RWTH AACHEN UNIVERSITY

APUCS: Active Tangible Input Devices for Capacitive Multitouch Surface

Master's Thesis at the
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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Aachen, July2015
Jan Thar

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Abstract

In this master thesis we developed a circuit to use tangibles, haptic input devices, on capacitive touch screens. While touch screens have the advantage that user interface and controls can be adapted depending on the user's requirement, the haptic feedback is missing. This can be added with these tangibles, which can be placed on the screen and are recognized by it. Tangibles which can be detected by a capacitive touch screen were already developed, but they are filtered by the touch screen software after a while if they remain stationary. In this thesis we developed and tested different circuit variants to circumvent this filtering. We employed a sensor which can detect the measurement signal of the capacitive touch screen and therefore knows if it is located on the table. An integrated light sensor can verify the position, and can be further used to determine the orientation. Each tangible communicates by bluetooth with the table and can be identified with a unique id. Therefore a unique design of the pattern, which can be detected by the table, is not necessary.

Überblick

In dieser Masterarbeit wurde ein Schaltkreis entwickelt um Tangibles, haptisch fühlbare Eingabeobjekte, auf kapazitiven Touchscreens verwenden zu können. Während Touchscreens den Vorteil haben, dass Benutzerinterface und die Eingabeschaltflächen je nach Bedarf angepasst werden können, fehlt das haptile Feedback, wie bei physischen Eingabegeräten. Dieses haptile Feedback kann durch Tangibles auf der Touchscreenoberfläche bereitgestellt werden. Es wurden bereits Tangibles entwickelt, die von kapazitiven Touchscreens erkannt werden, allerdings werden ihre Signale nach einer gewissen Zeit herausgefiltert sofern sie sich nicht bewegen. Um diese Filterung zu umgehen wurden in dieser Arbeit zunächst verschiedene Schaltungsvarianten aufgebaut und getestet. Die besten Resultate erzielten wir mit einem Sensor der das Messsignal des Touchscreens entdecken kann und dadurch weiss, dass er sich auf dem Tisch befindet. Dies kann ausserdem über einen integrierten Lichtsensor verifiziert werden, der zusätzlich genutzt werden kann, um die Ausrichtung zu bestimmen. Die Kommunikation mittels Bluetooth zum Tischsystem erlaubt zusätzlich die einzelnen Tangibles eindeutig zu identifizieren. Ein unterschiedliches Design der Muster, welche von dem Tisch erkannt werden, ist daher nicht notwendig.

Acknowledgements

First of all, I want to thank Prof. Dr. Borchers for supervising my thesis and working at his chair, and Prof. Dr. Øvergård for being my second examiner.

Secondly, I want to thank Simon Völker for advice, patience (with all the not-working prototypes) and feedback. I want also thank Christian Thoresen for his valuable input (especially for his comparator circuit).

Special thanks to Florian Busch for the tangibles passive marker system and René Linden for covering the touch table software side.

And of course I want to thank everyone else who supported me - like my family, especially Jens Thar for thesis correction.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in colored boxes.

Definition:
Excursus

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in American English.

Download links are set off in colored boxes.

File: myFile[a]

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[a] http://hci.rwth-aachen.de/public/folder/file_number.file

Chapter 1

Introduction

We as a human can perceive a physical input device like a button optically and haptically. The haptic feeling allows an eyes–free interaction, while the optical senses gives additional feedback. These real buttons have normally a fixed arrangement which is not customizable for different applications, and also the optical view is not changeable. Therefore, the connection between an input device and the virtual user interface is not always clear, since input controls have to be reused for each application and can not be rearranged or relabeled for different applications.

As an alternative you can add small screens on the buttons, resulting in setups like the optimus popularis[1] keyboard. In this arrangement, we can at least change the visual clues of each button, but the button arrangement is still fixed. Therefore, we still have a suboptimal solution, since hardware input arrangement and graphical user interface might not be matched.

With a touchscreen, we can place input controls everywhere on the screen. Therefore, the graphical user interface and the physical input location can be arranged at the same spot. The disadvantage of this approach is that the touchscreen lacks haptic feedback, excluding eyes–free and fast interaction.

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[1] http://www.artlebedev.com/everything/optimus/popularis/

There are several approaches to overcome this issue.

Vibrational motors can give haptic feedback, by changing the amplitude of the vibration depending on the position of the finger relative to a virtual button. Such a system was developed by Nashel and Razzaque [2003]. Yatani and Truong [2009] developed a device where a matrix of vibrational drives allows to feel pattern on the display which give haptic clues.

Another approach by Bau et al. [2010] employes electrical charges with different amplitude and loading frequency to change the perceived friction of the screen's surface. This method is not applicable on capacitive touch screens since it will disturb the measurement.

All these approaches can only be used if the finger is already placed on the screen and work only well on a small screen like a smartphone screen.

For bigger screens, an interesting approach is to place physical objects, so called tangibles, on the screen. They are formed like the corresponding classical physical input device. If they can be detected by the touchscreen, the graphical user interface can be adapted, so that visual clues are arranged around or, for transparent tangibles, even below the tangible. The tangibles are then used for haptic feedback, while they are recognized as touches by the screen. They can be arranged freely on the table and therefore, can be adapted depending on the field of application.

related work

In this thesis we start in chapter 2 "Related work" with an overview about different approaches to build tangibles for touch tables. Different kinds of sensing touches and tracking the position of tangibles are possible. In our approach, we focus on the commercially available capacitive touch screen. Therefore, we do not need to build our own table or to extend the table with additional sensors. This lowers the entry barrier and simplifies the construction. Voelker et al. [2013] already developed such a passive tangible for capacitive touch screens. This thesis addresses the remaining obstacle that the tangibles touch pattern is filtered out after a while if the tangible is not moved.

design process

In the chapter 3 "Active tangible design" we first examine the different available sources which can be used to prevent, detect or counter the filtering algorithm of the touchscreen. We made prototypes for most of these variants to test them. Our final prototype features a combination of a light sensor and a scan line detection of the capacitive touch screen's sensor field in combination with a bluetooth communication to the computer. We eliminated the need for different touch pattern by using the bluetooth id for identification. The light sensor helps to determine the orientation of the tangible.

evaluation

This sensor is then tested and the power consumption is estimated to determine the necessary battery size. The results can be found in chapter 4 "Evaluation". The power consumption is within acceptable bounds: The resulting tangible can continuously work more than two days.

summary and future work

In chapter 5 "Summary and future work" we conclude the thesis with an overview over possible alternative sensor usage and improved tangibles: Already equipped with battery and bluetooth, the tangible can be further extended with additional sensors or actuators.

Chapter 2

Related work

In this chapter we will describe the different approaches to use tangibles on touchtables.

Projector and camera system over the table

Wellner [1993] proposed to combine the desktop metaphor with the real world desktop environment. On this so called DigitalDesk a projector and a camera is mounted above the desk. The projector allowed to display virtual content on the surface, while the camera is used to detect user input. The possible application of this system in Collaborative work was demonstrated with a tic tac toe game, where the two players are seated on different desks. Each player draws his moves on a paper which is simultaneously projected on the other desk.

The combination of camera and projector was also utilized by Underkoffler and Ishii [1998] in a so called I/O bulb (figure 2.1). They created a learning environment where physical objects are used to simulate a laser system. Laser, reflectors, lenses and beam splitter can be placed freely on the table, while the simulated laser pathway is displayed at the same time.

One important limitation of this type of desks is that input and output sources are above the table. While the user is manipulating the tangibles parts of the desk are shadowed. This disturbs both input and output of the system.

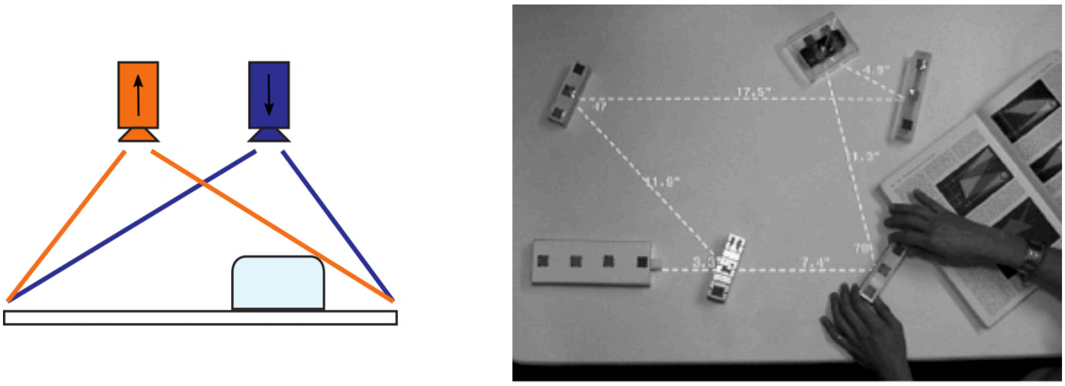

Figure 2.1: Illuminating Light. A camera (orange) above a table scans the position of tangibles - representing optical components. A corresponding image of light propagation is then calculated and displayed with a projector (blue) mounted over the desk. Image source: http://www.inventinginteractive.com[a]

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[a] http://www.inventinginteractive.com/2010/06/04/oblong-and-before/

Camera over the table, display

Tabard et al. [2011] (figure 2.2) kept the camera above the tables to track input and positions, but they used a computer screen as display. This system is intended to help workers in biology laboratories. For example, probe racks can be tracked with the camera and additional information for each probe can be displayed on the screen.

While the visual output in this setup is the desk itself, the camera remains above the table. Therefore it is still obstructed by the user.

projector and camera from the bottom

In a tabletop system for music performances Jordà et al. [2007] (figure 2.3) utilized a marker system for visible light on tangibles. Here, the camera is mounted below the table and tracks the tangibles through the semitransparent surface. Tangibles with different functionality can be distinguished by a visible marker pattern (so-called fiducials), while connections between the tangibles are defined by proximity rules. These connections are displayed on the surface by a projector which is also mounted below the table.

Instead of tracking visible marker the following systems one could use marker for an infrared camera, placed together with the projector below the table. Infrared light

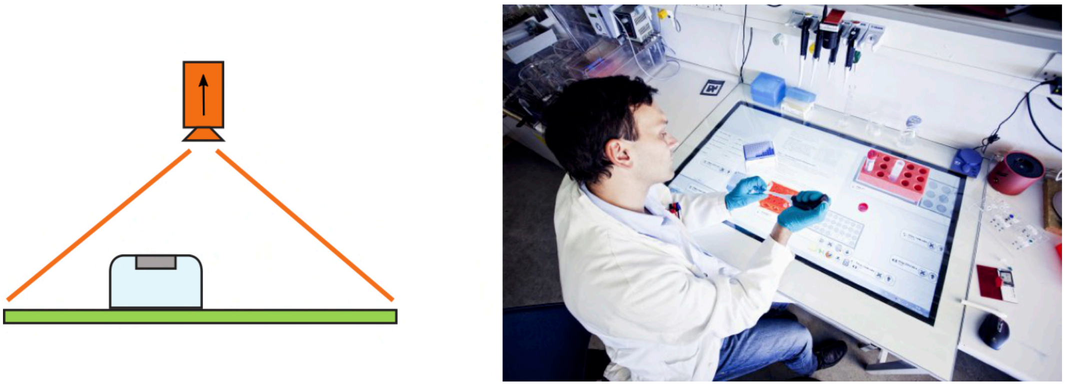

Figure 2.2: eLabBench: A camera (orange) above a screen (green) detects the position of probe racks. Additional information can be displayed on the desk. An infrared pen can be used for notes. Image source: http://www.version2.dk[a]

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[a] http://www.version2.dk/artikel/digital-revolution-i-laboratoriet-46-touch-skaerm-med-rfid-laeser-og-objektsporing-goer

is either fed into the sides of the screen surface (frustrated internal reflection - FTIR) or the screen is indirectly illuminated from the bottom. The first one is better for detecting markers, while the latter is better at detecting finger touch. Both systems can also be combined.

