Digital Force White Paper

Date: 16th June 2007
(Last Build: June 16, 2007)

A Novel Concept for an Optical Push Button

Mario Trams
Mario.Trams@digital-force.net

Digital FORCE

Digital Force / Mario Trams
http://www.digital-force.net

A Novel Concept for an Optical Push Button

Mario Trams

Mario.Trams@digital-force.net

Abstract

This work discusses a new concept for an optically controlled, simple and sexy push button. The presented work can be circumscribed by the question: How to turn a simple LED indicator light into a push button? Or even more: How to include a push button functionality into an LED indicator light?

1 Introduction

There are many applications featuring lots of push buttons associated with illuminating LEDs. A good example are car cockpit consoles with various controls not needed to be discussed in detail here. In need/desire for a simple replacement of mechanical push buttons in a certain project there came up a lightening idea: What, if an LED status indicator light itself could be turned into a push button? I.e. there is one or more LED indicator in some front panel and when this indicator is being touched this is interpreted as activation of a push button. The same light that is being used for illumination would turn into an active part of the button system.

This idea has been implemented in a first prototype and is described in more detail within this paper.

While the presented concept is being promoted as a "novel" one, it might have been already silently implemented somewhere by someone. However, as of this writing there has been found not a single indicator for this — neither in view of readily available commercial products, nor in form of a conceptual proposal (patents, publications etc.).

Before coming to the new optical push button system, some related systems (state of the art) will be discussed.

The remainder of the paper deals with various aspects of the optical push button system from the conceptual principle to aspects of the implementation as well as possible future improvements.

It has been tried to keep the text somewhat general. Notwithstanding some basic knowledge of electronics design is assumed/helpful at a few passages.

2 State of the Art Optical Buttons

Especially in the context of industrial automation there are used a vast amount of so-called *optical proximity sensors*. They are able to detect whether or not some object is located within a certain area or a certain distance (not to confuse with light barriers).

Those systems usually make use of infrared light. Mostly an infrared LED combined with an appropriate light sensor are used. Both optical devices are usually positioned in an angular alignment to focus a certain distance.

Although such optical proximity sensors inherently implement the basics for a push button, they are not really suitable for that purpose.

Note: There are also concepts of optical buttons around making use of light barriers, sometimes in junction with mechanical components. Those systems are outside the scope of this paper.

The following two subsections provide a short insight into two existing interesting systems.

2.1 VISHAY TCND3000 / ELMOS E909.01

These two devices are meant to be used together and obviously form the only optical touch sensor system available on the market these days.

The VISHAY TCND3000 [1] is an integrated infrared LED / photo sensor combination including a second infrared LED for compensation purposes.

The ELMOS E909.01 [2], [3] is an integrated circuit containing the required analog and digital circuitry. While the E909.01 is usually used in junction with the infrared light based TCND3000, its principles can be applied to visible light as well.

The E909.01 is not just a touch sensor. In fact, it is a reflective proximity sensor including a touch function. The touch function is implemented not by watching for a certain amount of light reflected by the approaching object, but by evaluating velocity and acceleration of the touch object (i.e. finger). That is, a button activation is qualified through the following requirements:

- The object needs to approach the senor's surface at a velocity below a certain threshold.
- The object stops at some distance in front of the sensor with an acceleration below a certain threshold.

- The object stays at rest in front of the sensor for a certain time.

These three conditions make the sensor very robust against unintentional triggerings.

As another innovation the E909.01 implements a mechanism referred to as *High Ambient Light Independent Optical System*, or HALIOS in short [4]. This system is based on two LEDs A and B and one Sensor. Both LEDs are pulsed in anti phase. While the light from one LED (say B) reaches the sensor directly, the light of the LED A reaches the sensor indirectly via the reflective route. The intensity of the compensation LED B becomes adjusted so that it — as seen by the sensor — matches the intensity of the light that is coming from LED A and is reflected back onto the sensor. So the intensity (current) for the compensation LED B is a direct function of the distance the reflecting object has from the Sensor. A more detailed description can be found in [4].

The advantage of HALIOS when compared to a traditional LED/sensor setup is a simplified sensor setup that does not need calibration and suppresses influences of steady external (ambient) light.

However, it should be noted that HALIOS cannot provide a full suppression of ambient light. This is because once the sensor becomes fully saturated there won't be any evaluable signal any more.

For the targeted application this optical button concept did not seem a suitable solution. One of the primary requirements was the use of visible light. Currently there are exclusively infrared LED/sensor combinations available (VISHAY TCND3000). Although the concept can be easily applied to visible light, the mechanical construction appears rather complicated and requires special machinery. Furthermore the general concept covers more functionality than required for a simple push button solution. Essentially, it is a motion sensor converted into a push button. Last but not least, later we will see that the button concept to be presented herein formally does not require any ambient light suppression mechanisms.

2.2 Exploitation of the Evanescent Field

There is a pending patent [9], [10] that is exploiting an effect that is known to appear with electromagnetic waves — including light. This patent has its roots in another patented technology that is making use of an optical system for constructing a pressure sensor [8].

The basic concept consists of a special prism or light conducting material in general, a light source (LED), and a photo sensor. The setup of the system is made in a way so that the light from the LED is reflected via total internal reflection from a surface of the prism and received by the sensor. See also figure 1. So usually the light emitted by the LED is passing the prism via total internal reflection directly to the photo sensor.

There is phenomenon called *evanescent field* [11] that is building up at the surface outside the prism directly beneath the area reflecting the light. Assuming an optimal (planar) surface, all light should be reflected by total internal reflection. However, because of electromagnetic wave properties light is partially leaving the prism before entering it again (ideally). The space that is filled with this light is called evanescent field and its "thickness" is proportional to the wavelength of the light. This explanation might be mathematically/physically not the best one, but it is sufficient for our considerations.

The light that is temporarily leaving the prism can be disturbed by the presence of objects within the evanescent field. That is, light becomes absorbed and/or reflected/directed into different directions than the normal one. This effect is also referred as *frustrated total internal reflection*. Consequently, this results in a reduction of the light that is received by the photo sensor.

Obviously it is possible to construct an optical touch sensor from this setup. The basic setup of such a button is illustrated in figure 1.

