds, the threshold acceleration may range from low-g threshold to high-g threshold (i.e., 10 g–2000 g). Contact time refers to the duration the movable electrode and stationary electrode remain in steady contact. The mechanism of contact enhancement refers to the approach used for the inertial switch to extend the contact time.

### 3.1. Inertial switches using squeeze-film effect for prolonging the holding time

Matsunaga et al. [18, 32] reported a single-axis inertial switch by utilizing squeeze-film effect for side airbag systems to extend the contact time (figure 2). When the device is subjected to a sufficient acceleration, the mass moves along the sensitive direction and touches the stationary electrode. The contact time is determined by the squeeze-film damping force between the glass and the mass. It is experimentally verified that the contact time decreases as the input acceleration decreases. The test holding time of the on-signal reaches 6 ms under the acceleration of 53 g. The test contact resistance with the $A_u$ micro-spring electrode is 600 mΩ. It is clear that the test results can meet the requirement of the side airbag system. However, this kind of designs requires a large contact surface for generating the high squeeze-film damping force requiring that the size of the proof mass to be very large, which is not desirable for miniaturization. On the other hand, the contact time of inertial switches is affected by many factors, such as the acceleration amplitude and the elastic restoring force. Especially for the high-g values, the squeeze-film becomes weaker than the elastic restoring force. Hence, it requires a higher squeeze-film damping force in order to extend the contact time.

#### 3.2. Inertial switches with CNTs to prolong the contact time

Lee et al. and Choi et al. [41–43] reported a uniaxial inertial microswitch using carbon nanotube (CNT)-contact pads for prolonging the contact time, which is illustrated in figure 3. The designed threshold acceleration is decided by the spring constant $k$, the effective mass $m$, and the gap spacing $l$. $k$ and $m$ mainly relate to lithography and deep ion etching, so they are easily controlled. However, the gap spacing $l$ relies on the grown length of the CNTs. So, it is crucial to control precisely the grown length of the CNTs in order to achieve the precise threshold level. In this work, the same length of the CNTs bundles can be obtained by utilizing the bistable mechanism and the self-termination characteristic of the CNT growth process. The chevron thermal actuator can switch the bistable flexure from one stable equilibrium state to the other. It can be seen from a gap formation process [43] that the gap spacing $l$ is the distance between the two different stable equilibrium positions. Therefore, $l$ can be precisely controlled by designing various bistable flexures. The CNTs on the surfaces of the two electrodes can change their surface properties. When the device is accelerated up to an acceleration at or above the threshold value, the movable electrode moves forward in the sensing direction, colliding with the stationary electrode. As shown in figures 4(a), a pair of CNT bundles on the two electrodes makes contact, and the external circuit is switched on. Once the movable electrode gets closer to the stationary electrode, the CNT-contact electrodes are elastically deformed. In addition to the elastic properties of the nanotubes, there is also friction adhesion between the carbon nanotubes. It makes the two electrodes maintain a longer contact time due to the

| Orders of acceleration threshold | Application events | The location in this paper | Reference |
|---------------------------------|---------------------|---------------------------|-----------|
| 1 g                             | Motion and orientation detection in health applications | Section 4.1 | [24] |
| 1 g                             | Free-fall detection to protect the hard drive disk (HDD) of a laptop | Section 4.4 | [23] |
| 10 g                            | Detection for a rocket motor ignition system | Section 4.2.1 | [25] |
| 10 g                            | Safe/armed position convertibility in safety and arming unit (SAU) | Section 4.2.2 | [27] |
| 10 g                            | Damage detection in special goods transportation | Section 4.3 | [28, 29] |
| 1000 g                          | Impact detection for fusing munitions | Section 4.2.3 | [26, 30, 31] |

**Table 1.** Summary of typical low-g and high-g switch application events.
friction adsorption between the CNT contact pads. Therefore, the deformable CNT-contact electrodes can improve the contact effect between the two CNT contact pads. As a result, the contact time of the inertial switch in this case is much longer than the conventional inertial microswitches without CNT-contact pads as shown in figure 4(b).

The test results of the fabricated devices [43] demonstrate that the contact time is 114 µs, while the identical conventional inertial microswitches without CNT-contact pads as shown in figure 4(b).

Table 2. Summary of some of the reported inertial switches.

| Directional sensitivity | Actuation direction | Acceleration threshold sensitivity | Mechanism of contact enhancement | Contact time | Reference |
|-------------------------|---------------------|-----------------------------------|----------------------------------|--------------|-----------|
| Unidirectional          | Vertical direction  | Low-g                             | Squeeze-film damping force       | 6 ms         | [18, 32]  |
|                         |                     |                                   | An elastic beam with holes       | —            | [21]      |
|                         |                     |                                   | Movable contact point            | 12 µs        | [10]      |
|                         |                     |                                   | Electrostatic force              | 30 µs        | [2]       |
|                         |                     | High-g                            | Flexible electrode with a spiral spring | 50 µs        | [38]      |
|                         |                     |                                   | Electrostatic force              | Persistent   | [39, 40]  |
|                         |                     | Low-g and high-g                  | Electrostatic force              | Persistent   | [23]      |
|                         | Horizontal direction| Low-g                             | Deformable                       | 108 µs       | [41]      |
|                         |                     |                                   | CNT-contact pads                 | —            | [42]      |
|                         |                     |                                   | A liquid-metal droplet           | Persistent   | [44–46]  |
|                         |                     |                                   | Latching mechanism               | Persistent   | [47]      |
|                         |                     | High-g                            | Transforming mass                 | —            | [48]      |
|                         |                     |                                   | Electrostatic force              | Persistent   | [27, 49]  |
|                         |                     | Low-g and High-g                  | Angled latching mechanism        | Persistent   | [50]      |
|                         | Tri-axial           | Vertical and horizontal direction | High-g                           | Synchronous follow-up            | 390 µs     | [54, 55]  |
|                         |                     |                                   | Flexible electrodes              | —            |           |
|                         |                     | Low-g and High-g                  | Elastic beam                     | 200 µs       | [56]      |
|                         |                     |                                   |                                   | 80 µs        | [57, 58]  |
|                         |                     |                                   |                                   | 255 µs       | [59]      |
|                         | Multi-directional   | Vertical and horizontal direction | Low-g                            | Deformable polymer-metal composite | 110 µs     | [60]      |
|                         |                     |                                   | Flexible electrode               | 40 µs        | [61]      |
|                         |                     |                                   |                                   | 120 µs       | [62]      |
|                         |                     | High-g                            | Flexible electrode               | 40 ~ 120 µs  | [63]      |
|                         |                     |                                   |                                   | 70 µs        | [64]      |