Weiss et al. [2008] extended this approach to mechanical more complex tangibles like sliders or buttons. Here, user input like moving a slider mechanically modifies the marker pattern of the tangible, which is detected by the camera. The display can display additional content corresponding to the state of the input device, while the tangible gives haptic feedback.

In a more recent approach, Zimmerer et al. [2014] used a commercial touch screen for a tabletop game. Optical fiducials are tracked to detect the position of the playing pieces. A QR-code scanning provides additional information that is displayed on a smartphone, and a leap motion sensor as well as speech recognition further refine gameplay.

adding movement

Not only the user can arrange the tangibles - it is also possible for system to rearrange the tangibles on its surface (Weiss et al. [2010] (figure 2.4)). Small magnets are added to the marker, and a grid of electro magnets below the sur-

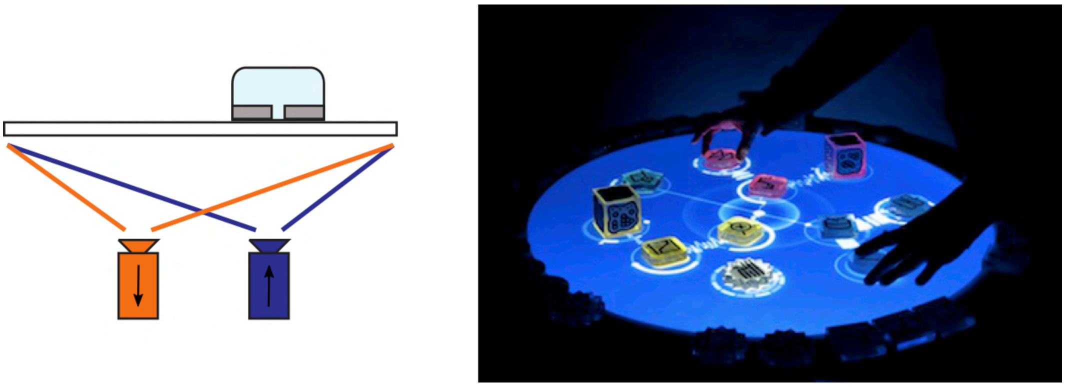

Figure 2.3: Reactable: A camera (orange) and a projector (blue) are mounted below the table. The camera tracks optical markers at the bottom of the tangibles, while the projector displays the screen image. Image source: http://mtg.upf.edu[a]

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[a] http://mtg.upf.edu/project/reactable

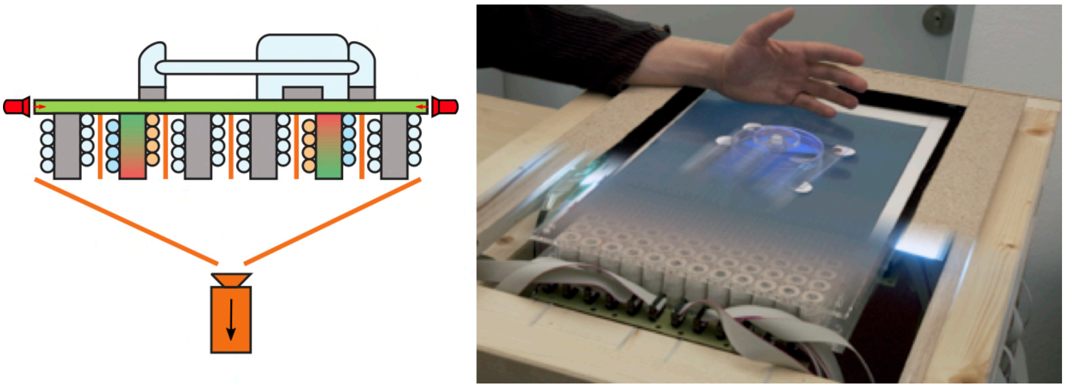

Figure 2.4: Madgets: A grid of electromagnets (grey) allows the system to move tangibles on its surface. Fibre optics between the magnets guide infrared light to a camera system (orange) below, which determines the position. A screen (green) on top of the magnets displays optical information. Infrared light is fed into the sides (red) for the infrared tracking. Image source: http://www.malte-weiss.de[a]

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[a] http://www.malte-weiss.de/portfolio/projectDetail.php?idname=madgets

face of the screen can move the tangibles. In addition, the magnets can also manipulate the state of each tangible, like moving the knob on a slider or raising a button. Even ringing a bell and powering a LED is possible. A screen on top of the magnet array gives optical feedback, while optical fibers conduct infrared light from the display's surface to a camera system below.

Krzywinski et al. [2009] developed small (two wheel) robots that can move on a touch table. They utilized a combination of indirect IR and the FTIR illumination to track marker movement and finger touches. These robots can be therefore tracked with a marker pattern on their back. A bluetooth communication with the table allows control of these robots. A pong game served as a demonstrator. In this game, the players controlled the robots with finger touches.

Pedersen and Hornbæk [2011] (figure 2.5) took a similar approach based on small commercial robots with a xBee modules for communication. The robots can work as input devices with force feedback.

Similary, Nowacka et al. [2013] let a small robot move on an optical touch screen. In this case the robot can communicate with the touch screen by infrared LEDs. These LEDs are also used to detect the position of the robot with a light pattern at the bottom, while phototransistors are used as the back channel. An acceleration sensor and gyroscopes control movement, since communication from the table is too slow. These sensors can also detect gestures by moving the tangible or a tapping at it.

While touch screens of this type are commercially available, infrared light has the clear disadvantage that changes in the ambient light disturb the touch recognition. In addition the camera system below the table makes the system relatively clumsy. This can be reduced with a fiber optic system to the camera or with infrared emitters and receivers integrated in the screen surface.

acoustic detection

Kurata et al. [2005] utilizes surface acoustic waves to detect finger touches on the touch screen system. Since the acrylic base of their tangibles is invisible for the touch screen, they are instead tracked with an ultrasonic system from Nishida et al. [2003]: Each tangible emits signals with an integrated ultrasonic sender, which are then received by a set of ultrasonic receiver distributed in the room. The tangibles has an unique id and either represent a worker or a tool like a clipboard, map or manual which are used to organize the workflow. Simple gestures for e.g. focus and copy can be

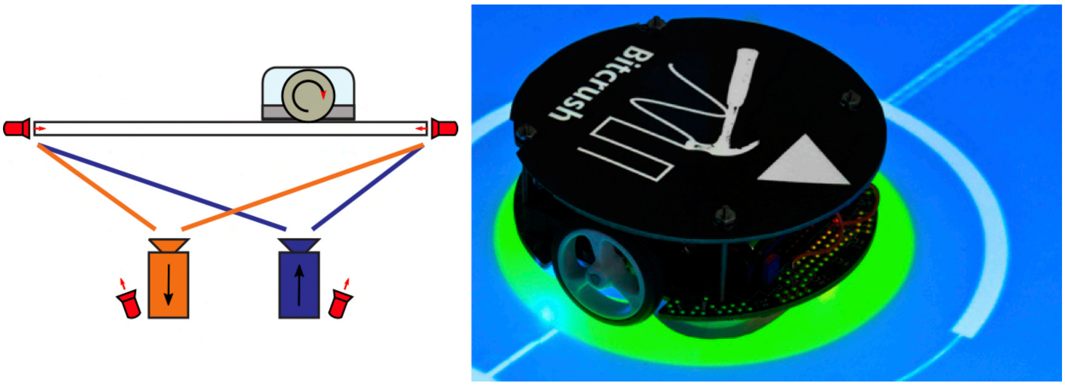

Figure 2.5: TangibleBots. Optical marker on small robots are tracked with an infrared camera (orange). Infrared Light is fed from the sides and indirect from below (red). Screen content is projected (blue). Infrared diodes and photodiodes on the robot are used for communication. Image source: http://esbenpedersen.com[a]

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[a] http://esbenpedersen.com/index.php?p=publications

recognized by the system.

RFID and magnetic induction

Jacob et al. [2002] took a different approach: The ID and position of RFID tags on small tangibles is recognized on a whiteboard. Each tangible represents content. Command tangibles can be placed on top of these. They can be for example used to show more detailed information of the content of a tangible with the projector which displays an image at the whiteboard.

Arfib et al. [2009] (figure 2.6) also used RFID tags. A matrix of 64 antennas determine the position of each tangible. As a further extension, interaction with a tangible (like pressing a button) can activate a secondary RFID tag within the tangible, allowing additional data flow from the tangible to the screen.

Patten et al. [2001] combined two Wacom tablets to form a touch screen. The Wacom mouse system provides a unique ID to track a tangible over both tables. A sensing coil within each tangible changes the electromagnetic field induced by the Wacom table. This allows the localization of the tangibles. Since the tablets only allow to detect two tangibles, each tangibles randomly activates it's sensing coil only for a short time, so that never more than two tangibles are active

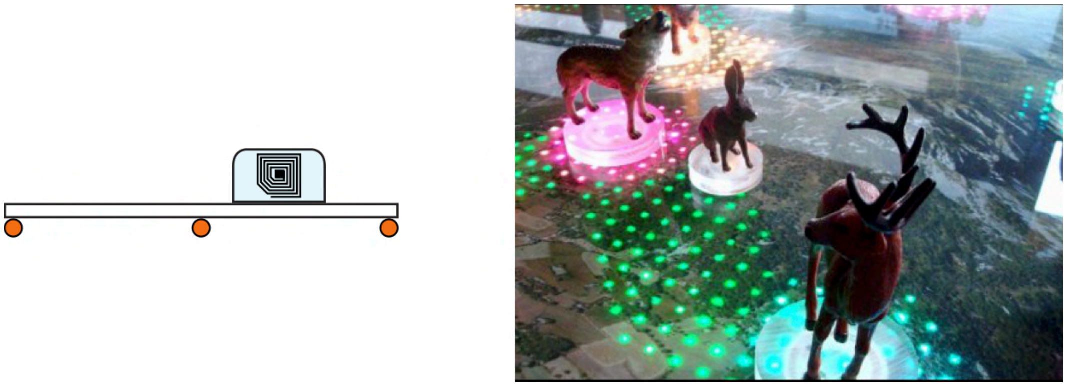

Figure 2.6: Tangisense: A grid of RFID antennas below the table (orange) determines the position of tangibles on the table with a led matrix. Image source: http://www.echosciences-grenoble.fr[a]

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[a] http://www.echosciences-grenoble.fr/actualites/tangisense-une-table-pour-apprendre-et-negocier

on the screen. Therefore the latency of the overall system is bigger. To counter this, the tangible carries a capacitive touch sensor that can activate the tangible's sensing coil directly. A number of modifiers and dials can be added on top of each tangible as additional input sources. Finally, a projector can display an image onto the surface of the table.