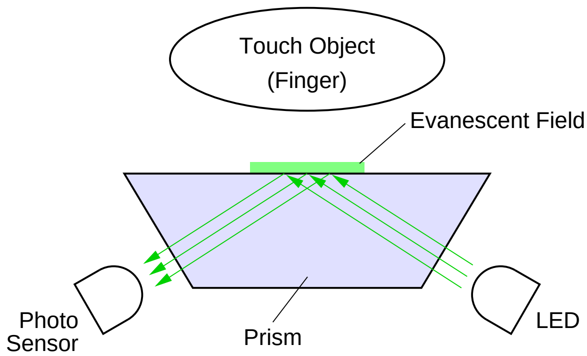

Fig. 1: Basic Evanescent Field Effect Button

The fundamental difference between a touch sensor based on this principle compared to the previously described one including all other reflective proximity sensors, is that this one is really sensitive for touching a surface. The surface needs to be really touched by an object in order to sense this event. This is not completely true as there are distances in the range of hundreds of nanometers to few micrometers sufficient, but in the context of push buttons this virtually means touching the surface.

This technology is rather new and there seem to be no products available on the market yet. Nonetheless there seem to exist prototypes of such a button.

Besides the discussed basic configuration based on a prism there have been also proposed other derivations. One is, for instance, a glass fiber that is wound

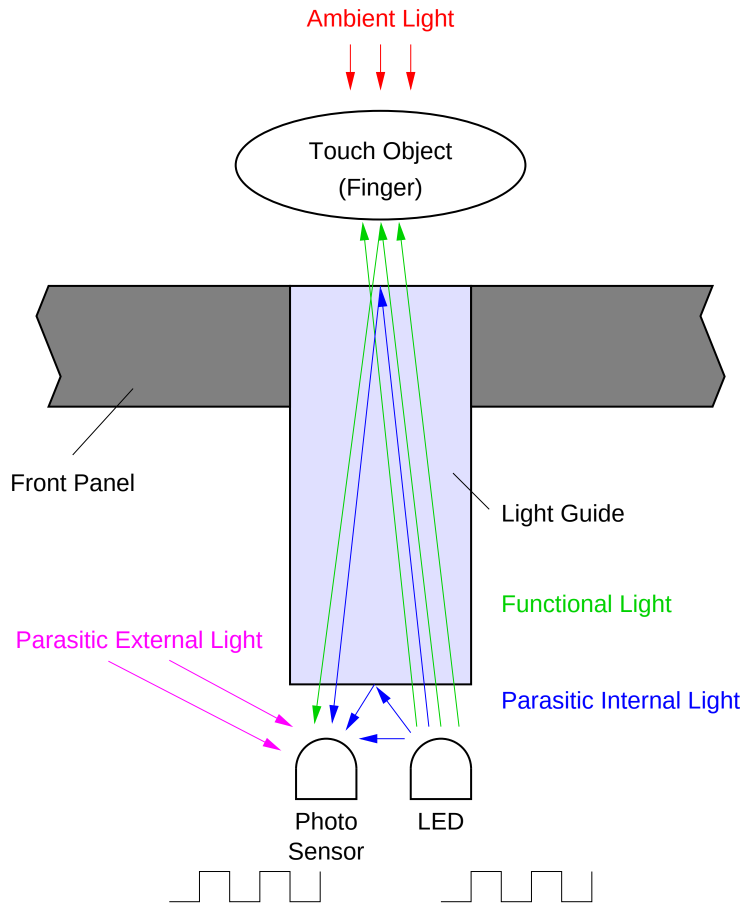

Fig. 2: Fundamental Operational Principle

several times. In the sensitive area the fiber is exposed to the environment. Light is sent into one end of the fiber and the other end is feed into the sensor. When touched at the exposed area, the evanescent field is disturbed at many places with the result that the effect becomes multiplied, hence resulting in larger changes in light intensity at the sensor.

3 The new Optical Push Button Concept

3.1 Fundamental Principle

The basic principle is shown in figure 2.

There is an LED and a sensor. Both are positioned closely together. There is a light guide leading the light from the LED towards the exposed area in a front panel (or whatever). When an object is approaching the surface of the light guide's exposed end wall, light becomes reflected back into the light guide and hence into the sensor.

The light guide is formally not a fundamental requirement. However, it is intended for providing a defined lighting spot at the front panel. Furthermore the light guide could be used for directing the light around corners etc.

The LED is being pulsed at a certain frequency usually in the area of hundreds of Hertz. When the "button" is being "pressed" (activated), some of the pulsed light arrives at the sensor and hence creates a waveform in phase with the LED frequency with a certain amplitude.

One interesting aspect of this setup is automatic suppression or exclusion of ambient light. That is, as soon as the exposed surface of the light guide is being touched, all external light becomes blocked automatically. Of course, this assumes that the front panel is not translucent.

Figure 2 does introduce four different kinds of involved types of light:

- *Ambient Light*
  This is the ambient light which the button/device as a whole is exposed to.
- *Parasitic External Light*
  Parasitic external light is mostly sourced by ambient light and will be different from zero in case of a translucent front panel when there is no special shielding of the sensor from other light sources.
- *Functional Light*
  Functional light refers to light emitted by the

LED and is used for the actual function of the push button.

- *Parasitic Internal Light*
  This kind of light is emitted by the LED as well, but is actually not desired. It is brought to the sensor either directly or due to internal reflections of the light guide.

3.2 Simple Analog Electronics

The sensor provides an analog signal that needs to be preprocessed before it can be handled by digital circuitry.

In a very first attempt there has been implemented a very simple signal conditioning electronics consisting just of a comparator with a hysteresis. Figure 3 illustrates this setup.

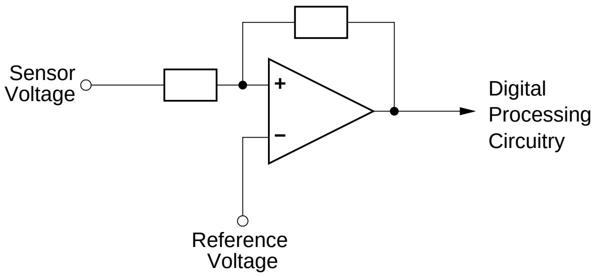

Fig. 3: Most simple Analog Hardware

The merely analog output signal of the sensor is fed onto a comparator in order to convert the sensor signal into a digital signal. This is required as the sensor output usually has a swing of tens to hundreds of millivolts and cannot be directly fed into digital circuitry. The reference voltage of the comparator has been adjusted so that a logic high is generated when the sensor voltage exceeds a certain level. The purpose of the hysteresis is described further below.

The reference voltage of the comparator basically defines the sensitivity of the button. A lower value means higher sensitivity, as less activity at the sensor is causing the comparator to turn its output high. Of course, the reference voltage must not be below the sensor voltage present during the LED–off phase.

This approach requires a good shielding of the sensor from any parasitic external light, of course. The point is that once the parasitic light is biasing the sensor so that its output lies always above the reference voltage, no pulses will be generated by the comparator and the push button is not functional anymore.