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Kuo et al [21, 65] designed a passive inertial switch that can realize the conductive function by using multiwall carbon nanotube (MWCNT)-hydrogel composite. The device structure is depicted in figures 5(a) and (b). It mainly consists of three parts: the water droplet in the V-shaped groove, an inductor/capacitor (L–C) resonator on the substrate, and a polydimethylsiloxane microfluidic chip containing MWCNT-hydrogel composite. Figures 5(c) and (d) show the working principle of the switch, which is different from the working principle of the general mechanical inertial switch. Initially, carbon nanotubes hydrogel composite and water droplet are separated by the microchannel in the different two areas. The designed water droplet in the reservoir is considered as the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode. When the acceleration is greater than the designed threshold level in the horizontal direction, the water droplet moves into the hydrogel cavity through the microfluidic channel. While the hydrogel swells, it bends the flexible floating electrode downwards, thus decreasing the gap and transforming the movable electrode.
Figure 2. The bulk micromachined silicon mechanical acceleration switch structure. Reprinted from [18], Copyright (2002), with permission from Elsevier.

Figure 3. Schematic of the inertial switch using the deformable CNT-contact electrodes to extend the contact time. (a) A suspended movable electrode and a stationary electrode with bistable structure. (b) The CNT bundles synthesized on the surfaces of two electrodes are considered as the deformable electromechanical contact pads. © 2011 IEEE. Reprinted, with permission, from [43].
the capacitance variation by the resonance frequency. Correspondingly, the acceleration value can be calculated by the capacitance variation.

Although the fabrication process of this type of inertial switch is not complex, the fusion of water droplets with the hydrogel composite is an irreversible process. This device is only one-time use. In addition, the water droplets may leak or evaporate due to sealing imperfection. This kind of devices requires very high sealing conditions in order to guarantee the quality of the inertial switch, which further complicate the requirements for packaging.

3.3. Inertial switches using liquid-metal droplet (LMD) as a movable electrode

Yoo and Park et al [44–46] presented a microscale LMD in a micro-structured channel that serves as the movable electrode for detecting the applied acceleration. The designed and fabricated single-axial inertial switch is depicted in figure 6. Several kinds of channel configurations are designed for various threshold levels. An LMD is initially placed in the microstructured channel as an initial off-state, as depicted in figure 7(a). When the applied acceleration is greater than the threshold value, the LMD as the movable electrode passes through the neck and flows toward the stationary electrodes. Hence, a stable contact is carried out, keeping a stable on-state, as is depicted in figure 7(b). However, the fabrication process is very risky due to the fact that the LMD is made of mercury, which is highly toxic. There are non-toxic LMD alternatives to mercury, such as gallium and eutectic gallium indium.

Based on a similar principle, Huang et al [53] presented a microfluidic time-delay inertial switch as shown in figure 8(a). It mainly consists of silicon and glass substrates, which fill in working fluid (glycerol). Figure 8(b) demonstrates...
the working principle of the microfluidic time-delay inertial switch. First, the glycerol as the working fluid lies in the storing reservoir as an initial off state. When the applied acceleration exceeds the threshold value, the glycerol moves from the storing reservoir to the sensing one, and then the external circuit realizes a stable closed state. The response time here represents the time it takes for the glycerol to cover the sensing electrodes and the switch becomes in on-state. Measurements
of the fabricated inertial switch with working fluid (glycerol) show that the response time changes from 4.1 to 10.9 s when the design parameters vary from valve angle $\beta = 30^\circ$ and the neck-width $w = 1000 \mu$m to $\beta = 60^\circ$ and $w = 500 \mu$m. The main advantage of this design is the replacement of the highly toxic mercury by glycerol, which is safer to fabricate and also avoid undesirable effects on the environment. Hence, the selection of the working fluids is very important in practical application.

3.4. Inertial switches with latching

In this class of devices, upon contact between movable and stationary electrodes, both electrodes are locked by a latching structure to effectively perform a high contact reliability function. Currano et al. [47, 51] designed a latched single-axial inertial switch (figure 9). When the device is subjected to an acceleration that exceeds the threshold value, the switch is switched on, forming an external electrical circuit. This designed latching structure prevents the movable electrode from moving back to its original position, even after the applied acceleration event is over, and the external electrical circuit remains closed. The contact time is extended indefinitely.

One issue with such a switch with a latching mechanism is that it can be only used once (one shot). Therefore, it is necessary to design a reset actuator, which can unlatch the switch to be able to reuse it. The original position of the stationary electrode can be changed by the thermal reset actuators driven by electric current in order to realize the unlatching function. Figure 9(b) demonstrates the working principle. Firstly, the movable electrode starts to contact the stationary electrode under acceleration (figure 9(b) (ii)). If the acceleration is sufficient, the mass moves all the way beyond the latch and realizes the lock function (figure 9(b) (iii)). Finally, the mass settles back against the latch into its resting state (figure 9(b) (iv)). Although these types of inertial switches can effectively realize a stable contact, the reset process is complex. The need for reset logic in the overall system may limit its application.

Reddy et al. [52] designed a latching inertial switch as shown in figure 10. Figure 11 shows an overview of the zero-power inertial switch before contact and after an applied acceleration event, respectively. The proof mass moves forward in the sensitive direction and contacts the stationary part when the device is subjected to an acceleration that exceeds the threshold value. The springs (4) and an electrostatic actuator (5) connect the latch parts (3) to the stationary part (6). They can be integrated for reinitializing the device when the coupling between the latching parts is released. Considering the advantage of reusability, the designed inertial switch can be used to last for long-term RMON applications; particularly when the power supply is limited. The different accelerations make the proof mass reach the corresponding latch position and realize multi-threshold events monitoring. Meanwhile, the proof mass is prevented from moving backward by the hook-shaped latch after the applied acceleration event.