Ishii and Ullmer [1997] employed magnetic field sensors to detect the position of tangibles (called physical icons - phicons). For example they represent landmarks and geospace objects on a projected landscape.

These approaches have the disadvantage to demand more complex and therefore more expensive sensor technologies, while generally, they provide no advantage over touch tables.

Nowadays commercial touch screens - ranging from the small smart phone screens to the big table top touch screens screen use capacitive touch technology. This technology exploits the different effects of a grounded body and empty air on an electrical field to determine the position of the grounded body (like a human finger).

Most of the tangibles made for this kind of touch screen connect the human body and the touch surface and therefore only work while being touched.

For example Kratz et al. [2011] built a rotary knob for video manipulation where the knob is connected electrically with two distinct markers below the tangible. The rotation of the knob can be determined by the movement of the touch points of these two marker on the screen.

Stackable Tangibles, passive blocks but also dials and sliders, were developed by Chan et al. [2012]. Each Tangible is put on the underneath tangible in such a way that an additional marker per stacked block on the lower block is connected with the outer hull, which were unconnected before. By touching the staple, these markers are grounded and can be detected by the system, which can determine the height of the staple by the number of touch points. Similarly, the sliders and dials are build with so called zebra rubber, a material which conducts electrical current only in vertical direction. Therefore touches, e.g. representing the slider position, are conducted downwards to the touchscreen.

Yu et al. [2011] identified tangibles either by a marker pattern by switching the grounding connection between the marker and the human finger with a relais on and off.

Rekimoto [2002] et al. build a capacitive touch screen. On this touch screen they can detect multitouch gestures and can estimate the distance of a finger to the screen. Bridge-shaped tangibles with conductive material forming marker at the bottom can be detected from the screen when touched.

Voelker et al. [2013] (figure 2.7) showed that it is possible to detect even untouched tangibles on a capacitive touch screen. Conductive markers on the screen are connected with each other. With this connection slightly above the screen the marker is grounded by inactive parts of the screen. As a result the screen can detect the marker as a touch input source. These markers can even be made entirely transparent by using transparent conductive foil for the markers and their connection. They are still filtered out after while if they are not moved.

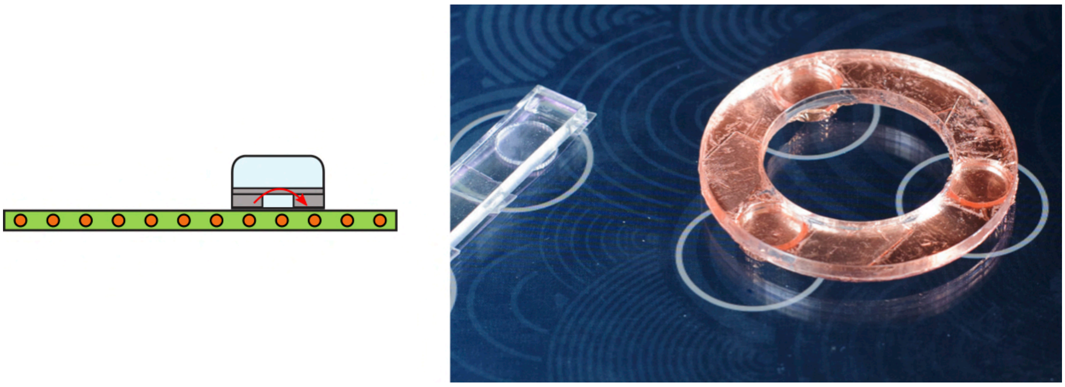

Figure 2.7: Pucs: Conductive markers are connected with each other slightly above the conductive touch screen. The markers are virtually grounded by the bridge structure. Therefore, it can be detected by the capacitive touch screen.

Chapter 3

Active tangible design

Using a commercial capacitive touch screen as a platform for a tangible user interface is a promising way: This touch screens can detect reliably finger touch input, it is not influenced by light emissions and tangibles with connected conductive pads can be detected. Some minor issues still exist which prevent the usage of passive tangibles in certain scenarios - mainly that tangibles which remain stationary for a while are filtered out. The goal of this thesis is to overcome this issues with a active circuit on the tangible. In this chapter, we will explain the basic properties of a capacitive touch screen and present the different approaches to bypass the filtering process.

3.1 Basic considerations

sensing changes of electric field

A capacitive touch screen measures the changes in the electric field above the screen: For example, a finger will ground the field locally (figure 3.1 - left side). This finger touch signal can be simulated by placing a conductive bridge above the surface which allows a capacitive coupling between the current transmitter wire (where the voltage impulse is applied) and some passive transmitter wires (as a ground connection) as shown by Voelker et al. [2013].

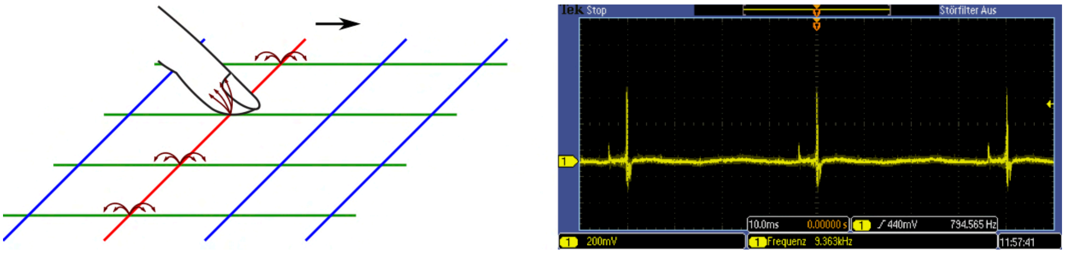

Figure 3.1: A capacitive touch screen uses two orthogonal sets of electrode wires (left picture). On one set (blue/red - transmitter) a voltage impulse (red) is applied at one wire after another. On the other set - the sensing wires (green - receiver) a different field can be sensed depending on wether a finger or another grounded object is on the screen or not. The resulting voltage impulse sensed on one point of the touchscreen is shown at the right side: The spikes correspond to the times when the scan line (voltage impulse) is applied at a wire below the sensing pad.

filtering

The disadvantage of this passive approach is that the resulting touch point will be filtered after a while - static touch points can be seen as a kind of background noise which has to be filtered (adapting the table to the environment) - a touch screen is optimized to detect input changes (pressing button) and not static input (holding a button).

bridges are not working if aligned

Also, the bridge is not working if it is aligned along the transmitter wire, since the ground potential effect is equal to the potential of the transmitter wires. Therefore the touch screen senses the standard field from this transmitter, not recognizing the marker. This can be solved by making the tangibles bigger (such that the ground plane is big enough) or by using a pattern with more pads. In both cases the resulting tangible has to be quite big. Smaller tangibles might be preferable depending on the application.

Alternatively adding active electronics might circumvent these design-dependent issues, which can use the following input sources.

electrical field changes

A stationary tangible is filtered because its influence on the field is constant. Therefore, changing the applied field to a marker by the tangible itself or switching the bridge between the markers on and of seems to be an solution.

light emission

Secondly one can use the light emission of the screen to detect pattern. Since only visible light can be used on a capacitive touch screen, the light pattern might disturb the user if its frequency is not high enough.

acceleration

An acceleration sensor provides another variant: As long as a tangible is not accelerated, it will stay on the same position. In this case, the biggest challenge is that the sensor signal is not related with the touchscreen: Moving a tangible outside the screen and having finger touches on the screen similarly to the tangibles footprint will prompt the system to think that the tangible is on the screen. Latency is another challenge - on one side the acceleration has to be detected and reported quickly to the system, but it has to be filtered from noise on the other side.

magnetic field

A compass module can help to determine the orientation on the screen (especially when a second stationary compass module is mounted within or on the touch screen). The question if a tangible is stationary the screen can not be answered with this input source.

3.2 Programming

programming

We kept programming as simple: The Arduino IDE[1] was used to program the robot for endurance testing, the Energia IDE[2] in combination with a TI Launchpad[3] was used to program the MSP430G2553 as micro controller for the sensor evaluation. The bluetooth low energy module BLE112[4] was programmed with the Bluetooth Smart software[5] and a CC debugger[6] .

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[1] http://www.arduino.cc/

[2] https://github.com/energia/Energia

[3] http://www.ti.com/ww/en/launchpad/msp430_head.html

[4] https://www.bluegiga.com/en-US/products/ble112-bluetooth-smart-module/

[5] https://www.bluegiga.com/en-US/products/software-bluegiga-bluetooth-smart/

[6] http://www.ti.com/tool/cc-debugger

3.3 Communication - Bluetooth

Most of the above mentioned variants of an active tangible need a feedback channel to the touch screen system. In order to keep the required special hardware at a minimum we decided to use bluetooth, since it is either preinstalled in most computer systems or it can be added simply with a small usb to bluetooth bridge.

classic Bluetooth

The first prototypes use a serial bridge with classic bluetooth like the HC-05 or HC-06 modules. They are easy to use by replacing a wired serial connection between computer and micro controller. Arduino, Energia and Processing can therefore communicate with the tangible just like a serial connection after establishing a connection.

However, classic bluetooth draws more energy than its successor bluetooth low energy (BLE). In addition, BLE is better supported by Apples programming environment.

BLE - Serial Bridge

Therefore, we switched to corresponding serial bridge modules for BLE: The HM-10 BLE module is pin compatible to the above mentioned modules, except the pin for programming via AT commands. One alternative is the HM-11 module, which has the same functionality but nearly half the size. One disadvantage of these modules is that the programming via AT commands is not to working reliably - after pairing the bluetooth module with another module, programming is not allowed anymore. The bluetooth module will then work in its standard configuration instead of the intended one. Since the tangible has slave functionality the pairing can not be easily delayed.

BLE - programmable

Therefore we switched to fully programmable BLE modules like the BLE112. They can also replace the whole micro controller: The BLE112 offers analog measurement and an integrated comparator. We kept instead a MSP430 as a low power micro controller for sensor evaluation but replaced the serial connection to the BLE module with two digital lines for each signal bit (inverted and non inverted).This allows the BLE module to sleep until it is woken up with a pin change interrupt (changing the voltage level at an input pin). Since the BLE module can only detect one interrupt edge direction per port (either the voltage transition from high to low or the low to high will trigger an interrupt) using the signal and the inverted signal as an input forces a corresponding edge direction in every case.

The BLE113 consumes even less power , but it is much harder to solder by hand - the solder pads are located below the module.

Another option is the PAN1740 module. It features a much smaller form factor and very little power consumption compared to the BLE112 module. But because of the very small footprint it is nearly impossible to solder such a module by hand, so we did not use this module.

3.4 Prototypes

In this section we will describe the demonstrators for the different approaches to circumvent the filtering of stationary tangibles.

