A Novel Virtual Button User Interface for Determining the Characteristics of an Impulse Input Based on MEMS Inertial Sensors

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ABSTRACT

This paper introduces a novel application of MEMS accelerometers in consumer electronics for 'Virtual Button' technology. The MEMS accelerometer is designed to measure low-g acceleration and sense tapping motion on a cell phone, consumer electronic, medical user interface, or harsh environment user interface. In this paper we outline this patent pending application and discusses the modeling and analysis of the accelerometer designed for this purpose. Prior art in impulse localization with inertial sensors is discussed. The features of the Virtual Button user interface are presented and applications of Virtual Buttons applied to medical, touch screen, and hand-held electronic devices is discussed. The initial considerations for the design of an accelerometer with an operating range of 0.5-20 m/s^2 and noise levels of less than 0.124 $mg\sqrt{Hz}$ are also presented.

Keywords: MEMS Inertial sensors, consumer electronic devices, vibration sensors, Virtual Button technology, MEMS software, infection control, user interface

1 INTRODUCTION

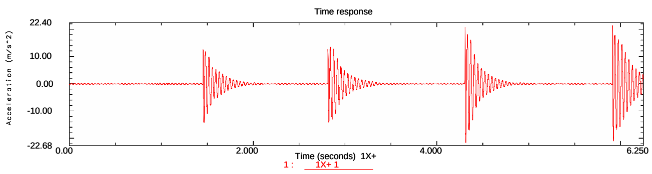
Lower prices, advances in packaging, durability and sensitivity ratings have allowed MEMS (Micro Electro Mechanical Systems) to move from automotive and industrial applications into the consumer electronics market. The use of MEMS inertial sensors in consumer electronics devices has become popular in recent years. Currently, their main use includes tilt detection, gesture recognition and drop detection. This paper discusses a novel patent pending application of MEMS accelerometers which is meant to augment or replace mechanical buttons and capacitive touch screens on small consumer electronics devices such as cell phones. "Virtual Buttons" are extremely rugged and are ideal for harsh environments such as industrial and military applications. Virtual Buttons are also ideal for sensitive environments such as those found in medical applications because buttons can be placed on any existing surface, including curved surfaces, and there are no cracks or crevices, not even small crevices as found around membrane buttons. Because there is no direct connection between inside and outside the device, the Virtual Button is safe for steam chambers and ethylene oxide cleaning and can be made IP 68 compliant. The technology relies on the use of MEMS accelerometers to create 'Virtual-Buttons'. A Virtual Button is a predetermined input signal based on the amount of acceleration, its direction, its duration and its respective patent pending recognition software. These Virtual Buttons can therefore be programmed and completely customizable. Virtual buttons can be assigned any role by the programmer or user, and possibly placed anywhere on the device depending on the user requirements and spatial resolvability.

The technology behind Virtual Buttons relies on vibration analysis principles and pattern recognition composite vibration profile to locate the precise position of the tapped Virtual Button input on the device. While some of the pattern recognition and vibration analysis concepts required for Virtual Buttons are commonly used in the fields of voice recognition, optical character recognition, and vibration testing, they have been combined in a novel set of algorithms for the purposes of Virtual Button detection. Properties such as the resonant frequency of the device under test (DUT), its damping, amplitude as well as modes of vibration are analyzed. The distinction between current inertial sensor input schemes (e.g. tilt, gesture recognition, etc.) and this Virtual Button implementation lies in the input analysis scheme. For tilt and gesture recognition, the inertial characteristics of the DUT are analyzed to determine overall movement while Virtual Button technology allows determination of impulse location. Prior methods of using inertial sensors for determining location of impulse normally rely on triangulation of signals or analysis of surface waves. For the Virtual Button case, accelerometer signals reflective of the rigid body, bending, and twisting modes of the DUT are analyzed to determine location of impulse, allowing greater freedom in location of sensing hardware and user input surface.