Singh et al. [50] proposed an inertial switch with an independent angled latching mechanism as shown in figure 12, which is made-up of a serpentine spring-mass system with an independent angled latching mechanism and multiple contacts. The switch’s behavior was observed when the mechanical shock 3500 g applied to it. Its test resistance was about 100 M\(\Omega\) in the off position and 2 \(\Omega\) in the on position, respectively.

3.5. Flexible electrode inertial switches

In the conventional designs, both the movable and the stationary electrodes are very stiff, which leads to an almost rigid collision. This is especially true for the conventional bulk micromachined silicon inertial switch. The contact-bouncing behavior is unavoidable and the contact time is extremely short. When switch-on time is extremely short, it can be
Figure 10. (a) SEM image view of the fabricated inertial switch with multi acceleration thresholds. (b) SEM image of the close-up of the latching component. Reproduced from [52]. CC BY 4.0.

Figure 11. Schematic view of a designed inertial switch (a) in unlatched state and (b) in latched state. Reproduced from [52]. CC BY 4.0.

Figure 12. (a) SEM image of the fabricated switch. (b) The enlarged view of the movable electrode and stationary electrode. © 2021 IEEE. Reprinted, with permission, from [50].
Noetzel et al [48, 66] reported two inertial switches, which consist of a proof mass and a beam as the spring. Design 1 in figure 13(a) shows the proof mass located at the tip of the cantilever beam while design 2 in figure 13(b) demonstrates the proof mass located in the middle of the cantilever beam. The contact time of design 1 is very short. A desired prolongation of the contact time was realized by design 2. When the position of the proof mass changes from the center of the cantilever beam to its tip, the contact-bouncing effect is significantly reduced. Correspondingly, the switch-on time is greatly extended because of the elastic deformation by replacing the rigid proof mass by the compliant cantilever tip.

As shown in figure 14, Yang et al [10] reported a vertically driven micro-switch with compliant bridge-type beams serving as flexible ground electrodes. This decreases the stiffness of the ground electrodes and improves the contact effect of the micro-switch to some extent. The characterization of the fabricated prototype indicates that the test switch-on time is less than 12 μs.

On the other hand, Cai et al [2] redesigned a centrosymmetric structure switch with one multiple-hole cross beam as the ground electrode. A contact point was introduced replacing the proof mass as the movable electrode, as illustrated in figure 15.
Table 3. Comparison of three structural designs of switch electrodes. © 2009 IEEE. Reprinted, with permission, from [2].

| Inertial micro-switches | Rigid stationary electrode (traditional design) | Compliant stationary electrode |
|-------------------------|-----------------------------------------------|-------------------------------|
|                         | ![Rigid Stationary Electrode](image1.png)       | ![Compliant Stationary Electrode](image2.png) |
| Load form               | ![Rigid Load Form](image3.png)                  | ![Compliant Load Form](image4.png)               |
| Contact process         | ![Rigid Contact Process](image5.png)            | ![Compliant Contact Process](image6.png)         |
| Contact area on the proof mass | ![Rigid Contact Area](image7.png) | ![Compliant Contact Area](image8.png) |
| Deformation of the stationery electrode | ![Rigid Deformation](image9.png) | ![Compliant Deformation](image10.png) |

In addition, the movable electrode, from the original design to the redesigned one, is changed from the proof mass to a contact point, as shown in table 3. So the contact area between two electrodes changes from two edges to one point in the center. Correspondingly, the distributed load becomes a concentrated one. Therefore, the contact effect in the redesigned structure is improved effectively. The tested contact time is about 30 µs under 85 g in the redesigned device, which is much longer than the original one.

Figure 15 shows that the inertial switch has a contact point suspended by a spiral spring instead of the fixed point [38]. By introducing the spiral spring, the inertial switch can form a dual mass-spring system. This can enhance contact and reduce the contact-bouncing behavior by replacing the rigid contact point by the flexible spiral spring. The test results show that a steady switch-on time of over 50 µs is obtained, which is significantly improved compared to the inertial switch that has a fixed contact point installed in the center of the proof mass. The inertial microswitch with a spiral spring was fabricated with the multilayer electroplating technology. The researchers in [38] optimized electroplating to reduce residual stress in the electroplated nickel structures, as indicated by the planar structures in figure 16.

Xu et al [54, 55] designed an inertial micro switch with synchronous follow-up flexible electrodes, as depicted in figure 17(a). Both the movable electrode and the stationary electrode are optimized to prolong the contact time. As shown in figure 17(b), the two electrodes consist of a spring-shape structure and a double-stair shaped structure, respectively. In the design, the x and y directions are equal. The vertical direction is the z-off-axis sensitive direction. The designed constraint layer can suppress the vibration of the inertial switch in the vertical direction (out-of-plane) so that it improves the single-axial sensitivity of the inertial switch. Meanwhile, the constraint structure can reduce the contact-bouncing behavior so that the stable signal and high reliability can be achieved. The device has a switch-on time 390 µs under the acceleration of 466 g.
3.6. MEMS inertial switches with electrostatic force assistance

One concept that has been proposed to resolve the issue of short contact time is through using the combination of electrostatic and acceleration forces to induce the pull-in instability in the proof-mass/moveable electrode. Then, the moveable electrode collapses making a direct contact with the stationary one. Because, in this case, both the moveable and stationary electrodes form a capacitor; they remain locked on contact even after the acceleration signal goes away. In addition, these switches have the advantage of being tunable; i.e. the threshold of triggering is adjustable depending on the applied bias voltage [3].
An analytical expression of the static electrostatic pull in the equation is expressed as [3]:

\[ V_{\text{pull}} = \sqrt{\frac{8kd^3}{27\varepsilon A}} \]  

(4)

where \( k \) is the spring constant, \( d \) is the distance between the stationary electrode and movable electrode, \( A \) is the effective overlap area between two electrodes, and \( \varepsilon \) stands for the permittivity of the gap medium.

In 2006, Younis et al [23] proposed the use of the combination of electrostatic and acceleration forces to realize tunable inertial switches, ‘smart MEMS switches triggered at a pre-set threshold value’, for both low and high values of \( g \). The \( g \)-switch with adjustable threshold can be carried out by the combination of mechanical shock and electrostatic force. One can adjust the \( g \)-level of the switches by controlling the voltage.