3.4.1 Miniaturisation scan signal amplifier

Amplified signal from one electrode is fed into another

Christian Thoresen developed a circuit to amplify the signal corresponding to the san lines (figure 3.2). Whenever the scan line arrives below a sensor pad it can trigger an reinforced impulse on a second pad. This Turning on and off results in different signals at different times, therefore the filter algorithm of the touch screen should not remove the touch point from the screen.

depending on size of the circuit additional ground plane is necessary

The miniaturization of the circuit (figure 3.3) resulted in the following findings:

- A breadboard or stripboard version has a much higher inert ground mass than a miniaturized version on a tiny printed circuit board (PCB) with sur-

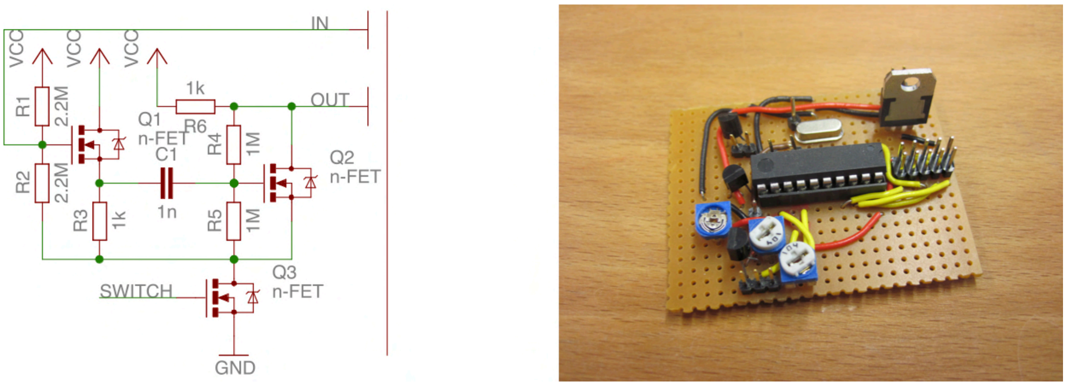


Figure 3.2: Amplify the scan line: The voltage impulse from an input electrode on the touch screen (right side of the circuit diagram) triggers a two stage amplifier. The amplification circuit can turned off with a third transistor. The output signal lays on another output electrode on the screen. The right side shows the initial breadboard prototype from Christian Thoresen

face mounted components (SMD) depending on the size of the circuits. Therefore an indium titan oxide (ITO) conductive foil has to be used as ground plane, limiting the extend of miniaturization of the tangible. The transparent foil shrinks it optically, but the electrical contact between ITO and PCB can not done by soldering.

- For a reliable signal both signal pads have to be very narrow on the surface. This can be hardly guaranteed in the real world.

These points prevent an reliable signal with the miniaturized version of the circuit. Therefore variants with other technologies has to be examined. In all cases directly with a miniaturized version to take the first finding into consideration.

3.4.2 Switch mass connection

switching mass area

The next variant utilizes a disconnectable mass plane above the screen. This area is connected with a pad via a relay (figure 3.4 - left side) or a digital switch (figure 3.4 -

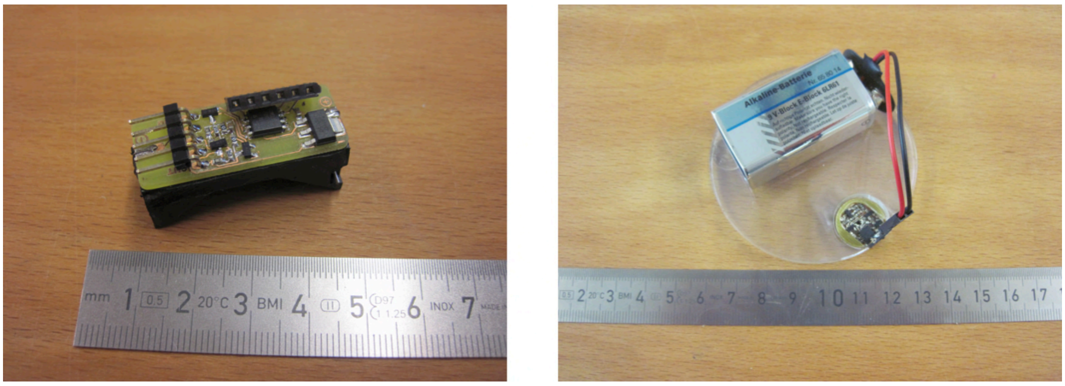


Figure 3.3: Smaller versions: Left side: Attiny13 controlled amplification circuit on a 12v battery holder. Right side: MSP430 controlled amplifier with an external ITO ground plane

right side). This allows to turn the mass connection on and off. Since a pad without mass connection is not detected by the touchscreen, and the connected one is filtered out after a while, the switching should result in a stable (pulsating) touch point.

switching bridges between pads

In a similar version, the electrical connections between three pads are connected one after another with switches. Therefore it is guaranteed that for each pad at least at one time connecting bridge is established which is not parallel to the transmitter lines.

no reliable touches produced

Neither version works reliable. The main challenge is that we can not use an ideal switch - the integrated circuit versions are optimized for either for a low on resistance or high off resistance and not both of them as needed. Even the relay is not working properly in this use case - the voltage impulses have very little power and voltage.

3.4.3 High voltage

higher voltage produces ghost touches

Using unconnected devices might result in different ground levels on both devices. This can be one of the reasons why the amplification circuit was not always working as expected. One solution is to enlarge the voltage difference on one device. This increases the chance that a de-

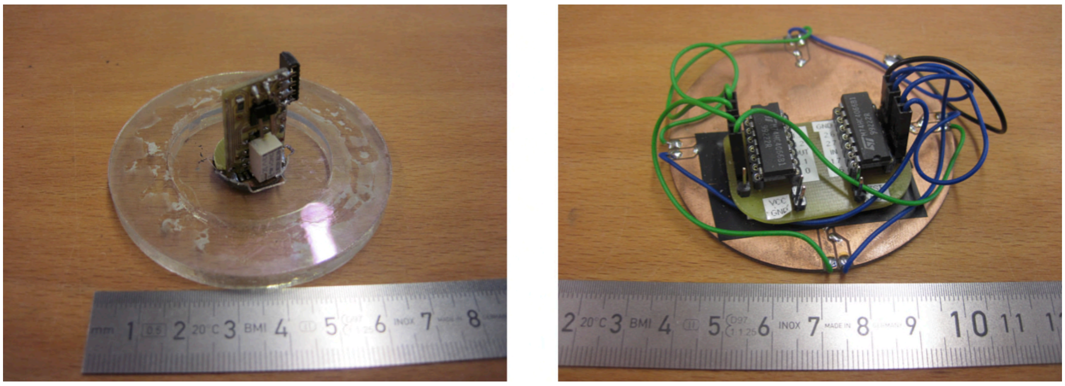


Figure 3.4: Left size: A small relay switches a mass plane on and off. Right side: A fourfold switch connects three pads one after another (reducing the problems if two pads are on the same scan line.)

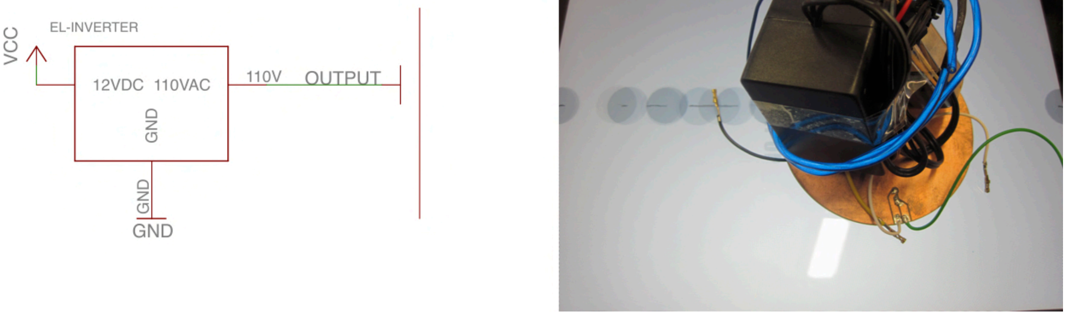


Figure 3.5: High voltage impulses produced by an electroluminescence inverter are applied on one pad of the tangible.

tectable field change happens on the receiver line of the touch screen. But even in this case no reproducible signals can be found: It ranges from no touch point detected at all to a set of flickering touch points on one line (as shown in figure 3.5). This even causes sometimes a crash of an application and opening a new one by itself.

3.4.4 Acceleration sensor

stationary (filtered) tangibles are not accelerated

Since only stationary tangibles are filtered after a while detecting the acceleration of a tangible can be used to counter the filtering algorithm: If the stationary tangible is filtered

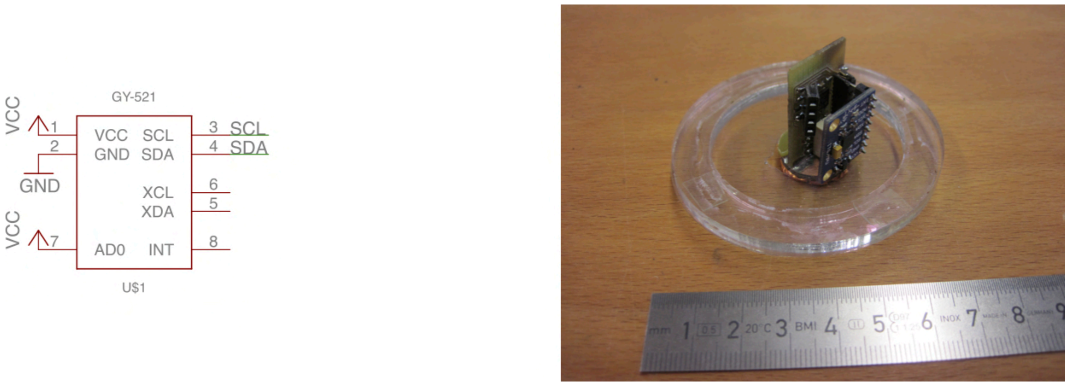


Figure 3.6: A GY-521 module connected to the micro controller detects if the tangible is moved.

out but no acceleration (besides earth gravity) can be detected it has to be at the same position as before. Only when an additional acceleration occurs the tangible is removed from the screen. A simple acceleration sensor module (figure 3.6) is used to test this variant.

latency, fake touches are problematic

There are two main issues with this approach as mentioned before: The signal has to be filtered to remove noise, has to detect slow accelerations and has to react quickly for a low latency. The main issue is that the acceleration is independent wether the tangible is on the touch screen or off screen - identification of the tangible is not possible and the tangible can be easily simulated with finger touches.

detection which side is at the bottom

On the other hand, such an acceleration sensor is perfectly suitable to detect which side is at the bottom of the tangible if something like a dice has to be made.