The requirement of the hysteresis as shown in figure 3 is a conclusion of the non-ideal behavior of a practical implementation. As earlier illustrated in figure 2 we do also have a parasitic internal light component that is reaching the sensor from the LED even when the button is not activated. While a non–translucent barrier between the LED and the sensor will block light coming directly from the LED, other light reflected back from inside the light guide cannot be blocked. So this means there will be present a faint sensor pulse signal all the time.

In case steady ambient light is entering the light guide it is causing a lift of the sensor voltage, hence lifting the faint pulse signal that will be present always.

For a non–activated button the ambient light can lift the sensor signal into the range of the comparator's reference voltage and it will generate regular output pulses in phase with the LED stimulation. This is surely not wanted as it suggests an activated button (mistriggering).

The hysteresis copes with this issue very easily. It needs to be properly adjusted so that the faint sensor pulses caused by unwanted reflections cannot result in an according pulse train at the comparator output.

3.3 Enhanced Analog Electronics

In order to make the circuitry more robust against influences by ambient light it has been somewhat extended by introducing a differentiation. The basic setup is shown in figure 4. The colored/numbered nodes are just for reference for some oscilloscope screen shots discussed later in the text.

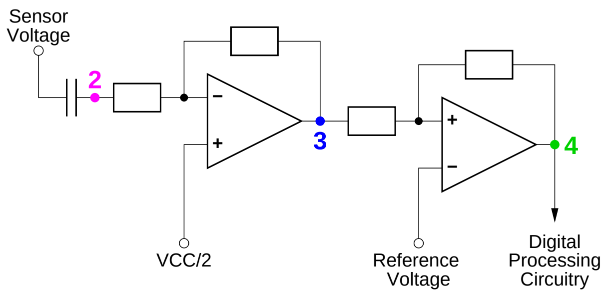

Fig. 4: More sophisticated Analog Hardware

In first instance there is an AC coupling of the sensor signal via a series capacitor. This eliminates a constant bias voltage that might be introduced by steady parasitic external light reaching the sensor.

Before the differentiated sensor signal is fed through the comparator much like in case of the simple circuitry, it is being amplified by an inverting OpAmp setup. At the same time the differentiated signal becomes centered across the half supply voltage by driving the non–inverting input of the amplifier with the half supply voltage accordingly. This is to avoid negative input voltages at the OpAmp due to the differentiating series capacitor. The amplification has been found useful in order to get a wider band for the comparator's input, hence making the sensitivity control more smooth. From a theoretical point of view the amplification might be not necessary.

Note: The inverting amplifier causes a phase shift of the output signal of 180 degrees. This does not matter, however.

As a result of the enhanced setup the button is becoming more stable even when it is not completely shielded from parasitic external light. Of course, this cannot be an ultimate solution as once the light sensor is becoming completely saturated (i.e. by exposing it to direct sunlight) there won't be any dynamic signal anymore to differentiate. However, this setup has been proven to work very well under "normal" lighting conditions without any special shielding of the button setup.

3.4 Digital Processing

So far we have just considered the general concept and the analog section of the push button design. The digital processing is almost as simple as the analog processing. In first instance there needs to be generated a pulsing signal for driving the LED. One is usually using a value greater than 100Hz here.

As for the evaluation of the digitized sensor signal there is just one basic rule: For an active condition we need to see one and only one rising or falling edge of the signal during each LED cycle. In other words, both LED and sensor frequency match each other.

Though there need to be taken some additional precautions regarding debouncing. This includes both *on–debouncing* as well as *off–debouncing*. I.e. the button won't be immediately recognized as activated when the basic rule is fulfilled in a single cycle. Instead, one would wait for a couple of consecutive cycles where the condition is satisfied. The same counts for releasing the button. This debouncing is especially important when considering ambient light generated by a light bulb driven by standard 50Hz AC voltage. Under some unfavorable conditions a single pulse might be generated by the sensor resulting in activation of the button. A simple debouncing as described can cope with this situation easily.

Btw., in that context the frequency of the LED pulses should be set to some "odd" value. I.e. not necessarily to multiples of 50Hz or 60Hz which are common frequencies in our households. Perhaps it would be even better to introduce a slightly randomized frequency.

In the test setup all this digital processing hardware has been put into an FPGA (Field Programmable Gate Array), which allows a very simple and efficient implementation basically consisting of some counters.

Such a digital processing principle can be used without any modification for both presented analog circuitries.

3.5 Some Implementation Facts

The following subsections discuss a few of the relevant implementation details, concentrating on optical devices and mechanical properties.

3.5.1 Sensor Selection

An Avago APDS-9002 [5] has been used as light sensor. It has a sensitivity characteristics close to the human eye and has its peak sensitivity at approx. 625nm (orange). For more reddish colors the relative sensitivity drops nearly to zero so that the sensor is almost blind for wave lengths greater than approx. 640nm. So this sensor is not really suitable for red buttons. For green light (500nm – 565nm) the relative sensitivity ranges from approx. 40% to 80%. So this sensor is suitable for green, yellow, and orange colors. Blue might work as well, but red will be problematic. White light will work fine as well, of course, as it contains something of all.

The APDS-9002 is coming in a small 0805–like form factor (2mm × 1.25mm and 0.8mm high), is operating from a 2.4V–5.5V power supply, is rather low–cost, and just requires an external resistor for converting the sensor current output into a voltage.

The rise and fall times of the sensor under special measurement conditions are specified with approx. 1ms typical and 2ms maximum. This is resulting in a bandwidth of 500Hz typical and 250Hz maximum. Those are no great numbers, but they are sufficient for this application.

3.5.2 LED Selection

For the LEDs there have been used Kingbright KPTD3216MGC (Mega Green; approx. 570nm) as well as Kingbright KPTD3216SYC (Super Bright Yellow; approx. 590nm). For details see also [6] (**Note:** The part numbers seem to have been converted into APTD... meanwhile). Both LEDs are coming in a 1206 form factor.

Those LEDs are low current types which is important for low power consumption of the optical button. Furthermore they feature a comparatively narrow opening angle of 50 degrees by integrating a so–called *Dome Lens* that is focusing the light. Standard 0603 or 0805 LEDs usually have an opening angle of far more than 100 degrees. A low opening angle has been selected for high efficiency. I.e. bringing as much as possible light into the light guide while reducing the amount of light brought directly from the LED onto the sensor (see parasitic internal light in figure 2).

Both LED types (green and yellow) where successfully used with a rather large current limiting resistor of 560Ω at a system voltage of 3.3V and were switched with a small NPN transistor. In case of the green LED the current is approx. 2.5mA which is a quite acceptable value. As the LEDs are usually operated at a 50% duty cycle, the effective current is even just half that much. The transistor is formally not needed, but was used due to other design constraints not to be discussed here.