Figure 18(a) shows a schematic of such a device. Figure 18(b) shows simulated results proving the concept through nonlinear reduced-order and finite element models for a cantilever beam forming an upper proof mass. The silicon cantilever microbeam parameters are the length \( L = 100 \mu m \), the height \( h = 0.1 \mu m \), the width \( b = 10 \mu m \), and the gap between two electrodes \( d = 2.0 \mu m \).

In 2007, Younis et al [33] demonstrated the concept of smart MEMS switches experimentally for low-\( g \) range. The tunable nature of the new switch is tested by different values of DC voltages. Figure 19 illustrates the pull-in voltages against the shock load. It is clear that for any point of the tested shock amplitude and voltage above the solid line, the switch is activated. Otherwise, the switch is off state.
In 2012, Quakad et al. [39] demonstrated experimentally a similar switch concept for very stiff beams and showed the pull-in-shock curve. For their beam, the shock threshold beyond which there is a pull-in phenomenon is 200 000 g at a DC load of 5 V. This indicates that the beam is very stiff, becoming impractical to test the beam. Figure 20 shows that the pull-in voltage drops from 82 V to 5 V when the shock amplitude increases from 0 to 200 000 g. Therefore, an electrostatic force is used to bring down the threshold of collapse to a range where the device can be tested using the in-house available shock testing equipment. Hence, such an approach is helpful to test the reliability of MEMS microbeams under shock at low cost.

The micro cantilever beams were tested by a drop-table machine, figure 21, under the combination of shock and electrostatic loads on them. The tested pull-in voltage is 84 V when the shock load is zero. The microbeam is biased by different DC voltages and shock loads and the results obtained are shown in table 4.

In 2013, Ramini et al. [34] proposed a low-g switch in the sub-g level. The idea is based on using not only electrostatic DC load, but also an AC load, in addition to the acceleration signal. Experimental investigation demonstrated that the switch can be activated at small levels of acceleration lower than 0.02 g. When the amplitude of acceleration 0.04 g with a period of 0.05 s applied on the resonator, there is a switching action of the device as shown in figure 22. In fact, the resonator experiences dynamic pull-in hitting the lower electrode. The experimental results as shown in figure 22(c) agree with the numerical simulations shown in figure 22(d).

As the inertial switch with electrostatic force discussed above, the moveable and stationary electrodes form a capacitor. Upon pull-in, contact is made with another separate drain circuit to indicate switching, which is isolated from the actuation circuit. Jia et al. [40] designed a cantilever-type inertial switch under the combined effect of mechanical shock and electrostatic pull-in force to extend contact time. The threshold value ranges from 1000 to 5000 g by controlling the voltage. The inertial switch still can maintain the on state under the electrostatic pull-in after the shock event is over. A sketch of the cantilever-type shock switch and SEM micrograph of
Figure 22. The response of the resonator for $V_{DC} = 50$ V and $V_{AC} = 55$ V at 151 Hz. (a) The acceleration pulse of amplitude 0.04 g with a period of 0.05 s. (b) The absolute experimental displacement of the proof mass. (c) The measured relative motion of the proof mass to the substrate. (d) The numerical simulation of the relative motion. Reproduced from [34]. © IOP Publishing Ltd. All rights reserved.

Figure 23. (a) Structure diagram of the cantilever-type shock switch; (b) SEM images of the fabricated devices. Reproduced from [40]. © IOP Publishing Ltd. All rights reserved.

the prototype devices is illustrated in figures 23(a) and (b), respectively.

Using the same principles, Zhang et al [35, 36] presented a heterogeneous integrated inertial switch, which can maintain a stable contact between two electrodes utilizing the electrostatic force locking, as illustrated in figure 24. The test threshold increases from 24 g to 50 g by controlling the bias voltage from 44 V to 38 V. The devices are fabricated by the non-silicon surface micromachining and silicon-based technologies.

Li et al [37] designed an inertial micro switch with multi-step pulling action and electrostatic force locking. As shown in figure 25, these array-type interconnection structure are the fixed electrodes and they mutually insulate with the pulling electrode by air. The test contact time is about 540 $\mu$s. Compared to the conventional inertial switch, the flexible
Figure 24. Structure diagram of the switch with electrostatic force assistance. (a) Three-dimensional sketch of the inertial switch before and after bonding. (b) Bottom views of the switch. (c) Top and bottom views of the switch and (d) its side view. Reprinted from [36], Copyright (2019), with permission from Elsevier.

Figure 25. (a) Structure diagram of the proposed electrostatic force-assisted contact-enhanced MEMS inertial switch. (b) Schematic of the array-type fixed electrode and pulling electrode, and (c) top view of the moving electrode. Reproduced from [37], with permission from Springer Nature.

Connecting multi-plane proof mass (movable electrode) can carry out the multi-step pulling action, which eliminates the bouncing behavior and reduces the pull-in voltage.

Kim et al [27, 49] developed a bi-directional tunable acceleration switch with pulling and pushing comb-drive actuators, as shown in figure 26, which are used to increase or decrease the threshold level of the switch. The threshold level can be controlled by the potential between the stator electrodes and the rotor comb electrode. This is possible because the magnitude of the threshold increment or decrement is proportional to the square of the electrical potential. The threshold value of the designed switch is 10.25 g without a tuning voltage. Furthermore, it is increased up to 17.25 g or decreased to 2.0 g by 30 V tuning voltage to pulling and pushing the
Inertial switches with multiple thresholds

Most of the inertial switches are designed as a single threshold. Such switches are all binary with only on-off information preventing more precise information and knowledge on the severity and intensity of impact. Such quantitative information is very important, for instance for the diagnosis and treatment of head impact, in which the severity of the injury depends on the magnitude of shock. The conventional way to detect the different threshold levels is to integrate several inertial switches with various threshold accelerations on a single chip. Currano et al [56] presented a full chip with five inertial switches of various threshold values that vary from 50 g to 250 g. As shown in figure 27, the mass and the gap between the two electrodes are kept constant for the five individual switches. In addition, the spring width is also kept constant. In order to achieve different thresholds, the elastic coefficient of the spring is changed by designing the different angles traversed by the spring.