3.4.5 Light sensor

photodiode detects light pattern on screen

As an alternative, a photodiode can detect the brightness of the screen. Since sequentiell pattern can be detected this can be used to determine the position of the tangible on the screen: A greyscale image where each coordinate is represented by a unique greyscale value can be used to determine the rough position of the tangible. The position can be further refined by displaying a smaller version of the same

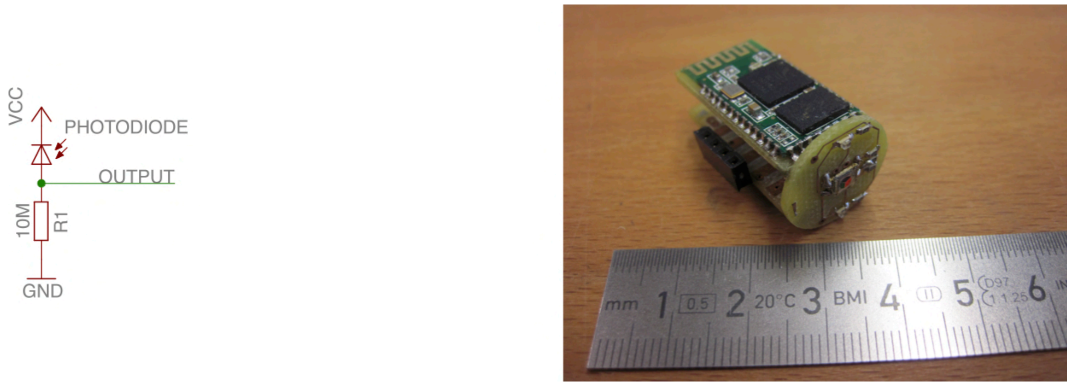


Figure 3.7: Either a single photodiode or three as a RGB sensor are connected with load resistors to detect brightness changes on the screen

pattern smaller at the estimated position. A complete black and white screen can be utilized at the beginning to automatically calibrate the sensor. Additionally two of these sensors allow to determine the orientation of the screen, since two certain points of the tangible are known.

photodiode with load resistor low resolution and slow

In a first version, a basic circuit is employed: The photodiode is connected with a load resistor (figure 3.7). The voltage over the resistor can be measured. The disadvantage of this circuit is that it is relative slow, since the induced photocurrent has to be dissipated over a large resistor.

measured rgb values overlap

The RGB sensor would theoretical allow a faster determination of the position, since instead of one greyscale image three colors can be tested in parallel. Since each of the three internal photo diodes not only detect their own color but also parts of the other two colors the independent test of three different color gradients on a screen would only work with a very low color resolution, which reduces the applicability.

intelligent light sensor not fast enough

An intelligent light sensor (figure 3.8) instead of the photo diode with load resistor delivers a higher brightness resolution which would allow finding the position of the tangible with the same accuracy in fewer steps than the photo diode with load resistor. On the other hand this kind of sensor is much slower because of the integrated evaluation circuit. As a result the whole evaluation is slower. Therefore, this

Figure 3.8: A photosensor with integrated evaluation circuit like the TCS3471 (RGB sensor) or TSL2561T (day light sensor) allows for higher resolution and easier evaluation

variant was not pursued further. For the same reason, the RGB version was not tested.

photodiode with transimpedance amplifier

Another standard, but slightly more complicated, circuit for measuring light with a photodiode is a transimpedance amplifier (figure 3.9). The photocurrent is fed into the inverted input of an amplifier. The output of this amplifier is coupled with this input over an resistor. Since the same voltage level has to be on both the inverted and the not inverted input, and the latter is grounded, the output current has to be the same size as the photocurrent and the micro controller can detect a corresponding voltage over a large back coupling resistor.

framerate to slow to hide scanning

With this circuit several measurements per frame are possible, and sufficient grey colors are reliably distinguishable. The limiting factor is the frame rate of the table: It is not possible to hide the scans from the human eye either by slightly changing the color or by showing the grey scales between the visible frames faster than the eye can watch. The insufficient brightness resolution of the sensor prohibits the first variant and the table's maximum frame rate is not high enough to support the second version.

photodiode useful for start scan and position control

Therefore the light sensor is unsuitable as a standard sensor to detect position and orientation. However, it can scan for different tangibles while the touchscreen is started and

Figure 3.9: A photodiode with transimpedance amplifier. The current produced by the photodiode is direct cancelled with a reverse current. This results in a quick response.

as a control for orientation and identification while a tangible is detected on the screen.

3.4.6 Scan line detection

scan line triggers interrupt event

The last variant detects the scan line of the touch table with a comparator circuit (by Christian Thoresen). A small electrode on the screen capacitively couples the tangibles circuit with the transmitter lines of the touch screen. This input electrode is then connected to one input of the comparator and coupled over a resistor to a voltage divider at the second input of the comparator. A variable resistor allows to adapt to different voltage levels when the comparator should trigger a signal (figure 3.10). This is necessary to suppress noise and adapt to different signal strength of the touch screen field, so that the distance from the electrode to the screen can be adjusted.

In the static case no current will flow through the coupling resistor. The rising flank of the scan line will induce a current through this resistor, changing the voltage level on both inputs of the comparator and triggering a change of its output.

reliable detection if tangible is on screen

With this circuit a reliable detection of a tangible on the screen is possible. This allows to keep the last known po-

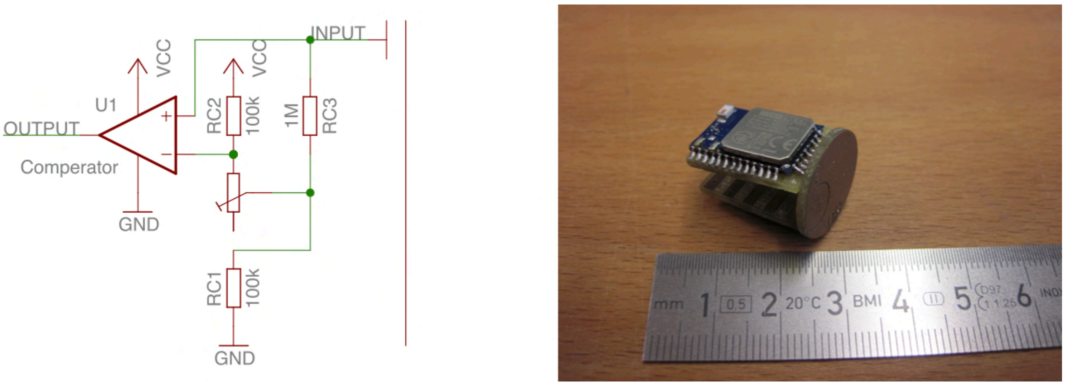


Figure 3.10: A comparator detects the voltage impulses of the scan line with a detector electrode on the screen (right side of the circuit diagram). The voltage impulse induces a current in the coupling resistor (RC3) between sensor electrode and a voltage divider (RC2, RC1), changing the voltage and triggering the comparator. A variable resistor creates an offset so the comparator is only triggered at a certain minimal signal strength.

sition of the tangible after filtering since movement of the tangible can be detected. The only minor obstacle is that the comparator signal can be triggered while the tangible is hovering over the screen with no pad (and therefore no touch) contact. This can be corrected by a secondary sensor (e.g. a light sensor) in combination with a pad pattern. With a light signal we can than check if a tangible is at the assumed position. A precise adjustment of the variable resistor to the used touch screen further reduces the possible hovering distance.

3.5 Final approach

3.5.1 Function

Therefore, we decided to combine the scan line detection with the comparator and a light sensor with transimpedance amplifier. A MSP430G2553 controls both input sources - the scan line detection can either use the internal comparator or, if multiple detectors are used, an external comparator like the MCP6561T-E/LT.

The analogue measurement of the signal of a daylight sensor (TEMD6200FX01) by a transimpedance amplifier (MCP6L01T-E/LT) yield the light level below the tangible. This signal is then send over a BLE112 module to the computer.

race between timer and scan line detection

The MSP430 is sleeping while waiting either for a timer event from the internal timer or a comparator wakeup event. As long as the tangible is not on the screen, the timer will count for a certain time before triggering an interrupt and start over. This event indicates that the tangible is not on the screen. Otherwise the scan line detection will trigger an interrupt and reset the timer. Since the time period between two scan line detections is shorter than the time period of the timer, timer interrupts will not happen while the tangible is on the screen.

brightness detection

If the micro controller is woken up by a comparator interrupt it will then measure the light level before falling asleep again. The impulse of the scan line itself is strong enough to superimpose the light sensor. Therefore the controller will wait one millisecond after the interrupt event before conducting the measurement.

communication

Both boolean informations (if the tangible is on the screen and if it is bright below) are transferred to the bluetooth module. Since the module itself should also sleep most of the time - only waking up either for communication events with the outside world or pin change interrupts for information change - the information is passed through four data lines presenting both boolean values and their inverted values. This allows independently from the actual boolean value that always a certain type of pin change interrupt happens (e.g. a high-low transition), since the BLE112 can only detect such a certain transition and not both types of interrupt transitions at a same time at one port.

functionality

Each tangible has a unique id for the communication with the computer and two UUIDs where brightness and if the tangible is on the screen are stored. Only these two values which can be queried by this UUIDs have to be updated. The light sensor allows to check if the position of the tangible is valid and to distinct different tangibles independently from the pad layout. Therefore, only one standard pattern is needed for all tangibles. This makes production easier and reduces the size of the tangibles, since some minimal distances have to be kept and different pattern results in bigger tangibles.

Three pads in a relative compact pattern guarantee that the tangible can be detected. Even if two of them are aligned with a transmitter line and therefore one disappears, the orientation of the pattern can still be detected by means of a light pattern.

3.5.2 Modules

adaptive PCB

The first approach of this layout uses a small sensor module which is connected by a flat flex cable(FFC) with an external BLE112 module (figure 3.11). The plug/cable combination allows relative free tangible designs, since the small modules can be placed everywhere and multiple modules can be connected with the bluetooth module. The plug is also used for programming the BLE112 module and the MSP430. Two of the cores of the plug on the sensor module are used for the spy-by-wire programming interface of the MSP430. The main reason why this version was abandoned later was that the FFC plug was hard to solder and prone to breaking, and the flat flex cable itself was not designed for shortening. These issues renders the whole system as not reliable enough.

final versions of the PCB

Instead, the whole circuit including the bluetooth module were combined in one rigid PCB version, with different form factors depending on the field of application(3.12). The larger design allows an easier assembling. Without the FFC cables, these versions are far more reliable. They also use one inverted and a non inverted data cores per data bit. Therefore, no changing between different interrupt transitions is necessary for interrupt handling: Independent of the current boolean value a change of the value will trigger e.g. a high-low transition on one of the two cores.

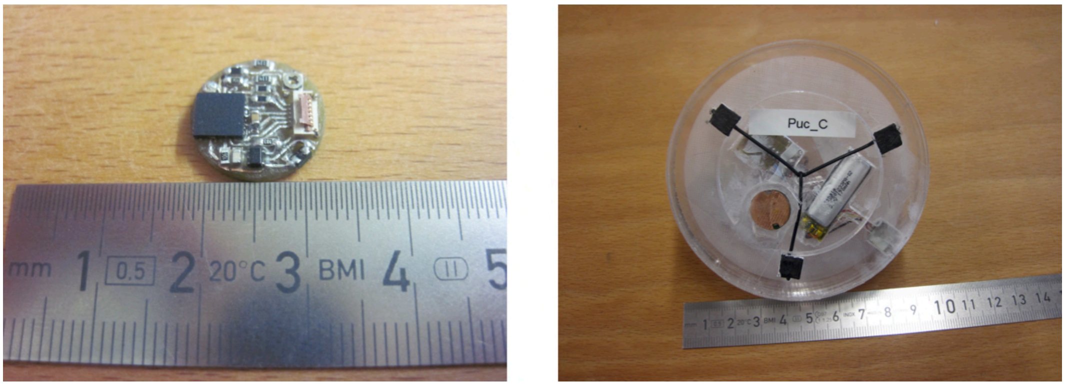


Figure 3.11: The compact design: MSP430 with both scan line detection as well as amplified photodiode on a small printed circuit board. It is connected by the bluetooth module with a six core plug for a flat flex cable. Left side: Sensor module. Right side: Mounted circuit within air hockey puc

The basic module (figure 3.12 - left side) is optimized for the minimal passive pad pattern which can be reliably detected on the screen. A small free area (left side of the PCB) provides space for additional functionality: E.g., adding two DC driver modules to control two small motors directly from the bluetooth module or adding a serial interface for a connection from the bluetooth module to an external micro controller. Other designs (figure 3.12 - middle and right side) are made to fulfill different space requirements depending on the applications.