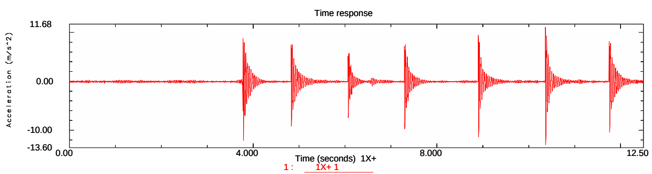
2 INITIAL SIGNAL CHARACTERIZATION

Critical parameters in the development of a MEMS accelerometer for a user interface based on the dynamics of motion include size of sensor proof mass, damping of proof mass, natural frequency, and method of transduction. Each of these parameters should be designed for the type of input signal to be sensed. Therefore it is essential to characterize this input signal. Measurements were made with a Bruel &

Kjaer 3035AG accelerometer affixed to the side of a Samsung SGH Ee316 mobile phone. Tapping intensity is described as light to medium and is expected to be close to the intensity in commercial use. Figure 1 shows the time domain response for the tapping test. The graphs show that the amplitude of acceleration is roughly between 10 and $20\, m/s^2$.



(A)



(B)

Figure 1 - Time history input characterization (A): Tapping on bottom of phone (B): Tapping on top of phone

The measurement also includes the natural frequency of the phone in the horizontal in-plane rotational mode with 11-12 Hz. The input acceleration in the contingency of dropping the device on concrete from a height of 1m was simulated resulting in a maximum acceleration of $45{,}000\, m/s^2$. The MEMS accelerometer will be designed to withstand such inputs without damage. Only one mode of vibration on the Samsung phone was investigated for these measurements. Future work will characterize all the primary modes of vibration and the first bending mode to ensure that these modes fall within the amplitude and frequency domains determined above.

3 PRIOR ART IN IMPULSE RECOGNITION

Several companies, including IBM [1], Qualcomm [2], Research in Motion [3], and Seiko Epson [4], have developed Time Difference Of Arrival (TDOA) methods to triangulate the position of an input. Such methods use microphones or inertial sensors. Each of these patent/patent applications enables a tap localization method to a greater or lesser extent.

The triangulation or TDOA method is completely different from the tap localization of VBT Innovations Inc. discussed in this paper that analyzes accelerations and vibrations in determining unique shapes and composite vibration profiles.

HTC and Samsung have both filed patent applications [5],[6] that use very simple methods of determining the location of an impulse input, and are limited to a very course resolution of inputs. The methods disclosed in these patents are not related to the VBT method.

A method of categorizing the location of an impulse using acoustic signals has been disclosed by Sensitive Object [7]. This patent discloses an impulse localization method with very specific analysis of acoustical waves that travel in an acoustical interface when the interface is impacted.

The disclosed comparison methods by Sensitive Object are significantly different from the patent pending methods of VBT in at least three important ways, 1) physical phenomena analyzed, 2) comparison algorithm, and 3) functionality offered. Sensitive Object relies on acoustical signals while VBT focuses on lower frequency motion and vibration of a device. Sensitive Object discloses very specific algorithms used for comparing high frequency acoustic waves, notably time domain multiplication of sensed signals with reference signals and frequency domain multiplication of phase components of sensed and reference signals. Finally, the differences in physical phenomena measured dictate unique functionality offered by VBTI's CVP method compared to the functionality offered by the Sensitive Object method, notably that sensors can advantageously be placed on the Printed Circuit Board (PCB) of the connected electronic device as opposed to the acoustic interface that is receiving an impulse.

4 FEATURES OF VIRTUAL BUTTONS

4.1 Flexibility and Scalability

Virtual Buttons can be applied to the existing surfaces of nearly any device. No overlays, glass covers, borders, cracks or crevices are needed. Furthermore, there is no restriction on thickness or material of the surface to which Virtual Buttons are applied.

Virtual Buttons can be applied to a wide array of geometries and contours. This technology does not suffer from the same restrictions of many touch sensing methods that are constrained to planar surfaces. Capacitive and resistive touch screens, for example, require the application of thin layers on all interactive surfaces.

This technology is highly scalable with applications ranging from hand-held devices to wide screen televisions. Such functionality can be achieved without the need for additional sensors. In contrast, the cost of traditional capacitive and resistive touchscreen technologies rapidly increases with increasing size.

4.2 Entire Device Surface

The addition of Virtual Button technology to a device frees up the entire device surface for touch input. Users interaction is enhanced through the use of all devices surfaces: the sides, back, base or any other . Those buttons can be configured to control device peripherals, navigate in the user's operating system or interact with specific applications.