Selvakumar et al [67] reported a threshold level detection microsystem, which consists of an array of different threshold levels switches illustrated in figure 28. The switches were fabricated by utilizing the bulk-silicon dissolved-wafer process. The process enables the switches to employ different silicon inertial masses. Table 5 shows the range of threshold levels for

![Figure 26. A schematic view of the proposed bi-directional acceleration switch. Reprinted from [27], Copyright (2014), with permission from Elsevier.](image)

![Figure 27. Full chip with five acceleration threshold sensors. Reprinted from [56], Copyright (2013), with permission from Elsevier.](image)
correspond to the first, second, and third threshold levels, a group of three at each side, and stationary electrodes, which levels is mainly made up of the proof mass, movable electrodes figure forming quantitative acceleration measurements. As shown in acceleration is increased from 10 g to 100 000 g. Xu et al. demonstrated the concept based on a set of multiple metal beams and contact pads. The different beam dimensions lead to different beam deflections when the acceleration is accelerational. The designed device is a two-axis switch, which can trigger in all directions in a single plane. The test results show that the fabricated device prototypes can sense an acceleration range of 800 g–2600 g.

As shown in figure 10, Reddy et al. [52] proposed a multi-threshold shock sensor to record multiple threshold events. The latching part on the proof mass makes the discrete latch positions depend on the applied acceleration, and extend the contact time. The proposed shock sensor allows a threshold acceleration in a wide range from 20 g to 250 g with ten different threshold values.

### 3.8. Inertial switches with tri-axial and multidirectional sensitivity

Various application environments require different functionality for the inertial switch. Unidirectional switches have been widely used in many applications from safety systems, consumer electronics to RMON, etc. However, the unidirectional sensitive switches can only sense and detect acceleration in one direction. In many practical applications, sensors are required to detect multidirectional acceleration signals. Originally, the multidirectional inertial switch is composed of some unidirectional switches laid in different directions. However, this lead to the disadvantages of complexity, bulkiness, and less reliability [57]. Hence, there is an advantage in replacing multiple single-axial switches with a tri-axial or multidirectional switch.

Recently, several tri-axial or multidirectional inertial switches have been reported [58–61, 63, 64]. Currano et al. [56, 59] proposed a three-axis acceleration switch to detect the acceleration in $\pm x$, $\pm y$, $\pm z$ directions, which is depicted in figure 30. In this symmetrical design, the inertial switch cannot resist the reverse impact, and easily results in spurious trigger in the reverse sensitive directions because of the rigid contact in the sensitive direction. So the axial disturbance is very severe. Chen et al. [57, 60] demonstrated a tri-axial inertial switch with precise distance between the proof mass and the limit block as shown in figure 31. This design reduces the

| Threshold | Length $l_b$ and width $w_b$ of the beam ($\mu$m) | Length $l_m$ and width $w_m$ of the mass ($\mu$m) | 3 dB cut-off frequency $f_c$ (Hz) |
|-----------|-----------------------------------------------|-----------------------------------------------|-------------------------------|
| 1.5 g     | 100, 50                                       | 175, 114                                      | 45                            |
| 2 g       | 75, 50                                        | 100, 100                                      | 1120                          |
| 5 g       | 75, 50                                        | 200, 100                                      | 670                           |
| 10 g      | 50, 50                                        | 100, 100                                      | 9918                          |
| 50 g      | 60, 15                                        | 40, 63                                        | 39 793                        |
| 100 g     | 60, 30                                        | 40, 63                                        | 39 793                        |
| 1000 g     | 50, 30                                        | 35, 71                                        | 39 793                        |

*2.5 $\mu$m thick mass.*

the designs ranging from 1.5 g to 1000 g, with the inertial mass sizes increasing from 0.015 $\mu$g to 0.7 $\mu$g.

With the recent improvement of the inertial switch structure in terms of design and performance, a major research focus nowadays is on the development of a multiple threshold sensor using a single mass instead of integrating multiple switches with different threshold levels. So the multiple threshold inertial micro switches using a single mass [1, 52] can save space compared to the multiple-threshold switch, which consists of 5 proof masses [56]. In 1972, Frobenius et al. [1] demonstrated the concept based on a set of multiple metal beams and contact pads. The different beam dimensions lead to different beam deflections when the acceleration is accelerated in a direction normal to the contact pad. The threshold acceleration is increased from 10 g to 100 000 g. Xu et al. [68] reported a multi-threshold inertial switch capable of performing quantitative acceleration measurements. As shown in figure 29, the designed inertial switch with three threshold levels is mainly made up of the proof mass, movable electrodes (a group of three at each side), and stationary electrodes, which correspond to the first, second, and third threshold levels, respectively.
Figure 29. (a) Sketch of the multi-threshold inertial switch; (b) A close-up of the movable electrodes and stationary electrodes indicated by the blue dotted line in (a). © 2021 IEEE. Reprinted, with permission, from [68].

Figure 30. SEM image of the three-axis acceleration microswitch. Reprinted from [56], Copyright (2013), with permission from Elsevier.

Figure 31. Structure diagram of the designed tri-axial inertial switch with low axial disturbance. Reprinted with permissions from [57].
axial disturbance. In addition, it not only does sense the shock vibration in \( x, y \), and \( z \) directions, but also it avoids the crosstalk between the vertical stationary and the horizontal electrodes.

In 2012, Yang et al. [60] proposed a multidirectional inertial switch with a polymer–metal composite stationary electrode. Figure 32 shows the structure mainly comprises of a suspended proof mass, a series of cantilever beams as the lateral stationary electrodes, and a T-shaped structure as the vertical stationary electrode. This design detects the applied shock vibration from any radial direction in the \( x-y \) plane and \( z \)-axis. The threshold level of the fabricated device is generally uniform in the lateral and vertical directions. The test threshold level is about 70 g. The test switch-on time of the prototype in \( z \)-axis is 110 \( \mu \)s. Chen et al. [61] designed a similar multidirectional threshold sensor. Twelve lateral cantilever beams were designed as 30° tilted to the radial direction in the \( x-y \) plane, which extends the contact time when the threshold sensor is accelerated up to a sufficient acceleration in the radial direction. The characterization of the prototype shows that the test threshold accelerations in the lateral direction and the vertical direction are 65 g and 60 g, respectively. In addition, Xi et al. [63] designed a novel MEMS multidirectional-sensitive inertial switch that has different sensing directions in a half sphere, as shown in figure 33. When the switch is accelerated up to an acceleration component (threshold level or above in axial or radial direction), the movable electrode (the single proof mass) touches the vertical electrode or the lateral electrode, forming an electrical path. When the different acceleration amplitudes (380 g, 450 g) are applied on the device in the \( x \)-axis direction, the test contact time is about 40 \( \mu \)s, 60 \( \mu \)s, respectively. Cao et al. [64] also presented a novel MEMS inertial switch, which can sense the acceleration in any
radial direction of a hemisphere. The test threshold level of the switch in the x direction is 596 g.