3.5.3 Complete design

The final tangible system was the result of a collaborative work: Florian Busch made both housings and passive marker system, while Rene Linden developed the software of the table (application programming and framework). The author of this thesis contributed the active marker system.

tangible design

The whole design is shown in figure 3.13. Passive conductive marker are used for the initial detection of the position and orientation of the tangible. A lead plate presses the tangible against the screen surface to improve contact. The active circuit inside is the used to to identify the tan-

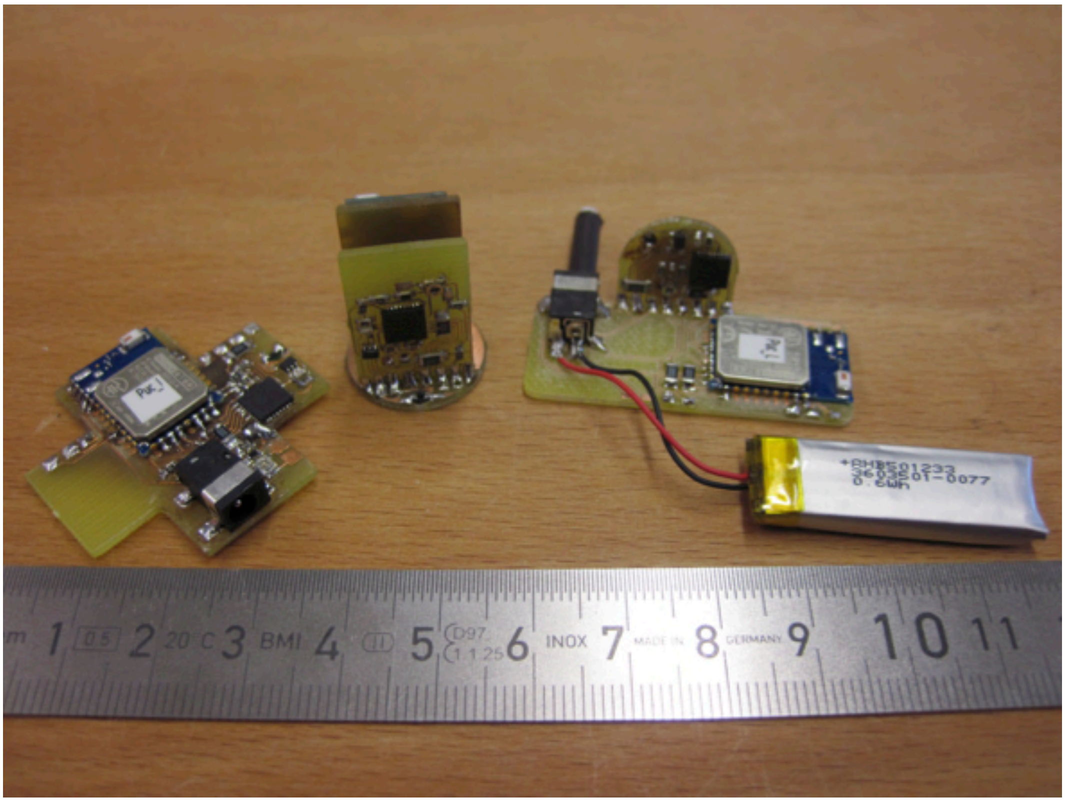


Figure 3.12: Different modules for different scenarios: Left: all components on a single but bulky PCB for rectangular tangibles (with spaces for a passive marker system in the edges). Middle: Components distributed on three PCBs with minimal surface space. Right: Two PCBs form a version with a small surface space but to be built in a bigger housing.

gible. It can evaluate light pattern below its position and relay the results by bluetooth to the computer. These results can be used to check the assumed position. Furthermore, it tells the system if the tangible is still at its place after the touch points of the pads are filtered out. This can be further checked by applying a light pattern below the assumed position of the tangible and comparison with the response values over bluetooth.

For demonstration purposes, several application were made.

air hockey

In the air hockey application (figure 3.14) each tangible represents a racket, their corresponding virtual representation

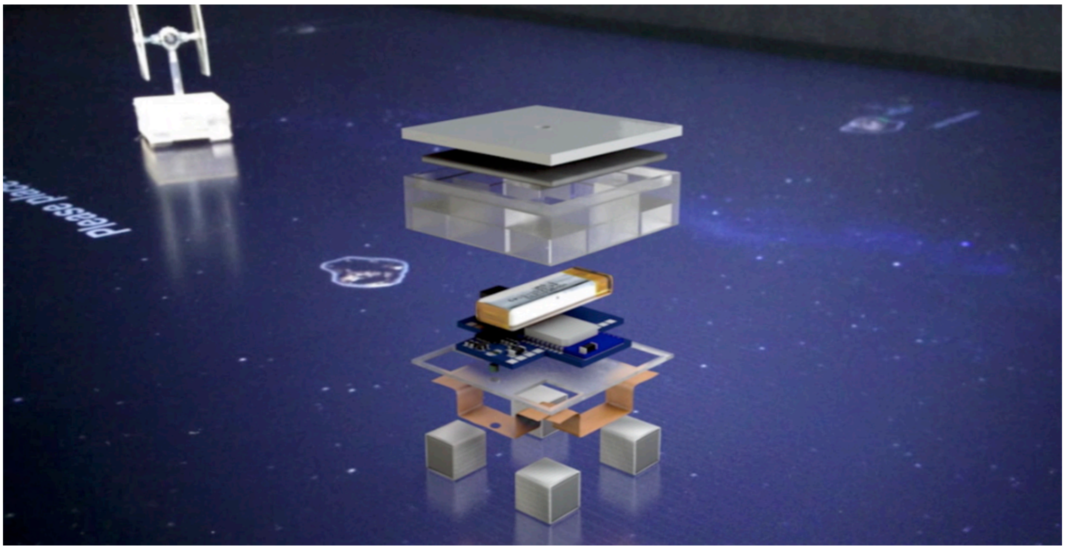


Figure 3.13: The assembly: A tangible stands upon four foam pads - three of them are conductive and connected with each other with copper foil. The housing consists of acrylic glas, where both pads are inserted from the bottom and the PCB and a battery from the top. A lead plate below another acrylic sheet functions as the top. (Picture and 3D rendering by Florian Busch)

can hit a virtual ball. Since the objects are round, the orientation of the objects does not matter. On the other hand the position has to be detected relatively exact and quickly, otherwise the ball movement will differ from the expected behavior. Since the tangibles are big, all three (symmetric) marker at the bottom are detected all the time as long as the tangible moves. The active circuit is only used for the identification of each tangible and for the position of the tangible if it stands still.

star wars tabletop game

A second scenario was the application of the tangibles for in star wars tabletop game (figure 3.15): Each tangible represents one playing piece. They can be moved for certain distances and orientations in each step. Therefore, both positions and orientations has to be determined precisely. Each tangibles features a relatively small marker pattern that is not always resolved by the touch screen. Thus the light sensor has to be used to correct the orientation. Furthermore, the figures stand still most of the time and are filtered after a while. The active scan line detection will tell the system that the tangible is still on the screen and there-

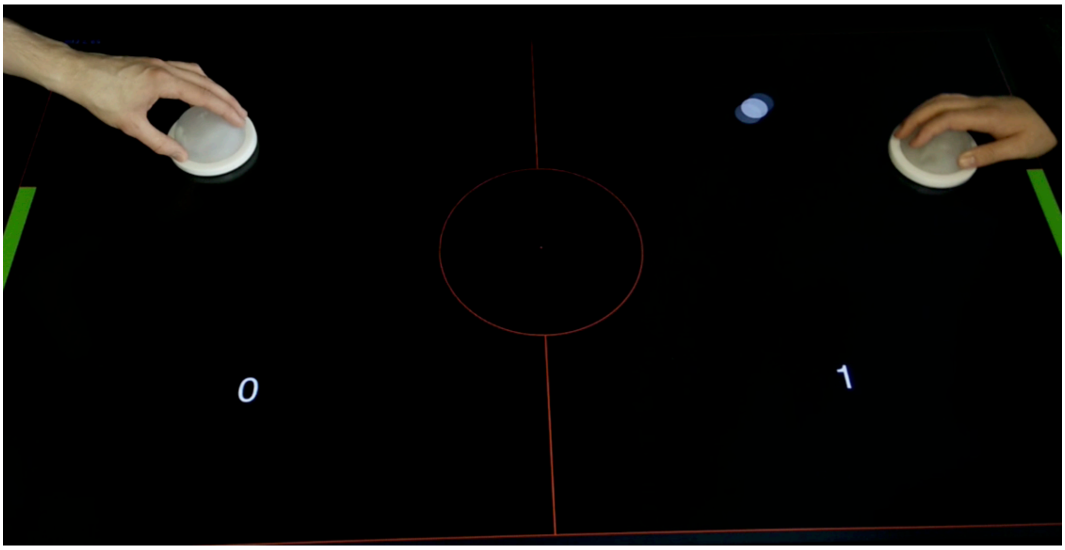


Figure 3.14: Air hockey: Tangibles represent rackets to play with a virtual ball. They require low latency and accurate positions.

Figure 3.15: Star wars tabletop game: Each tangible has to be detected with precise orientation and position.

fore has to be at the same position. The position can be also checked with the light patern, which additionally help to identify the tangible by a unique ID.

dice with multiple sensor pads

A tangible can also represent a dice. In one version (fig-

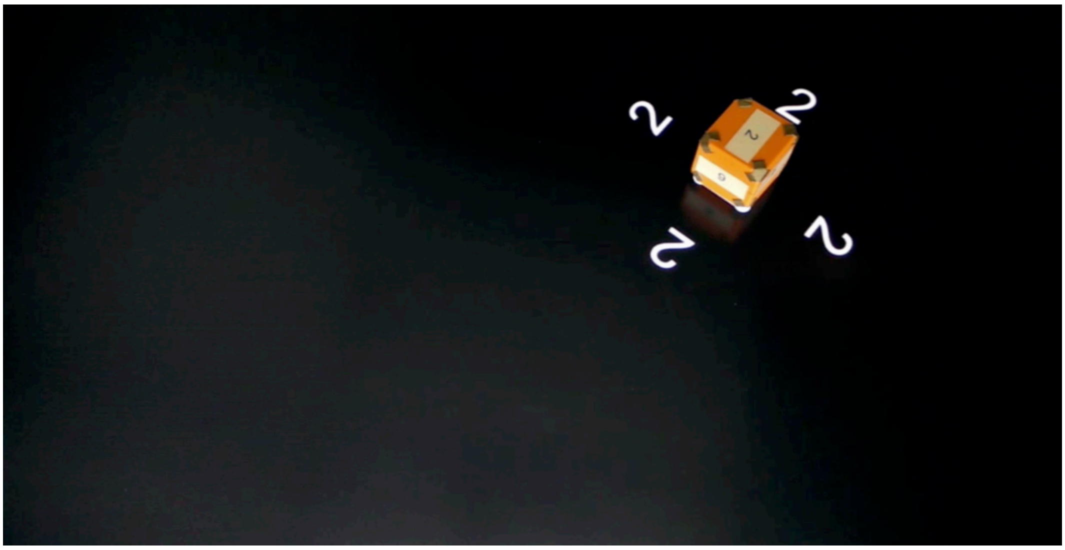


Figure 3.16: A dice: Each side of the tangible has its own sensor. Therefore, the side which is on the table can be detected.

ure 3.16) each side get its own sensor module, consisting of a comparator and an amplifier for the the photodiode, which are connected to central micro controller/bluetooth circuit for evaluation and communication. This is smaller and more cost efficient than using the basic circuit with a micro controller for each sensor pad. This solution has the disadvantage that the connected passive marker in each edge of the cube will conduct the scan line impulse to each side of the cube. Therefore the distance between the sensor module in the middle of the cube and the outer sides has to be big enough to ensure that the sensor will only sense the field below itself and not the indirect field from the passive marker.

dice with acceleration sensor

The standard circuit with a single MSP430 and its internal comparator connected with an electrode on each side of the dice in parallel can only detect if a side of the tangible is on the touch surface. The decision which of the sides is the one at the bottom is not possible, but this can be decided with an acceleration sensor which detects the earth gravity while it is not moving anymore.