4.3 Optical Clarity

Capacitive and resistive touch screen technology requires an overlay that reduces the clarity of the underlying image with possible adverse effects to image quality (such as brightness, contrast and color fidelity). Even Surface Acoustic Wave (SAW) methods require a piece of glass as an overlay, which blocks ~10% of the light transmission. With Virtual Button technology, this is not the case. Because vibrations are used to determine characteristics of an impulse, no overlay is required, not even a sheet of glass. Virtual Buttons can be applied to any existing surface with 100% uncompromised optical clarity.

4.4 Harsh Environments

Military and industrial settings often subject user interfaces to extreme conditions of dust and dirt, rain, pressurized washers, and even immersion, temperature extremes, and shock extremes. There are two ways in which a harsh environment affects a user interface. First, the harsh environment itself can compromise the user interface and even cause it to fail, and second, the harsh environment may modify the way in which a human might interact with the user interface. Humans wearing gloves because of the environment have a different form factor than the straight human finger. Gloves will also not work with many types of traditional touch screens.

While many user control interfaces would fail as a direct result of a harsh environment, Virtual Buttons can meet IP-68 requirements of being immersion proof and dirt proof, and are also well suited for temperatures of -40°C to 125°C and can survive shocks of 200,000 m/s^2.

Virtual Buttons are not subject to wear-out mechanisms related to usage, reducing the maintenance costs and cost of ownership.

For military devices with a traditional user interface can be augmented by Virtual Buttons so that even if the traditional interface fails, critical commands and functionalities are still available.

4.5 Sensitive Environments and Infection Control

Clean, easy to sterilize environments and devices are becoming more important for infection control in the medical field. [8] Traditional mechanical buttons, touch screens, and membrane buttons have small cracks or crevices around the edge of the interface giving "superbugs" a place to hide and causing problems for infection control. Because Virtual Buttons do not require any hardware on the outside surface of a device, no cracks or crevices are introduced. The featureless surfaces of a medical device with a Virtual Button interface allows for simple, quick, and effective sterilization procedures. No shelter is given to the "superbug" and hospital workforce efficiency is increased.

4.6 Integrated Directly into Existing Manufacturing Processes

All the hardware required for the Virtual Button user interface can be surface mounted to the existing printed circuit board of a device. Depending on the application, the Virtual Button user interface can use existing memory, processing power, and power supply, and the only addition to the bill of materials would be several surface mount sensors of approximately 5 mm X 4 mm for a total distributed footprint of <150 mm^2 at a cost of $6-12. Adding Virtual Button capability can be integrated in the existing manufacturing process.

4.7 Activated Surface Border

Nearly all user interface solutions require some kind of border around the outside of the activated surface. These borders have widths of 5 - 50 mm and depths of 0 - 25 mm for an activated surface. Such a border means there is a strip around the edge of the interface that can't be used for display purposes. This becomes problematic if multiple adjacent display surfaces need to have tap capability, as a "mullion effect" is introduced, breaking up the displayed image and interface. Virtual Buttons require no border at the edge of the activated surface.

4.8 Choice of Touch instrument

Users may have preferred interaction methods or input devices. The Virtual Button interface can distinguish between several modes of input such as a user's finger, a pen or credit cards. The device can then respond appropriately to different input modes.

A graphic artist may prefer to use a stylus. Restaurant patrons and servers may prefer to use credit cards. Other users may enjoy the simplicity and feel of using their fingers. Virtual Buttons can accommodate all these users.

4.9 Intelligence

As well as determining a touch or impulse input location, the VBT algorithms characterize touch intensity/pressure and touch focus. Touch intensity is a measure of the force a user impacts the device. Touch focus is characteristic of the input impact impulsiveness. As an illustration, a stylus typically produces a more impulsive accelerometer signal and hence a sharper focus than a the blunt portion of a user's finger.

Pressure and focus sensitivity can be used to enrich the user experience by adapting specific functions. Sensitivity can be applied to audio/video playback, digital painting and other programs. For example, tap intensity on an audio button serves as an indication of desired volume.

4.10 Cost

The low initial and operation costs of Virtual Button technology is made possible by recent developments in the MEMS industry. The cost of implementation of Virtual Buttons is a small fraction of the cost of competing touch surface sensing technologies such as those based on capacitive and resistive methods.