If not mentioned otherwise, the green LED was used for all further references to the light button for the remainder of this document.

3.5.3 Light Guide Selection

The used light guide was a Mentor 1216.1003 type [7]. The actual light guide is a simple cylinder with a diameter of 3mm. However, it includes a black foot/housing that can be plugged into a PCB. Hence the light guide can be easily mounted atop the sensor/LED combination. Furthermore the black housing blocks parasitic external light to some extend. Unfortunately, the housing does not provide a 360 degree shielding.

Because the housing of the 1216.1003 by default does not feed the light guide very close atop the sensor/LED combination, the hole in the foot has been slightly expanded. This allows for placing the light guide directly above the LED (see figure 5 later).

Note: A 5mm diameter version of the Mentor light guide (1216.1005) has been successfully used as well. Because of its identical PCB footprint of the housing it can be directly interchanged with the 3mm version.

Note: For initial experiments another Mentor light guide intended for a 3–LED configuration has been tested (1294.1001). The intention was to place the sensor under the middle position of the light guide and (possibly) two differently colored LEDs left and right besides the sensor. However, this configuration has been found to work rather bad. The amount of light brought back into the sensor was just too small. Although sufficient to be detected, the button characteristics was not that stable as for the simple light guide setup we are concentrating on here.

3.5.4 Mechanical Combination of LED, Sensor, and Light Guide

Figure 5 illustrates the mechanical integration of LED, sensor, and the light guide (drawn to scale).

The figure suggests that both sensor and LED could be moved slightly more towards the center line of the light guide. However, the intention of the larger than necessary gap between both was to put a shielding there, hence reducing the amount of parasitic internal light. But so far practice has shown that such a wall is not really necessary. Though, the improvement of the button's characteristics including a shielding have not been analyzed yet.

Another non–ideal fact can be seen in figure 5. That is, because of the rather tall LED the light guide does not extend directly to the surface of the sensor. This situation might be improved by notching the light guide appropriately.

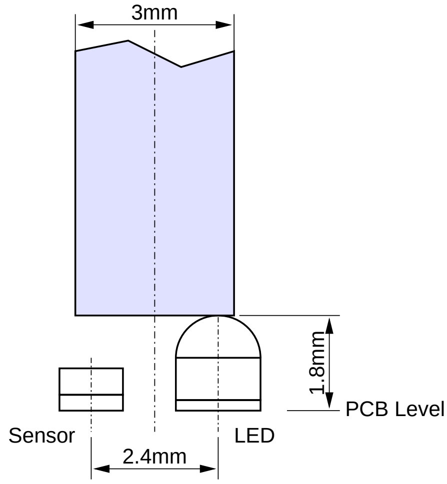

Fig. 5: Mechanical Dimensions of the Setup

Photographs of the first reference implementation of the optical button are shown in figures 6 and 7.

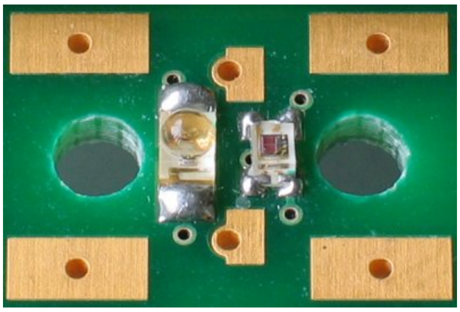

Fig. 6: Photograph of the Mechanical Setup with LED (left) and Sensor (right)

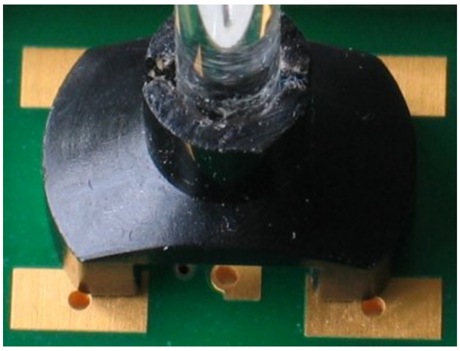

Fig. 7: Photograph of the Mechanical Setup including the Light Guide (Mentor 1216.1003)

The additional pads that can be seen on the pictures were intended for soldering additional shieldings (tinplates or similar) for better suppression of both parasitic internal and external light. As of this writing, this has been not tested yet.

3.6 Experienced Problems

The primary (and actually one and only) issue that has been found so far is about the button's sensitivity characteristics, especially finding a good compromise for different surfaces of the touch object.

One aspect regarding sensitivity is the rather strong dependency from the reflecting material (i.e. the finger). Actually this was clear from the very beginning as light is known for its bad reflection behavior on absorbing dark surfaces.

But finally the surface issue is not that big as it appears. Although such a button will very likely fail when the user wears gloves made of black fabric, this is a scenario that can be safely neglected for most applications.

Another issue related to the sensitivity is the active range of the button. I.e. the distance of the touch object from the exposed end wall of the light guide when enough light is reflected back so that the button is being recognized as activated. Ideally, this distance would be zero. This is illusionary, however. While in theory it might be possible to set the sensitivity accordingly, this will be only valid for a single type of surface and will be very critical with regard to LED/sensor degradation over the time as the button might fail.

But again, practical deployment and testing shows that even a distance between 5 and 10mm is not problematic when the button is operated via concise finger strokes. Nonetheless, in the following sections we will discuss some ways on how to improve this situation.

4 Optimizations

The following subsections are dealing with a few optimizations of the button setup and/or handling that have been already implemented or should be addressed in future.

4.1 Opto–Mechanical Tricks

The fundamental button setup as described in figure 2 generates a rather straight forward bundled light beam. This is illustrated in figure 8.

Because of the bundled light beam light can be easily reflected back into the light guide from a rather far distance. This is not necessarily wanted as it results in a large active range of the button. As described earlier, the active range should be as short as possible — at the compromise of keeping a wide range of supported touch material surfaces. The latter restriction forbids a simple reduction of the sensitivity.

So what would help out here is a dispersion of the light beam when it is leaving the light guide. Such a light scattering can be achieved very easily as illustrated in figure 9.