Chapter 4

Evaluation

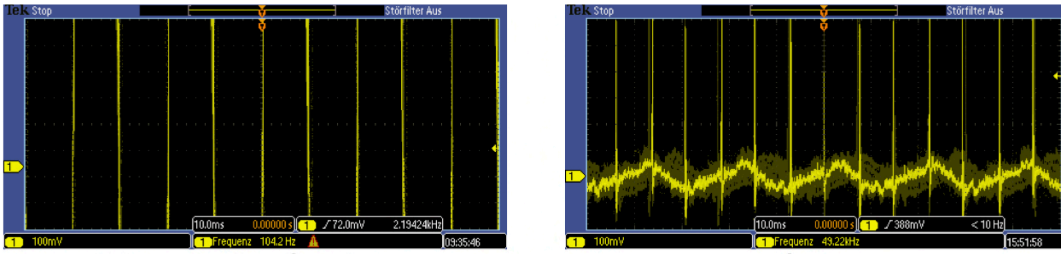
In this chapter, we investigate how reliable the tangibles are detected by different touch screen. Also, we evaluate the power consumption of the tangibles.

4.1 Scanlines of different Touchscreens

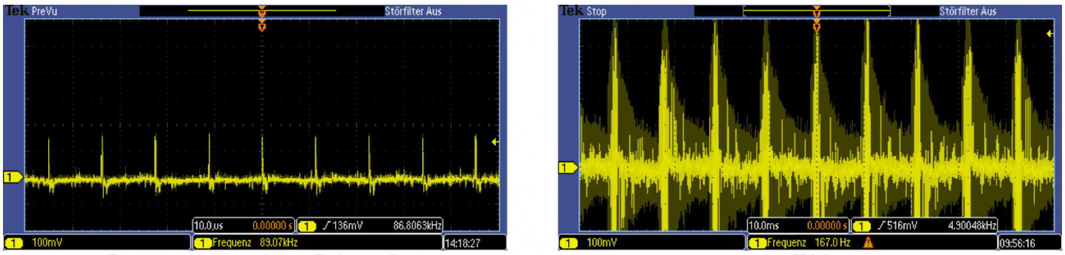
pattern on different touchscreens

First we evaluated the scan lines of different touch screens by placing a 1cm diameter electrode on the screen and measured the induced voltage against a surrounding grounded plate with an oscilloscope.

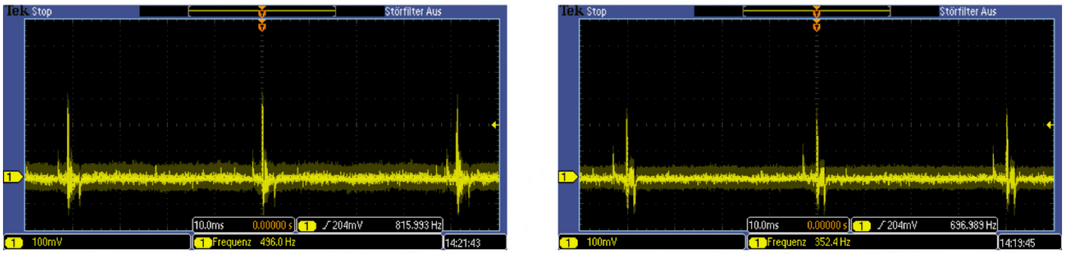
The results for different capacitive touch screens show that the scan line differs in amplitude and frequency of the peak - but the voltage itself peaks exist in all variants. Even with small screens from smartphones (fourth row in figure 4.1) such a voltage peak is detectable on the oscilloscope - but ist might be hard to detect with the comparator circuit. We did not further investigate these touch screens because they are also to small to be used for tangibles, and bigger ones (tablets, third row in figure 4.1) work well with the circuit. For all bigger touch screens (first and second row 4.1), that are large enough for our application, a strong enough impulse is detectable.



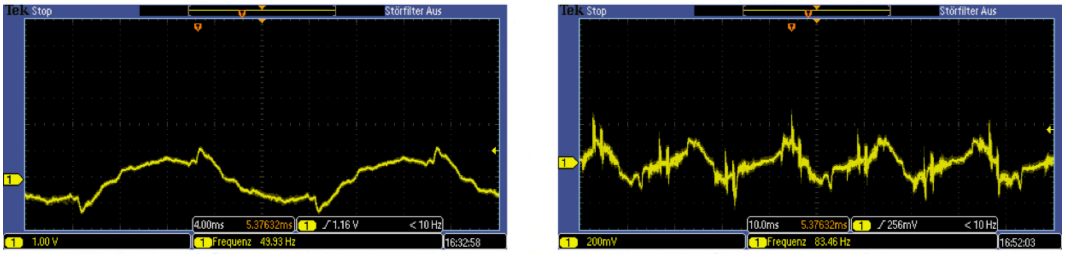
Microsoft Surface Acer



PerspectivePixel 3M



iPad4 iPad1



iPhone4 OnePlus One

Figure 4.1: Scan lines from different touch screens

4.2 Endurance test

A robot was developed to investigate the reliability of the tangible detection. The robot let us investigate the reliability of the passive marker detection depending on the orientation and the position of the screen.

first iteration: quick build

In its first iteration the robot (figure 4.2, right side) uses a multi turn servo to rotate the tangible, wich is connected with the robot by four springs. If robot, tangible and screen are not perfectly aligned, the spring mounting will restrain the tangible so that it will stand with all four pads on the screen.

A stepper motor controls the vertical movement of the tangible. The exact position is determined by two linear variable resistors.

Scan line detection

The robot placed a tangible multiple times (more than 70000 trials in total) with different orientations (73 distinct angles) and different places (each corner and the middle) on various touch screens (55″ microsoft touch screen, 27″ perspective pixel and iPad4). The field sensor detects reliably (100%) if the tangible was placed on the surface of the screen. Depending on the design we already get the confirmation that the tangible is on the screen when the tangible is still hovering above the screen: The electrical field spreads out continuously from the transmitter line, hence we can not adjust the circuit so that it will only trigger if the tangible touches the surface. The noise will otherwise result in an unstable signal for the placed tangible. But with a stable voltage source and a well adjusted circuit we can at least reduce the possible hovering distance to less than one millimeter. This will be tested in the future with the second iteration of the robot.

Light sensor usage

By placing the tangible with different orientations on the screen we can determine certain angles where not all of the three marker can be detected by the screen (figure 4.2, left side). This angle depends on the angle between transmitter and receiver wires. If only two markers are detected, the light sensor is used to determine the orientation: There are two possible orientations with distinct positions of the light sensor. Enlightening the screen below one of these positions and darkening the other one, we can determine the actual orientation of the tangible.

In few cases (2.2 % for the microsoft table) only one touch can be detected. The light sensor could still be used to determine the position but would take much longer, since the

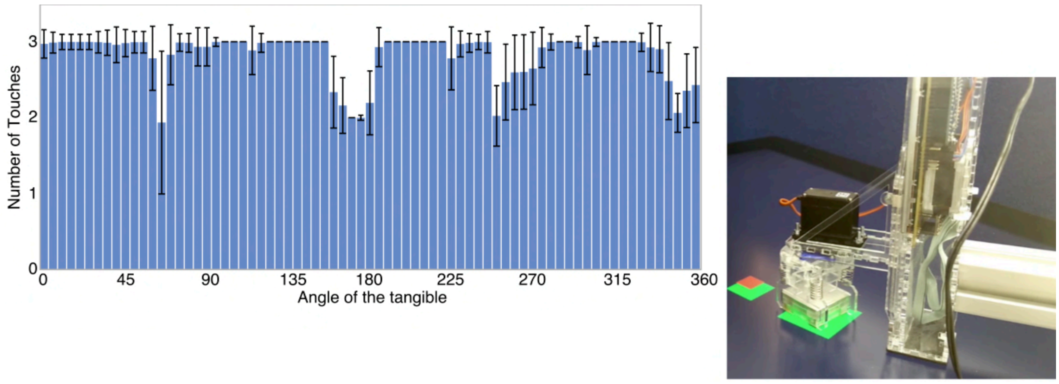


Figure 4.2: Right: The first version uses a multi turn Servo to rotate the tangible and a stepper motor to translate the tangible along the z-axis and a linear variable resistor to detect the z-axis position. Left: Results. Depending on how the tangibles is placed on the touch screen not all of the tangible's three connected marker of a tangible can be detected. In this case the light sensor can be used to determine the correct orientation. Execution and evaluation by Simon Völker and Rene Linden.

duration for finding the right orientation increases already from 50ms (three markers detected) to 190 ms (two markers detected), trying to find the right orientation for one marker is not feasible.

Triggering distance to surface

The tangible should reliable detect if the tangible is on the surface, but almost instantly detect when liftet of. Therefore, the distance to the screen when the sensor detects the scanline has to be small. This distance depends on several factors:

- The scan lines field strength: Bigger tables have emit stronger fields than smaller ones (tablets), the sensor will trigger already at bigger distances than on the smaller tablets.
- The tangibles voltage source: The induced voltage spike will have stronger influence on tangibles with a less voltage. For example a tangible with a 3V input source will detect the scanline on a bigger distance than the same tangible with a 3.3V input source.
- Electrode size: A bigger electrode covers more transmitter lines and can therefore induce a stronger impulse.

The adaption to the different field strength can be made with the adjustable resistor of the comparators voltage divider. A bigger resistor will result in a higher voltage spike necessary for triggering the comparator. To allow a minimal distance it is also necessary to use a constant voltage, the unregulated voltage of the battery will otherwise drop from 4V to 3V. To test the adapted tangible with a integrated voltage regulator (ongoing work), we developed a second robot especially with a higher resolution in z-axis.

second iteration: more rigid construction with precise z-axis control

This second iteration (figure 4.3, right side) is constructed with aluminium profiles instead of laser cut acrylic sheets. Using standard connectors for this profiles allows a precise mounting and guidance. Laser cut polyoxymethylen is used as sliding bearing for the moving parts. A small threaded rod is directly connected with a stepper motor and moves the holder (with a corresponding screw thread) vertically. The position of the holder is detected with a linear variable resistor. A secondary stepper motor rotates the tangible. Two variable resistors - shifted by 180 degree - are mounted on the axis of this motor to determine the actual orientation.