4.11 Resolution

On a test prototype of a Blackberry hand- held device a resolution of 10mm x 10mm allowing 48 tap locations on the front, back, sides, top and bottom. Preliminary tests show 92% accuracy with this resolution. Higher accuracies have been attained with in another prototype based on an LCD monitor with a 3x3 grid overlay.

4.12 Drag and Drop

This touch recognition method is based on the analysis of the vibration of portions of the device. This method is most reliable with impulsive taps. Virtual Button technology does not currently provide drag and drop capabilities since such operations do not produce significant enough vibrations for accurate tap recognition.

4.13 Multi-Touch

Virtual Buttons currently doe not provide multi-touch capabilities.

5 APPLICATIONS OF VIRTUAL BUTTONS

5.1 Medical Applications

Medical applications of Virtual Buttons include control of point of care test equipment (POCT) and medical tablet PCs, emergency buttons on hospital beds, and control of medical equipment arms. Here we describe the application of Virtual Buttons on Medical Clinical Assistants (MCAs) a tablet PC especially used by medical professionals.

Mobile Clinical Assistants (MCAs), Figure 2, can be carried around by doctors, nurses, and other health-care professionals. MCAs are gaining popularity in hospitals as they increase productivity by moving to fully Electronic Medical Records (EMRs). MCAs are replacing Computers On Wheels (COWs) because the small form factor makes them easily accessible and moveable from room to room. Furthermore, MCAs are far easier to sterilize than COWs. There are unique needs in the MCA field that can be met by the Virtual Button technology developed by VBTI.

Figure 2 - Example Mobile Clinical Assistant (MCA) [9]

Integrating Virtual Button technology offered by VBTI will enhance functionality and increase efficiency of the flexible MCAs. While there are many ways in which Virtual Button functionality can enhance the functionality, two examples of the type of functionality enhancements will be sufficient to show both the flexibility of the impulse recognition method of VBTI and how it can improve an MCA.

There are several programs commonly used by healthcare professionals and it is desirable that these programs can be quickly launched and that the user can quickly switch between active programs. This is easily accommodated with VBTI technology by adding five virtual buttons on the plastic casing along the side of the existing touch screen. Each of these buttons would correspond to the five main applications or functionalities of the MCA. To launch or switch to a particular application, the user would just have to tap the corresponding virtual button, saving the time associated with moving the cursor over a “Start menu” and choosing the program from a list. These buttons are shown as the blue circles beside the display in Figure 3. Naturally, if there are more than five common applications, the number of virtual buttons can be easily increased.

A “scrolling” functionality can also be easily incorporated on a tablet PC. The user simply impacts or taps on the side of the device in the direction of intended scrolling. This allows for quickly scrolling through large databases or lists of medicine or patient information. These buttons are shown with the blue arrows around the outside of the MCA in Figure 3.

Even with the two examples described above, there is plenty of space available on the housing, and even on the screen of the MCA, that can be enhanced with Virtual Buttons at no addition to the bill of materials once the two functionalities described above have been incorporated. Virtual buttons can be placed anywhere on the entire surface with a resolution of at least 2.5 cm. Increased resolution is expected with further development work.

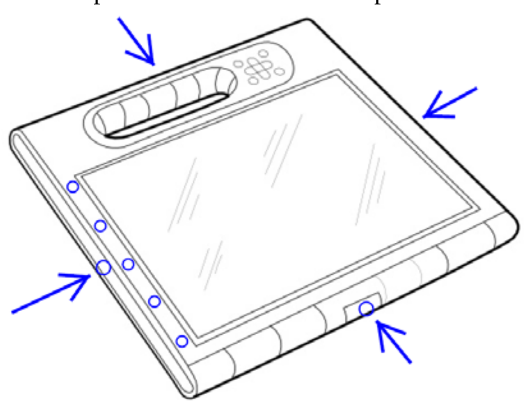


Figure 3 - A Mobile Clinical Assistant (MCA) can be active anywhere on the existing surface with a resolution of at least 2.5 cm, the arrows and circles show a few of the possibilities of Virtual Buttons on the existing casing of the device.

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5.2 Touch Screen Applications

With a motion sensor based system it is possible to augment existing monitors and screens with touch capabilities. Additionally, projected displays of any size can now be made interactive with no compromise to image quality.

Virtual Buttons extend interaction to include all the surfaces of the monitor including the edges, sides, corners as well as the support structure.