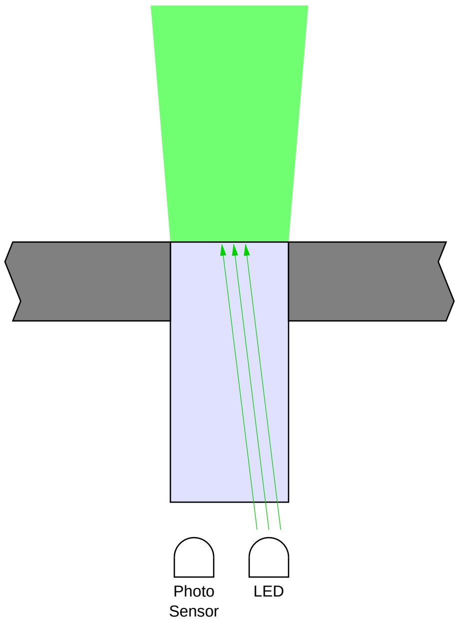

Fig. 8: Light Cone of a standard Light Guide Setup

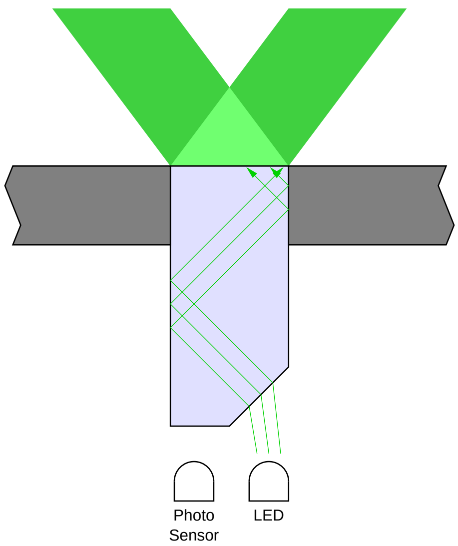

Fig. 9: Light Pattern of a beveled Light Guide Setup

That is, we introduce a bevel at the bottom of the light guide where the light emitted by the LED is entering the light guide. This bevel is causing a more or less strong refraction of the light waves as illustrated. When the light is leaving the light guide it becomes refracted back slightly. But because of the angular relations it remains mostly refracted when compared with the initial direction. From a section view as shown by figure 9 the light is leaving the light guide in a V-form. In a three dimensional view the light has the form of a concave frustrum. This behavior can be verified very easily.

This setup provides very positive characteristics in view of the desired narrow active range of the button in junction with a high sensitivity. Thereby we can benefit from two facts:

1. Because of the rather large exit angle of the light waves a far touch object tends to reflect the light not back into the light guide but somewhere into the environment.
2. The "empty space" of the frustrum cave not filled with light effectively reduces the amount of light reflected frontally back into the light guide when the touch object is located farther away from the light guide.

Practical experiments did prove the theory is working very well. A light guide with 3mm diameter has been beveled as illustrated in the scaled drawing shown in figure 10 (1.5mm × 3mm ⇒ angle is around 63 degrees).

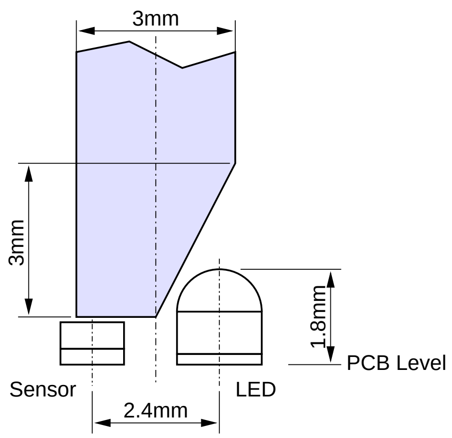

Fig. 10: Mechanical Dimensions of the beveled Setup

Note: The shown mechanical dimensions/angle do not have any analytical background. The are just coming from a hands–on design and other dimensions/angles might work better.

When compared against figure 5 we can see another advantage of this setup: The light guide directly reaches/touches the sensor surface. Hence more light is brought into the sensor (efficiency). On the other hand less light is brought from the LED into the light guide.

Under the same ambient/parasitic external light conditions and the same sensitivity settings the active range for a piece of white paper was approx. 5mm for the normal light guide while it was just approx. 2mm for the beveled light guide. In case of a finger the difference was approx. 2mm vs. 0.5mm. So this trick provides a significant improvement of the situation.

4.2 Active Use of the Sensor Dynamics

In figure 11 an oscilloscope screen shot of a non–activated button is shown. The colors and channel numbers match the special node numbers as shown in figure 4. A redundant description has been placed to the right of the according wave form as well.

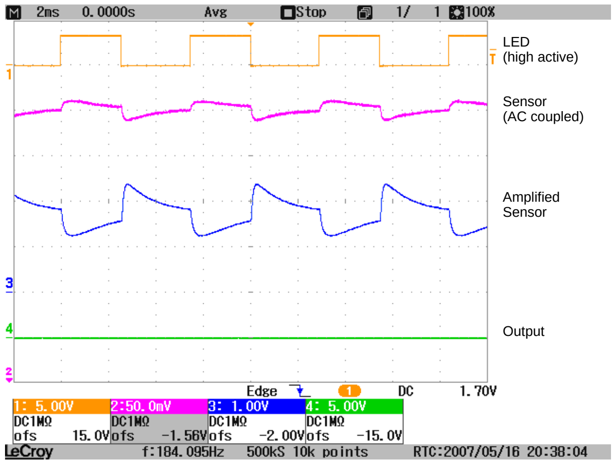

Fig. 11: Waveforms of a non–activated Button

Note: The careful reader might notice that the LED is not driven with an exact 50/50 duty cycle. This has some special reasons in junction with the digital circuitry that has been used and details are not to be discussed here. This circuitry does also allow the further reduction of the LED duty cycle in order to provide a dimming function. However, this has no impact on the actual button functionality.

The screen shot has been taken from a green button using a beveled light guide as illustrated in figure 10. Moreover it has been taken under dark conditions, hence eliminating any ambient and parasitic external light.

As it can be seen, we already get a rather strong signal feeding the comparator OpAmp (Node 3). This means that the effects of parasitic internal light are quite significant.

Before going more into details we want to have a look at an activated button. The according screen shot is shown in figure 12. The conditions where the same as for the non–activated button. A finger touching/covering the end wall of the light guide has been used for activation. Notice that channel 1 does not show the LED waveform any more but the voltage directly at the sensor output.

Clearly the sensor signal is becoming more strong, the amplified sensor signal exceeds a certain threshold, and a rectified output signal is generated.

Actually the screen shots were not provided in order to give an explanation of the analog hardware setup, as this is almost trivial.