Du et al [62] reported a low-g MEMS inertial switch with uniform omnidirectional sensitivity as shown in figure 34, which consists of a single circular proof mass supported by four Archimedes’ spirals springs, the lateral limitation block, and four radial electrodes. The threshold acceleration of the switch with uniform omnidirectional sensitivity is about 40 g, which can sense the applied accelerations from any radial directions in the x–y plane.

4. Applications

MEMS inertial switches show promising potential in many fields such as health-care, military, shipment monitoring during special goods transportation, and other shock monitoring applications. Here we overview some of such applications.

4.1. Health application

Ongkodjojo et al [24] demonstrated the concept of a new inertial microswitch, which can actuate an alarm system for calling for helps in order to minimize injuries when an elderly falls down. As illustrated in figure 35, the fall sensor is attached to the developed MEMS-Wear smart shirt, which was developed for geriatric healthcare [62, 69]. When an elder person falls down alone at home, the impact force exceeds a threshold acceleration of 4.8 g [24]. Consequently, the circuit forms an electrical path and produces the pulse signal. The smart shirt, which the G-switch is incorporated on, sends the acceleration signal to the personal computer for data processing through a Bluetooth transmitter. The text messages are then sent to the hospital. The power supply is only electrically connected to the alarm when the fall sensor is triggered. Thus, this kind of alarm system reduces significantly the power consumption due to the inertial switch’s advantage of zero power under the normal state. In addition, other advantages of using the G-switch are low cost and small size in comparison to the accelerometers or the gyroscopes.

Besides inertial switches, classical inertial sensors and accelerometers can also be used in the medical field, which play a key role in helping physicians in disease diagnosis. For instance, with the increasingly aging populations, it is essential to detect abnormal heart rates in order to monitor people’s health. Yue et al [70] reported a wearable sensor, which can be used to collect physiological data ballistocardiogram (BGC signal) during skiing. Then BGC signals are removed and then analyzed. In most cases, the wearable sensor can identify the abnormal heart rate. Amini et al [71] provided an advanced technique, which can recognize and sense the location of sensors on the patient’s body. Automatic on-body sensor localization is applied in health and medical monitoring systems in order to guarantee the accuracy of measurements. The automatic on-body accelerometers are used to capture the motion data by using this technique. Furthermore, the doctors can estimate the location of the automatic on-body device on the human body by the motion data.

There are ample opportunities to incorporate more inertial switches for health applications. Currently, these applications rely on accelerometers like Yue’s [70] and Amini’s [71]. With the rapid development of accelerometer sensors for health applications, we believe that, similarly, there is a promising future for inertial switches in such applications; with the extra advantages of saving power and resolving the huge data related issues compared to accelerometers.

4.2. Military application

The inertial switches are of great interest in military applications. MEMS inertial switches are also developed for missile ignition systems. It is well known that a missile generally has a safe-and-arm device, which can stop unintentional or accidental firing of a rocket motor. When the missile’s dimension is highly restricted, an inertial micro switch is of high applicability due to the advantages of MEMS. The inertial switches can be used to turn on or off an electrical path of ignition systems in the missiles application. The inertial switch is turned on when the missile is subjected to an acceleration at or above a predetermined threshold level.
4.2.1. The ignition system for cold launched missiles. Lee et al. [25] reported a MEMS switch that is applicable to the safe-and-arm device of a rocket motor ignition system for cold launched missiles. The main goal of the work is to realize a MEMS inertial switch, which can be triggered at a low-g level (about 10 g) in the sensitive direction. Also, the switch should withstand unintentional impact (about hundreds of g) in the off-sensitive direction in harsh military environments. The horizontal inertial switch is composed of the proof mass (plate) and four folded springs, as illustrated in figure 36. The electrical path is formed as soon as the impact force exceeds the threshold level at a low-g level (about 10 g). A finite element model using ANSYS software was used to optimize the design parameters.

4.2.2. Safe/armed position convertibility. Inertial switches are widely applied in military field, such as a safety and arming unit. For example, the ammunition is safely stored by safe/armed position convertibility [72]. The inertial switch should be initially set to ‘safe’ position in order to avoid the spurious trigger when it is subjected to any accidental impact force. The switch is set to ‘armed’ position by applying electrical signal when the switch is activated under the external acceleration beyond the threshold level. Finally, the switch will return to the ‘safe’ position without arming signal [73]. As shown in figure 37, two hook-shaped springs are regarded as mechanical stoppers [27]. Without arming, the proof mass is restricted to move because the stopper prevents the proof mass from moving towards the fixed electrode. The designed gap between the proof mass and the stopper must be smaller than the gap between the contact parts. Hence, the inertial switch maintains still at ‘safe’ position. The inertial switch reaches the ‘armed’ position when the stopper is opened. At this point, the electrical path forms when the external acceleration exceeds the threshold level. In addition, the threshold level can be decreased or increased once the voltage is applied on the pushing comb or the pulling comb.