5.3 Hand-held Consumer Electronics (MD)

Due to the small footprint and low power consumption of the MEMs accelerometers Virtual Buttons are ideally suited for hand-held consumer electronics applications. Virtual buttons can be placed on the hand-held device's screen , on the curved portions of the device. They may even be overlaid on top of existing user interfaces.

Virtual Buttons offer flexibility to OEMs and end-users. Since input locations are defined through software users have the ability to define their own button layouts and functionalities.

6 INITIAL CONSIDERATIONS IN MODELING OF ACCELEROMETER

In the evaluation of the performance of accelerometer designs, a set of lumped-parameter models is used to describe the device behavior as a function of physical design variables. The accelerometer is modeled as a spring mass damper system as shown in Figure 4.

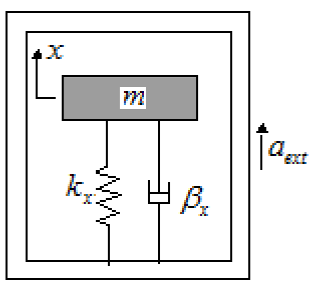

Figure 4 - Spring-mass-damper Model for the accelerometer

The differential equation for the displacement x as a function of external acceleration (a_{ext}) is:

$$m_x \frac{d^2x}{dt^2} + \beta_x \frac{dx}{dt} + k_x x = F_{ext} = ma_{ext} \qquad (1)$$

Where k_x is the spring stiffness, β_x is the damping coefficient, m_x is the effective mass, F_{ext} is the external force, and a_{ext} is the external acceleration. Analytical models of the spring constant, effective mass and the damping coefficient as functions of the design variables are given in the following sections [10].

6.1 Spring Stiffness Model

Due to the rigidity of the proof-mass, the U-spring used in this design dominates the stiffness model. The effective stiffness of the U-spring as shown in Figure 5, derived with energy methods. In this method, a force *(F)* or moment *(M)* is applied at the free end of the spring in the appropriate direction, and the displacement δ is found by Castigliano's second theorem. When only displacement from bending and torsion is considered, the total strain energy U of a linear structure is calculated [10] as

$$U = \sum_{i=1}^{N} \int_0^{L_{bi}} \frac{M_i(\xi)^2}{2EI_i} d\xi \qquad (2)$$

Where E is the Young's modulus of the material, L_{bi} is the length of the i'th beam in the spring, M_i (ξ) is the bending moment along the beam i, and ξ is the distance from the beam end. From Castigliano's Second theorem, the partial derivative of the strain energy U with respect to a given force F_j is equal to the displacement at the force point δ_j.

$$\delta_j = \frac{\partial U}{\partial F_j} \qquad (3)$$

Boundary conditions are applied to the beam ends, resulting in a set of simultaneous equations.

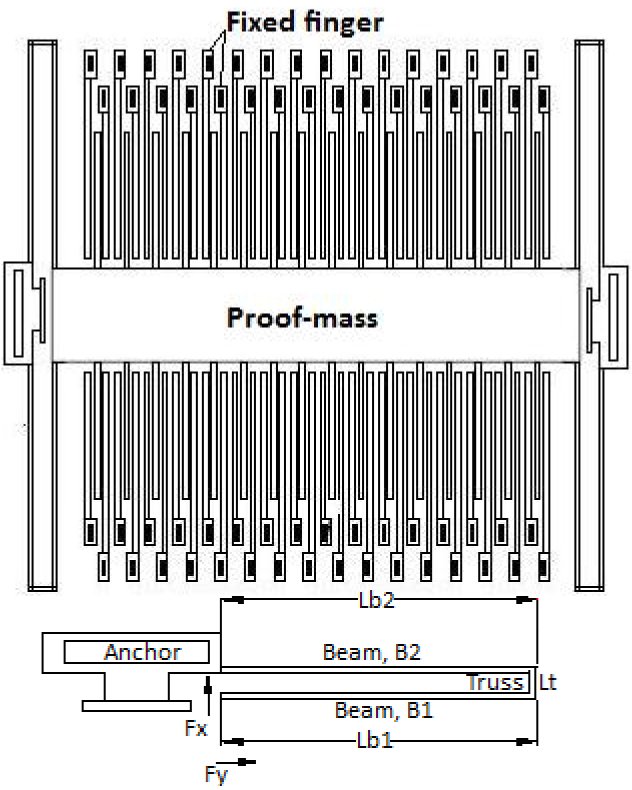

Figure 5 - Schematic of U-spring for stiffness calculation

Symmetry considerations used in the accelerometer give the boundary conditions $\delta_y = 0$ and $\delta_\theta = 0$. Solving the simultaneous equations from the energy method, the x-direction spring stiffness for the simplified case $L_{b1}=L_{b2}=L_b$ and $W_{b1}=W_{b2}=W_b$ is [10]:

$$k_x = \frac{12\alpha E I_b}{L_t^2\left(6\alpha L_b + L_t\right)} \qquad (4)$$

L_b and L_t are the lengths of beams and the truss, W_t and W_b are the beam and truss widths, I_b is the bending moment of inertia of beams b_1 and b_2, [11]

$$I_b = \frac{tW_b^{\ 3}}{12} \quad \& \quad \alpha = \left(\frac{W_t}{W_b}\right)^3 \qquad (5)$$

6.2 Effective Mass Model

The effect of spring mass on the resonant frequency of the accelerometer is taken into account with an effective mass model. Effective mass is calculated by normalizing the total maximum kinetic energy of the spring by the maximum proof-velocity, $V_{\max}$ [11]:

$$m_{eff} = \sum_i^N \frac{m_i}{L_i}\int_0^{L_i}\left(\frac{v_i(\xi)}{v_{\max}}\right)^2 d\xi \qquad (6)$$

Analytic expression for the velocities v_i, along the spring beams are approximated from static mode shapes of the U-spring deflection. The effective mass of the movable part of the accelerometer in the x-direction is [11]:

$$m_x = m_{pr} + 4m_{sp,x} \qquad (7)$$

Where m_{pr} is the total mass of the proof mass and the movable fingers, and $m_{sp,x}$ is the effective mass of the U-spring in the x-direction. For $L_{b1}=L_{b2}=L_b$ and $W_t=W_b=W$ [11]:

$$m_{sp,x} = \frac{\rho t w\left(192L_b^5 + 864L_b^4L_t + 1112L_b^3L_t^2 + 280L_b^2L_t^3 + 21L_t^5\right)}{280L_b^2(L_b + 2L_t)^2} \qquad (8)$$

Where ρ is the density of polysilicon and t is the thickness of the Poly1 layer in the PolyMUMPs® process used for fabrication of this prototype accelerometer.

6.3 Air Damping Model

The damping of the accelerometer is due to both structural dissipation and viscous flow of air around the structure. Since the amplitude of air damping at atmospheric pressure is in orders of magnitude higher than structural damping, the latter is ignored. Air damping of the top and bottom of the accelerometer topology can be classified as Couette-flow damping. Squeeze-film damping occurs between the comb fingers. The viscous damping and Squeeze-film damping coefficients modeled by Couette flow Hagen-Poiseuille flow respectively [11]:

$$B_{Couette} = \frac{\mu}{d_f}A \quad \& \quad B_{Hagen} = 7.2\mu l\left(\frac{t}{g}\right)^3 \qquad (9)$$

Where μ is the viscosity of air, d_f is the air film thickness and A is the plate area. l is the finger length, t is the finger thickness, and g is the air gap between adjacent fingers. The total damping coefficient for the system modeled by, using the sum of the individual Couette and Hagen-Poiseuille components.

The design of a MEMS accelerometer that is ideal for the Virtual Button application will be presented in a later paper. This will include analytical analysis, finite element analysis, and physical testing.

7 CONCLUSIONS

The patent pending Virtual Button user interface has features that make it unique compared to other interfaces. It is concluded that Virtual Buttons are different than all prior art for impulse localization using inertial sensors. Unique features include scalable integration of hardware into existing manufacturing process, design freedom for user interface designers in putting buttons in ergonomic positions, not limited by traditional hardware considerations. Other features include 100% optical clarity,

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the ability to make any existing surface active for input, and not only hard flat thin surfaces such as glass.

Virtual Buttons can be employed on medical devices, helping to prevent the spread of infection and reducing the complexity of sterilization procedures and the related strain on medical staff. Virtual Buttons also have advantages in harsh environments and consumer electronics.

The initial design parameters for a suitable MEMS accelerometer are contained herein. These have been used for the design and test of several accelerometers that are the topic of an upcoming paper.

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