What is raising special interest is the practical be-

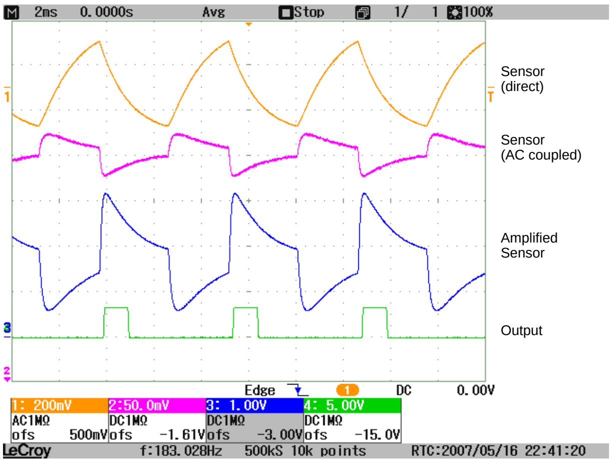

Fig. 12: Waveforms of an activated Button

havior of the sensor. The sensor has a rather high-impedance output which also manifests in the previously mentioned rather slow switching times. As a result, the sensor behavior is merely analog rather than binary in the frequency range we are interested in. Nonetheless the amount of change of the sensor signal is directly proportional to the change of the light intensity. This can be seen by the fact that the AC coupled (i.e. differentiated) sensor signal is more strong when the button has been activated. Of course, this is a fundamental requirement for the functionality.

So the when the light intensity is changing abruptly, the sensor output reacts also more or less abruptly before its change rate decelerates — a typical shark fin like capacitor charge/discharge behavior. Notice that this behavior is not introduced by the AC coupling of the analog processing hardware but is inherent in the sensor. But in the end this does not matter.

What kind of benefit we can draw from this behavior is that it is easily possible to construct a proximity sensor. That is, because the pulse width of the output signal is directly proportional to the amount of light reflected back onto the sensor and hence is directly proportional to the proximity.

This allows us to implement similar or identical mechanisms for button activation qualification as found in the ELMOS E909.01. I.e. the button wouldn't be recognized as activated just by the fact that there have been observed the right amount of pulses over a certain time (see section 3.4). Instead, a certain approach–decelerate–stop policy within a tight and defined time margin could be implemented, therefore reducing the probability of mistriggerings.

Well, on the other hand one has to admit that the current digital processing mechanism implementing a simple on/off debouncing is obviously working almost perfectly. So there does not seem any immediate need for implementing more complex and hence more resource demanding mechanisms.

Nonetheless there is a strong argument speaking for the introduction of such a mechanism: Robustness.

Analog hardware is prone to aging and temperature dependency. The current analog circuitry when considered in the overall context has a weak point: It's the more or less constant threshold voltage of the comparator generating the digital output signal. Two important rules have to be applied for this reference voltage:

1. This voltage needs to be small enough so that the button activation yields a proper output signal (i.e. the amplified sensor signal exceeds this level when the button has been activated).
2. Moreover it needs to be large enough so that it can be guaranteed that parasitic internal light cannot activate the button. See also figure 11 where a too small threshold would easily create a nice output signal.

The latter rule is more critical as a violation would result in a completely non–functional button. Even more worse, some effects could lead to a mistriggering in case the sensor signal stimulated by parasitic internal light is becoming more and more strong over the time (for whatever reason) and reaches the critical level some time. Surely, the first rule is critical as well. However, in case a finger does not provide sufficient reflection any more, one could use some other, better reflecting material in case of emergency. Basically this is the same problem as with a mechanical button that internally corrodes. At some time, in order to get it working, one has to hit it rather than just pressing it.

So the problem with not getting a digital signal at all (associated with rule 1) is merely inherent and there seems to be not really a solution. When the LED is worn out, it is worn out. Things like dynamically increasing the LED current appear difficult/impossible to implement, as there is no reference. And if they are implemented somehow, the increasing current will just speed up the final death of the LED even more. Hence we have to accept this situation — though we will see below that the situation can be slightly improved.

The issues with the fixed reference voltage with regard to rule 2 can be tackled by making use of the special dynamics characteristics that have been described. I.e. by evaluating the change of the output signal rather than just its sheer presence. Instead of setting the threshold voltage to a level high enough ensuring that there is no output signal for an inactive button, the level could be safely decreased much more. Possibly there might be already an output signal with a certain (short) pulse width present even though the button is inactive. When the button becomes activated the pulse will become wider. When it is being released, the pulse will become shorter again or vanishes.

These changes or this dynamic behavior of the pulse width would be detected and handled by the digital processing hardware accordingly. As result, the issue with the constant threshold and the variable analog signal characteristics has been almost eliminated. Of course, eliminating it completely is not possible. But its practical influences can be decreased significantly.

As another positive aspect this even increases the life time of the button by means of dealing better with aging LEDs: Because of the lower comparator threshold more weak sensor signals can be converted into digital pulses as well.

Yet another plus is a more relaxed button manufacturing/calibration, as it is not anymore that critical to take special care not to have a threshold voltage that is too low (rule 2).

As a conclusion it can be stated that it is worth to implement the discussed change of the digital signal processing and see how it does perform in practice.

Note: While ambient light is a secondary issue for the initial design idea (remember figure 2; ambient light is completely blocked during button activation), it might become critical for the proposed enhancement. That is, when we operate the button partially in a proximity sensor mode, it has to deal with ambient light as well. However, under practical conditions we are speaking about a distance of perhaps 1-2mm where a human finger is already providing a large shadow for most cases. Practical experiments are required...

4.3 Eliminating the Sensor

Note: This section is going somewhat out of scope of this paper and might be skipped.

It sounds somewhat ridiculous, but the sensor might not be necessarily needed in the design. This idea has been initially provided by Frank Göttsche (thanks for that!).

Essentially a photo sensor (diode or transistor) is based on a diode that has been optimized for sensing light. A photovoltaic solar cell too is nothing more than a diode that has been optimized for converting light into electricity in comparatively vast amounts.

So the question is: Can we use one and the same LED for both light emission as well as detection of light reflected back into the LED? Principally it should be possible, as photons hitting the diode structure manipulate the diode characteristics. So the actual question is whether the effect is significant enough.

A quick test with the green LED (Kingbright KPTD3216MGC) and a current limiting resistor of 560Ω did almost not yield any measurable result. The only observable effect was a more or less significant increase (tens of millivolts) of the LED forward voltage when the LED is turned off and is flooded with external light. "Flooding" means that "normal" ambient light is not sufficient. This would also disqualify the practical use of the LED as general photo diode. When the LED is turned on, there was no change of the forward voltage or the forward current measurable depending on external light — not to speak of light generated by the LED and reflected back.

Well, this result was expected, actually. But it was worth giving it a try. Maybe other LEDs are working better here, maybe not... Perhaps it is some day possible to construct a special device combining both optimized LED and photo sensor silicon — not by means of putting both LED and sensor onto a single die or into a single package, while this would be also a good deal for this application in general.