4.2.3. Application of safety and arming device. The MEMS Safety and Arming Device (SAD) plays a critical role in fuze applications. Generally, a normal inertial switch is in ‘ON’ state only when the applied acceleration exceeds the pre-determined threshold level, and otherwise it will be in the off state. So, a normal acceleration threshold switch is similar to the high-pass filter; however, this type of normal acceleration switch is still in on-state when subjected to an impact force far greater than the threshold level, making them unsuitable for some applications. In SAD, the special switch should be in the on state under the launching acceleration 6000 g, but maintains off state under accidental collision loads of 12 000 g. It is evident that the normal acceleration threshold switch cannot meet this requirement. Zhu et al. [30, 31] proposed a novel inertial switch with a specially designed filtering mechanism for realizing acceleration band-pass characteristics. The novel inertial switch can be triggered only when accelerated up to the load between the upper and lower cut-off threshold level, which is similar to the band-pass filter. As shown in figure 38, the proposed inertial switch mainly consists of the proof mass, serpentine spring, a latching mechanism, and an integrated filtering mechanism, which can be used to block the proof mass by transverse displacement. In figure 38, $t_1$ and $t_2$ are the times from zero to the time when the proof mass and the filter reach the critical position. Figure 39(a) shows the variation of $t_1$ and $t_2$ under the different amplitudes. With the increase of the
Figure 37. SEM micrograph of the fabricated prototype devices. The inertial switch is made of pulling comb, hook shaped spring, proof mass and stationary electrode. Close up of two hook-shaped springs. Reprinted from [27], Copyright (2014), with permission from Elsevier.

Figure 38. (a) Top view of the inertial switch with a filtering mechanism. (b)–(d) Close-ups of the switch. © 2021 IEEE. Reprinted, with permission, from [30].

amplitude, $t_2$ is smaller than $t_1$, and the filter reaches the critical position earlier than the proof mass. Then it will prevent the proof mass from moving forward (figure 39(b)), and the switch cannot form an electrical path. Figure 39(c) shows that the filter and proof mass reaches the critical position at the same time. When $t_2$ is larger than $t_1$, the proof mass will arrive in the critical position ahead of time (figure 39(d)). So the filter cannot block the proof mass. In short, the proposed inertial switch turns on if the applied acceleration is in the range of the lower cut-off threshold to the upper cut-off threshold. This kind of band-pass characteristics can be applied in the SAD field.

4.3. Application of MEMS inertial switches in special goods transportation

With the rapid growth of economic globalization, the global modern logistics industry has been developed substantially. It is essential for the special goods to detect damage when they are delivered, unloaded, and distributed. In the practical application, MEMS inertial switches can be embedded in goods and shipping containers that are used to monitor the transportation of special goods. MEMS switches are advantageous due to less power consumption, high sensitivity, low cost, and scale-up production. It is easy to know the health,
automotive airbag safety system, lifetime, and other item characteristics by monitoring those items [11, 74]. The switches give information for a user whether the special goods are damaged or not. As shown in figure 40, the inertial switches in the IoT system are used to monitor the overload impact during the transportation process. When the special goods are subjected to impact levels higher than the threshold level, the vibration threshold sensor outputs the signal pulse. Furthermore, the Radio Frequency RF device transfers the information to the information center, so as to carry out the real-time tracking. In addition, MEMS inertial switches are widely applied in various wireless sensor networks (WSNs) such as bridges, side airbag systems, and management systems [18, 75].

Recently, Ren et al [29] reported a self-powered inertial switch, which is applied in a wake-up system that can be used for the monitoring of cargos during transportation. The self-powered inertial switch is made up of parallel plates, fixed electrode, proof mass, movable electrode and the self-charging power unit as shown in figure 41(a). Figure 41(b) demonstrates the whole working principle of the wake-up system: energy harvesting and threshold triggering. When the device is subjected to a small vibration, the proof mass will vibrate up and down around the balance position. Correspondingly, the inducing charge begins to transfer due to the change of the capacitance of the parallel plates. The alternating current can be translated into direct current and thus it can be stored in the capacitor of a unit which is self-charging. When the impact force beyond the threshold level is applied on the self-powered inertial switch, the movable electrode touches the fixed electrode, which forms an electrical path. Then the charges stored in the capacitor will be released and generate the pulse signal.

When an automobile drives on a flat road, the self-charging power unit will collect and store this vibration energy from the environment as shown in figure 40(c). When the automobile drives on a bumpy road as shown in figure 40(d), the automobile body and goods will be subjected to a large shock impact. Embedding shock sensors in the automobile allows the monitoring of those special goods. Information from shock sensors can inform the user whether or not these special goods are damaged. In other words, a trigger signal will be generated when the self-powered MEMS inertial switch is accelerated up to or above the threshold values. It can be transmitted to the information center by additional radio frequency components. So the wake-up system can play a key role and have a potential application in special goods transportation. Compared to the accelerometers, a key feature of the inertial switch is that it consumes power only when it detects a shock event, so it is suitable for long-term monitoring applications.

4.4. Application of free-falling objects

In some practical applications, the switch must be triggered at a low threshold acceleration. For instance, for a laptop, a low-g switch of a threshold acceleration around 1 g, can be used to sense free falling; and hence can protect the hard drive disk upon falling. The low-g switches have potential applications in portable devices. Younis et al reported an MEMS switch
employing cantilever microbeams, which can be triggered under the threshold level (several g) before the impact [23].

5. The development trend and future main research directions

5.1. From a single-axis to multi-axis directions

The unidirectional sensitive switch can only detect acceleration in a single-axial direction. In the practical environment, the sensors need to monitor different directions of vibrations. Originally, three unidirectional switches in three individual directions need to be used together. However, it may lead to problems such as the sensitivity loss, installation error, and centroid deviation [64, 76]. Recently, the tri-axial inertial switch and multidirectional inertial sensors were reported as well. The tri-axial inertial switch can sense and detect three accelerations in the X, Y, and Z directions. The multidirectional sensors are used to detect multiple directions shock vibrations, which can provide substantial benefits, such as lower costs.

Compared to the unidirectional inertial switch, the tri-axial and the multidirectional ones improve the integration degree. For various applications, the directional sensitivity changes from a single-axial sensitivity to multidirectional sensitivity. In the future, research should try to improve the single-axial sensitivity of the unidirectional inertial switch and reduce the axial disturbances in the multidirectional-sensitive inertial switch. For example, the combined efforts of double layers suspended springs and constraint structures effectively lower off-axis sensitivity and improve single-axis sensitivity [77].

5.2. From single to multiple thresholds detection

As explained previously, many applications will benefit from determining more precisely the range of g that a body or an object was subjected to, rather than relying on a single binary information of exceeding a threshold or not. One approach is to combine many single-threshold switches; each of a different threshold; but this approach adds to the complexity, size, and cost of the system. At present, the design and performance of the inertial switches with the multiple threshold are still in the primary stage. Therefore, a main research direction is to design multiple threshold inertial switches of improved working performance, safety reliability, and system integration.