Apart from the apparent technical difficulties of turning an LED into a device capable of sensing its own emitted light there is also another hurdle for this application.

Let's assume the change of forward voltage is significant when light from the LED is reflected back into it. There needs to be a way to detect whether the change is induced by functional light or by ambient light. Formally this can be accomplished by pulsing the LED and checking the forward voltage for both on and off periods. This double check might be difficult to implement.

So all in all the circuitry (both analog and digital) required for such a concept seems to be quite complicated and it is questionable whether it compensates for the advantage of having just a single optical device (the LED).

Nonetheless this approach seemed quite interesting and worth to be mentioned here.

5 Future Work

The following tasks need to be (or should be) carried out in order to enhance the optical button concept described herein.

5.1 Development of Test Equipment

Tests that have been made so far were more "hands–on" and not the most objective ones. In order to be able to better compare different setups with others special equipment would be preferable. Especially this means some mechanical apparatus to be used for moving different touch objects in front of the light guide. This allows a good study of the button behavior under various conditions.

A most simple version of such apparatus could be a mechanical fixture including a screw to be used for moving the touch object along the axis of the light guide. However, for more sophisticated analysis including the dynamics of the touch process some active mechanism is required allowing to move the touch object at arbitrary velocities.

Apart from these fundamental issues the control of external influences is important as well — namely ambient light and temperature.

5.2 Evaluation of other LEDs/ Sensors/ Light Guides

There are many devices available on the market that could be analyzed for their use in such an optical button design.

As described in section 3.5.2 the LEDs have been specially selected to have a narrow opening angle. However, in section 4.1 we have seen that a narrow exit angle of the light from the exposed end wall of the light guide is not necessarily desired. May be a simple (and btw. cheaper) LED in a standard 0603 or 0805 package and a wide opening angle does perform with the same efficiency at the benefit of no necessary modification of the light guide.

5.3 Introduction of Multi Color Buttons

For some applications it might be desired to drive a single button at different colors. E.g. in order to signal different states or whatsoever.

This could be easily accomplished by using a duo LED, for instance. However, there might be some pitfalls regarding the different wave lengths and the according sensitivity differences of the sensor. So it might be difficult to use one and the same sensor configuration for different colors.

5.4 Implementation of enhanced Digital Processing

This basically refers to the implementation and evaluation of the mechanism as described in section 4.2.

5.5 Use of a Micro Controller

Clearly, placing the digital processing into an FPGA is not the way to go for general applications. In fact, the optical button in its current state is only suitable for designs where an FPGA is present anyway. Today's available FPGAs (as well as CPLDs) are not really suitable as exclusive optical button handlers because of their chip size. The same is valid for their cost and power consumption, if these are criterions for the application.

Unfortunately, time is not (yet) right for programmable logic devices with a considerable amount of logic resources in space saving packages such as SOT-23 or TSSOP-8. Of course, an ASIC could be produced — just as ELMOS did with their E909.01 [2]. But this is only suitable for mass production.

Meanwhile available standard components that can be attributed "programmable" and "tiny" are micro controllers. Good candidates are the Microchip PIC10F and PIC12F [12] series as well as the Atmel ATtiny [13] series.

PIC10F micro controllers are even available in a very tiny 6–lead SOT-23 package featuring formally sufficient 4 IO pins. 3 Pins would be required at least: One for controlling the LED, one as input for the preprocessed sensor output, and one as button activity indicator for evaluation by the actual design.

Some family members of the mentioned micro controllers even provide analog circuitry such as analog-to-digital converters or comparators. This should make it possible to move parts of the current analog circuitry into the micro controller.

It appears not that trivial to implement the required functionality into a tiny micro controller — especially in view of the enhanced processing as described in section 4.2. Nonetheless it should be possible.

5.6 Self Contained Button Units

Especially making use of tiny micro controllers should pave the way towards self-contained tiny optical button units with a footprint in the range of one square centimeter. In a minimal configuration those units would just have three contacts/wires (ground, power, button output). Just like the ELMOS E909.01 [2] they might also provide two contacts that can be short-cut using a bidirectional switch making them ideal candidates for direct replacements of conventional buttons — even in existing systems.

5.7 Self Contained Switch Units

Of course, this (any) push button concept can be extended to implement solid state switches. That is, the switch would be turned on by triggering the button once, and turned off again by triggering the button once more. This is just a simple toggle FlipFlop mimics. Assuming some more or less heavy MOSFET or Thyristor back end this can be also used for self contained high power switches.

Very helpful would be a multi color LED setup or some blink codes for signaling the current switch state.

6 Classification with State of the Art

In this final section there are discussed a few advantages and disadvantages of the light buttons in general as well as a comparison of the new optical button concept with the existing ones.

6.1 General Disadvantages

To start with two general disadvantages common to any optical button concept: They lack the haptics of mechanical buttons and they consume energy.

The haptics issue is a general one, of course, and is the price to be paid for having a mechanically robust and non-destructable button. Whether it is really necessary to *feel* and *hear* the button when it is being activated is merely a matter of opinion and surely depends on the application.

Some might argue safety and robustness are also issues for such buttons. Safety issues are related mostly to unintentional triggerings by touching the button accidently. However, there is no big difference in comparison with mechanical buttons. In either case special protections need to be used for critical applications. The question for robustness targets not at the button life time or cycle time, where any optical solution does have significant advantages. Merely it aims at the question of what could be done when the button is really failing for whatever reason. I.e. how one can cope with a defective button in the jungle or a mission to Mars. Any optical button is clearly much more complicated than any mechanical button and very likely there won't be any repair possible. But as the ultimate output of such a button is a simple low or high, or "connected" or not "connected", it can be still replaced by two simple open wires in some case of emergency.

6.2 General Advantages

Optical buttons have generally better lifetime in terms of cycle time and mechanical robustness. They can be also considered as *solid state* buttons having no moving parts.

Also they are more inherently protected against corrosion, which is especially important for aggressive environments such as for maritime applications. This does include water proof installations as well. Buttons involving moving parts can be more or less badly protected by using complicated, expensive, and mostly ugly sealing mechanisms. Optical elements (prisms for the evanescent field effect buttons or light guides for the solution discussed herein) can be directly glued into a front panel. The VISHAY/ELMOS solution, and to some extend also the solution presented by this paper can be placed behind a translucent pane.

Note: While speaking about water proof installations it should be mentioned that it's implications, especially water presence on the sensitive area have not been analyzed in detail yet.

Note: [9] is proposing an additional touching element in front of the prism. While the reasons for this have not been explained and it should not be formally necessary, it seems to be intended for increasing the area the evanescent field is being disturbed during button activation. Unfortunately, this would remove a lot of the inherent beauty of this concept as it complicates the mechanical design significantly and makes it mechanically less robust.

6.3 Power Consumption

Power consumption is almost everywhere an issue. For any optical button the LED is very likely the one contributing at most to the power budget. Fortunately they can be turned off on demand. The actual power consumption of the ELMOS/VISHAY solution is not completely clear. The data sheet [2] suggests rather high typical LED currents of 10-20mA. One value is even specified at 36mA, but the specification is not really understood in that point. However, the new button concept discussed herein is projected for total currents in the range of 3-5mA at a supply voltage of 3.3V or less. As described earlier, the green LED of the first reference design has been driven at approx. 2.5mA (1.25mA mean). The remaining circuitry is consuming current in the range of a couple of hundreds of micro Amperes. Even a small micro controller (once it is being used for the digital processing) typically will consume less than 1mA. So a total consumption of 3-5mA can be well achieved — and this is surely less than what is currently drawn by many simple indicator LEDs in cheap household devices. So it is not unrealistic to state that an indicator LED can be equipped with a button functionality at almost no additional power requirements.

The power consumption of an optical button based on the evanescent field effect should be comparable to the concept described herein.

6.4 Button Appearance and Illumination

The ELMOS/VISHAY solution is not suitable for providing an illuminated spot on a front panel. First of all it is based on infrared light making it useless as indicator or button identifier in darkness. Secondly, even when the infrared would be replaced by visible light it seems hard to realize based on the TCND3000 principle (mechanical setup). Though it might be possible to construct it differently.

The evanescent field effect button appears to have its fundamental issues as well. The question is whether it is possible to create small (say 3mm diameter) illuminated spots at a front panel. The size is the first issue. Normally such a button requires some kind of more or less complex prism where both LED and sensor are attached to. This will also require special manufacturing capabilities, although this might be no problem for mass production. Strongly related to the overall size is the sensitive area.

At this occasion it should be mentioned that the evanescent field effect has been found rather significant. In fact, during various experiments such a "button" has been implemented by accident. That is, touching the light guide at its perimeter (not at the end wall) does significantly remove light from it, hence reducing the light reflected back into the sensor resulting in a more weak sensor signal. The more the fingers are pressed against the light guide and the touched area increases, the more light is removed from it and the weaker the signal is getting.

However, this involved touching the light guide at a rather large area. Having just an area of a few square millimeters might require very sensitive (and hence probably expensive) sensors.

Another question is how to efficiently illuminate such evanescent field effect button, as this was one of the primary goals for the new button concept. The functional light of an evanescent field effect button is not leaving the prism through the sensitive area under normal conditions. Of course, one could use a second LED, but this is not really a solution from an energetic point of view. In fact, besides using separate LEDs it has been proposed in [9] to use one and the same LED for providing both functional and illuminating light. Perhaps this is possible by using a specially constructed prism. Although there might be a risk that light normally leaving the prism through the sensitive area could be reflected unfavorably back into the prism and into the sensor. In worst case this could bring back light into the sensor that should be removed actually, hence disturbing the sensing mechanism. It will be seen how this is being implemented finally once such buttons become commercially available.

Despite some disadvantages it needs to be stated that such evanescent field effect button concept is the most beautiful among all optical buttons including the one featured by this paper. The reason is plain and simple: The button is really sensitive for touching; all issues with reflection, proximity, and mistriggerings are ruled out by design.

7 Conclusions

This paper discussed a new, nonetheless rather simple approach for small and truly optical push buttons. The discussion is not left alone to the concept, but does include concrete details of a reference implementation as well.

Other interesting existing approaches to optical buttons have been discussed and compared as well.

The actual innovation of the presented concept is that it allows the combination of a tiny LED indicator light with a button functionality on a very small area. Furthermore it has been shown that the button function can come almost for free in terms of power consumption when compared to a simple indicator LED.

Assuming industrial manufacturing, the price tag of such optical push buttons will be very likely higher than for cheap mechanical buttons. However, high quality and very robust push buttons are rather expensive. An optical button as described herein should compete very well with those ones while providing additional benefits. Surely this does not mean that it renders any mechanical button useless.

Besides the successful reference implementation a couple of points for improvements have been shown, leaving plenty of space for future work. The reference implementation is already in use for a practical application and future will show how it is proving itself under real–world conditions.

References

[1] VISHAY Semiconductors: *TCND3000 — Reflective Sensor for Touchless Switch.* VISHAY Datasheet, Document Number 84606, Rev. 1.2, August 2006. See also `http://www.vishay.com/optical-sensors/list/product-84606/`

[2] ELMOS Semiconductor AG: *E909.01 Specification.* February 2004. See also `http://www.elmos.de/produkte/katalog/assp/datasheets/909.01/`

[3] ELMOS Semiconductor AG: *E909.01 — DESIGNING SYSTEMS WITH HALIOS SWITCH.* Application Note, 2006. See also `http://www.elmos.de/produkte/katalog/assp/datasheets/909.01/`

[4] HALIOS Web Site: `http://www.mechaless.com`

[5] Avago Technologies (formerly Agilent): *Agilent APDS-9002 Miniature Surface-Mount Ambient Light Photo Sensor.* Data Sheet, May 2005. See also `http://www.avagotech.com/products/product-detail.jsp?navId=H0,C2,C5213,C5251,P88961`

[6] Kingbright Web Site: `http://www.us.kingbright.com`

[7] MENTOR SMD Light Guide Systems Web Site: `http://www.mentor-components.com/products.phtml?cat=6`

[8] LEONI AG: *PRESSURE SENSOR COMPRISING AN OPTICAL WAVEGUIDE, AND METHOD FOR DETECTING PRESSURE.* International Patent, Publication Number WO/2003/069294. See also `http://www.wipo.int/pctdb/en` (World Intellectual Property Organization)

[9] LEONI AG: *Gebrauchsmusterschrift "Optischer Schalter oder Taster".* Deutsches Patent– und Markenamt, Patent Number DE 20 2004 007 092 U1, October 20th 2005. See also `http://publikationen.dpma.de`

[10] LEONI AG: *Offenlegungsschrift "Optischer Schalter oder Taster".* Deutsches Patent– und Markenamt, Patent Number DE 10 2005 021 008 A1, December 8th 2005. See also `http://publikationen.dpma.de`

[11] Recommended Evanescent Field Readings: http://en.wikipedia.org/wiki/Total_internal_reflection http://en.wikipedia.org/wiki/Evanescent_wave

[12] Microchip PIC Micro Controller Overview Web Site: `http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=74`

[13] Atmel AVR 8-Bit RISC Devices Overview Web Site: `http://www.atmel.com/dyn/products/devices.asp?family_id=607`