5.3. The development trend of low threshold and high precision

At present, the research on the low-g micromachined inertial switches has not occupied the mainstream. It is determined by the application fields. The current inertial switches are widely applied in many fields, such as automotive safety systems, defense security, military, and so on. The threshold level for such applications is usually higher than 30 g. With the development of health-care equipment, such as MEMS-wearable smart shirt, the inertial micro switch becomes one of the critical components of human body protection and inertial monitoring sensors, whose threshold is usually less than 5 g. Sawyer et al. [78, 79] reported and discussed high-precision MEMS inertial sensors by Silicon on Insulator (SOI) bonded wafer
process. High precision means that the threshold accelerations of a batch of fabricated devices are almost same. In most cases, a wafer manufacturer can make devices with ±1.0 µm dimensional tolerance. The threshold error range can be controlled within 2% for 1 µm tolerance. For the low-g switch, the biggest challenge is achieving high threshold accuracy. Therefore, the inertial switch with high precision and low threshold becomes the most important component of an intelligent equipment in future. Future researches should dedicate more attention to how to achieve high precision of the inertial switch with low threshold. This can be especially challenging considering that microstructures are usually too stiff; which can be an issue when designing low-g devices.

5.4. Improving the performance of the inertial switches

The performance of an inertial switch mainly depends on the response time, contact time, and other performance parameters that affect the safety and reliability of the device. In order to improve it, key factors need to be accounted for and investigated thoroughly, such as the anti-overload performance, contact stability, contact reliability, anti-interference performance, inter-axial interference performance and other performance parameters of the switch.

5.5. Future research using machine learning techniques

Falls affect the elderly all over the world and may become a very serious public health problem, even threatening people’s life. Although there are some commercial sensors for fall detection [80], they are unsatisfactory. They are criticized mainly due to the high cost and high false alarm rates. Ahmet et al [81] detect falls by using six wearable motion sensor units as shown in figure 42. Every unit mainly consists of accelerometer, gyroscope, and magnetometer. The author can distinguish falls from activities of daily living using six machine learning techniques (classifiers). In addition, two classifiers’ accuracy are all above 99%. This method is very applicable in the real world.

A standard accelerometer requires a constant supply power even when no acceleration exists. Wearable fall sensors, which comprises accelerometer, are battery-operated. However, these batteries are often required to be recharged. Compared to the accelerometer, inertial switches have the advantages of less power consumption, small size, simpler interface circuit, low cost and volume production. In a long lifetime or some small-scale systems with a confined power supply, inertial switches with less power consumption can last much longer [47]. Even though some commercial wearable sensors are available in the markets, the high initial and maintenance costs of the sensors make customers unsatisfactory [80, 81]. The inertial switch can reduce the running cost of the equipment because it draws no power at normal state. MEMS inertial switches are usually too stiff; which can be an issue when designing low-g devices.

Switches may be used to reduce the amount of data that need to be processed for the purpose of classification and building algorithms for falling detection, defects identification etc. For example, researchers in [81] used six accelerometers and six gyroscopes to detect falling using machine learning techniques. Each of these sensors has sampling rate of 25 Hz. The problem is that falling can happen at any time during the day. So, the system needs to handle (store, transmit, and classify) a large amount of data at all time. Alternatively, introducing a switch to such a system will insure triggering the needed sensors only when there is an event (need). This saves energy and alleviates the problem of dealing with huge amount of data making systems smarter and more efficient. So such switches may work with accelerometers and other inertial sensors to reduce the amount of data that need to be transmitted and processed by machine learning; and thus save power.

Gao et al [82] reported motion capture sensors, which can gather human motion data. The authors can choose the signal feature sequence that can identify the posture from the signal after the collected data format is processed. Therefore they can design a three-level hierarchical recognition algorithm of human pose based on these data. The experiments show that the whole system is reliable and applicable, which can meet the requirements of physicians for real-time monitoring of patient physiological parameters. There is opportunities to incorporate the inertial switch in such systems to reduce the amount of data, which need to be processed by machine learning techniques.

Figure 42. The configuration of the six wearable fall sensor units which is fixed on the volunteer’s head, chest, waist, right wrist, right thigh, and right ankle. Reproduced from [80]. CC BY 4.0.
5.6. IoTs applications

As its core, IoT relies on many sensors that are required to be wireless, low-power, multifunctional, and to adapt to complicated factors from outside environment. The inertial switches have been an excellent choice for IoT applications, such as for the vibration monitoring unit and WSN, because of its no-power at normal state, its passive characteristic, simple processing circuit and small electromagnetic interference.

With the rapid development of IoT, the inertial switch as a passive device has attracted great interest from the scientific to the industrial community. The WSN systems can send an overload alarm signal once detecting the shock level [24, 29, 74]. Particularly, the inertial switch can be used, where it is difficult to recharge the power supply. The power draw can significantly reduce the monitoring period before recharging the power source. It does not need a constant supply power, unless an acceleration event occurs, which can be a significant saving of running and equipment maintenance.

6. Conclusion

In this review, the recent advancements of inertial micro switches have been surveyed along with details on their working principle, the key performance parameters, and their categories (such as multi-threshold, the switches with electrostatic force, LMD). The review shows that the main performance parameters of inertial micro switches have been significantly improved in recent years, including the contact time, the sensitive direction, threshold acceleration, contact effect, and threshold accuracy. With regard to the high-g switch, an on-state test contact resistance can be reduced to 2 Ω. Concerning the low-g switch, the threshold level can be as low as 1 g. Inertial switches have a great potential for the current and new applications. For example, an inertial switch with a specially designed filtering mechanism can realize acceleration band-pass characteristics and be applied in the Safety and Arming Device. A self-powered inertial switch, which is applied in the wake-up system plays a key role in modern communication technology and has a potential application on special goods transportation. Finally, the development trend and future main research direction of the inertial switches have been discussed. Compared to the accelerometers, the inertial switches may reduce the amount of data, save power and help classification using machine learning techniques.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID ID

Qiu Xu https://orcid.org/0000-0003-3597-3497

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