Preliminary results of ongoing work with the distance adjustment

In a first test a 3V voltage regulator was included at the tangible. Instead of the adjustable resistor a fixed 18kΩ resistor is used in the comparators voltage divider. This tangible is than moved with the robot downwards until the comparator gets a stable signal from the scan line: The comparator has to detect the scan line for twenty times in a row with 100ms delay in between, otherwise the robot continue to move downwards (resulting in few more steps downwards, with one step equal to 0.004mm). The results confirm so far that a lower voltage result in a larger distance of the tangible to the screen when the scan line is detected. While the distance seems to be relative constant (+/- 1mm) distance with the 3V regulator, we get a small enlargement of the detection distance over measurement, maybe due to some kind of loading of the coupling electrode. This enlargement is even bigger while using an external 3.3V voltage regulator (figure 4.3, left side in combination with the results of the 3V regulator after data point 565), which has to be investigated further in future work.

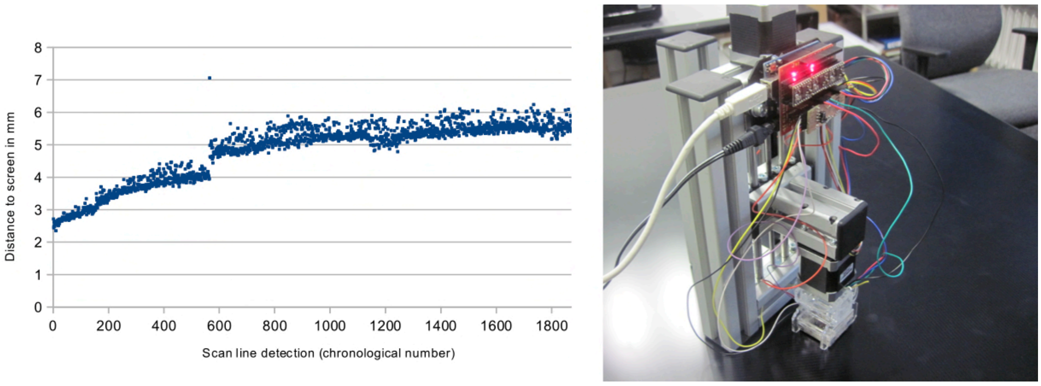


Figure 4.3: Right: The second version of the robot features a precise determination of the z-position with a stepper motor and a threaded rod. Left: Results. Starting with a 3.3V source of an arduino until touch number 565 - the 7mm outliner at this number is caused by switching to the tangibles internal 3V voltage regulator.)

4.3 Light sensor measurement

The light sensor was already used in the conducted endurance testings to correct the position when only two passive marker were detected. Since this is part of the software side of the system, the results were not relevant for this thesis. The light sensor itself uses a transimpedance amplifier, a standard circuit to measure photo current, therefore no reliability testing has to be done. The functionality of the light sensor is only tested while endurance testing, to determine the of orientation of a tangible if not all three marker are detected as touch points.

The MSP430G2553 has a sample rate of 200 ksps for analogue measurement (including the wakeup of the micro controller, the measurement will take 100 μs), and the bluetooth module will be updated with this information by a pin change interrupt. At most this will add a delay of 1ms for the wakeup of the bluetooth module. Bluetooth communication itself will last less than 3 ms.

The measurement itself takes place 1ms after a scan line detection, which happens on the microsoft surface table every 8.4ms (iPad: 44ms) in our setup. The bluetooth communication takes place every 22ms. Therefore, in a worst case scenario, a brightness change will be registered by the controlling computer after 33ms. Adding further time to process the information and a safety interval to make sure that the information is sent and processed, one brightness level has to be shown for at least three frames (at 60 fps frame rate) for the tangible-based recognition of the brightness level, processing and sending. In total, we display one brightness level for six frames to take the signal processing on the computer side into account. A test of the response time of the light sensor showed that we get a reliable response to a light change within this time.

4.4 Current consumption

For an estimation about the current consumption the circuit is connected by a ten Ω load resistor to the voltage source (3.3V). We measured the voltage above the resistor with an oscilloscope. We measured a significant voltage drop and current consumption within the load resistor itself, in combination with a approximation of the different current consumptions over time the results are only a rough estimation. This approximation does not take into account for the use case dependent current consumption: The update rate for the bluetooth connection is decided by the computer system and not the tangible itself, therefore the current consumption might be different for various systems. Therefore we did not employ more accurate measurements.

unpaired BLE module

With an unpaired bluetooth low energy communication the BLE112 module in our system will wake up every 256 ms. This time constant can be controlled by the BLE module itself (figure 4.4, right side). It starts up the internal voltage regulator and its micro controller unit and starts processing, resulting in a current flow of 10mA for 800μs. For another 80μs it draws 15mA. Then it starts sending data for 180μs with 40mA, waiting for 80μs at 15mA, trying to receive data for 140μs with 30mA for three times. In between (two times) it waits additional 160μs at 150mA. It concludes with a postprocessing for 800μs and 10mA.

As a result it draws on average 234μA while unpaired

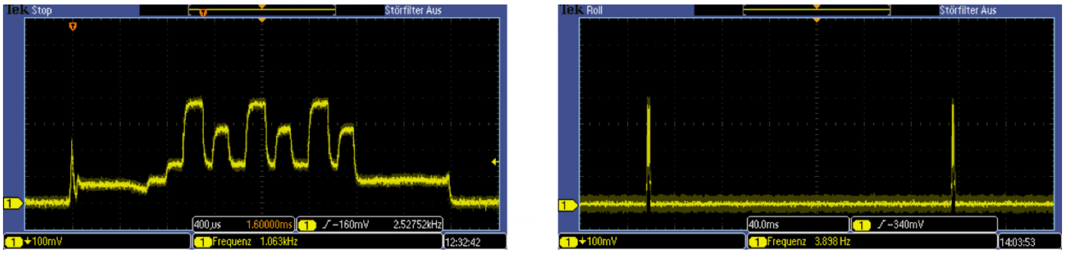


Figure 4.4: Unpaired BLE - Left: Current Consumption of the BLE module. Right: Period length between two communication events.Left side is on the enlarged communication event.

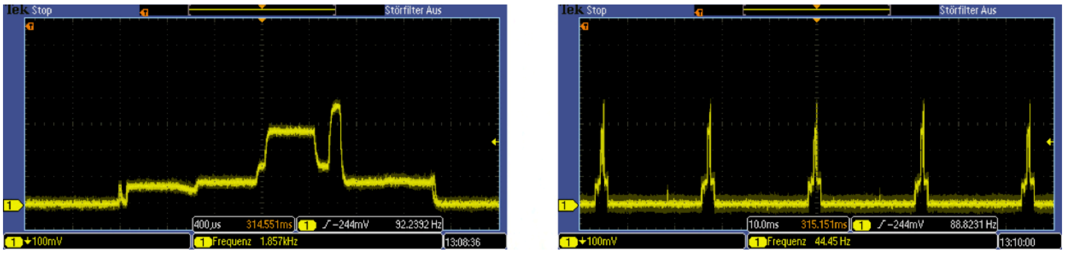


Figure 4.5: Paired BLE - Left: Current Consumption of the BLE module. Right: Period length between two communication events.Left side is on the enlarged communication event.

((800*10 + 320*15 + 420*30 + 240*15 + 540*40 + 80*15 + 800*10)/256 μA).

paired BLE module

If the bluetooth module is paired, the period between two connection between master and slave is reduced. This result depends on the master computer system and is not controllable by the tangible itself) to 22ms (figure 4.5, left side). It then starts up for 1200μs at 10mA. After it receives for 400μs data with 30mA, it waits for 100μs with 15mA before sending data again with 40 mA for 100μs. At the end additionally 800μs are used for postprocessing at 10mA before going back to sleep. This means the bluetooth connection alone draws on average a current about 1705μA ((1200*10 + 400*30 + 100*15 + 100*40 + 800*10)/22 μA).

analogue measurement

Besides the bluetooth connection the micro controller also draws current when woken up either by internal timer or comparator interrupts and by its analogue measurement. One important point is that we need a delay after the interrupt event before conducting the light measurement be-

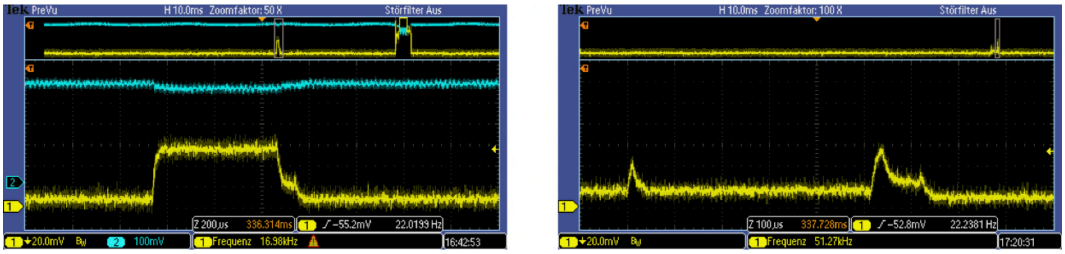


Figure 4.6: Left: Analogue measurement after wakeup with delayMicroseconds(500). Right: delay(1) (millisecond) between wake up and measurement

cause of disturbances by the scan line peak. A 500μs delay would be enough, but the delayMicroseconds() is differently implemented as the delay() function in the Energia programming environment. As one can see in figure 4.6 the micro controller will run with high current consumption for an exact timing of the microseconds (left side), while the delay() function (right side) uses a timer with sleep functionality. Therefore it was the easiest way in order to reduce power consumption to just wait for 1ms before measuring.

The wake up of the micro controller takes roughly 2mA for 30μs, while the analogue measurement consumes 2mA for 100μs.

wakeup micro controller

If the tangible is not on the table the wake up will be controlled by a timer event every 88ms (figure 4.7, left side). No analogue measurements will happen in this case, therefore we get an additional current on average of 0.7μA ((30μs*2mA)/88ms).

If the tangible is on the touch screen the comparator will trigger an interrupt before the timer. Therefore the current consumption depends on the touch screen. For the microsoft surface table we assume two comparator events per periode (two main peaks). After each event the tangible will wait one millisecond for the analogue measurement, therefore additional interrupt events should not happen.

With a period length of 8.4ms (figure 4.7, right side) we get a current consumption of 62μA (2* (30μs*2mA + 100μs*2mA)/8,4ms) for micro controller wake ups and measurements.

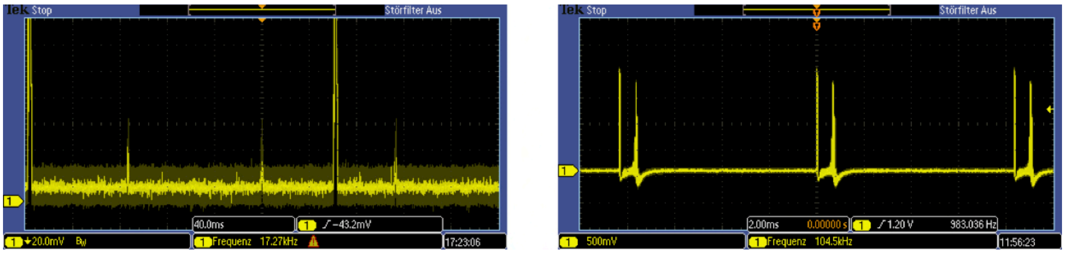


Figure 4.7: Left: period length by wakeup with the timer. Right: Wakeup via scan line

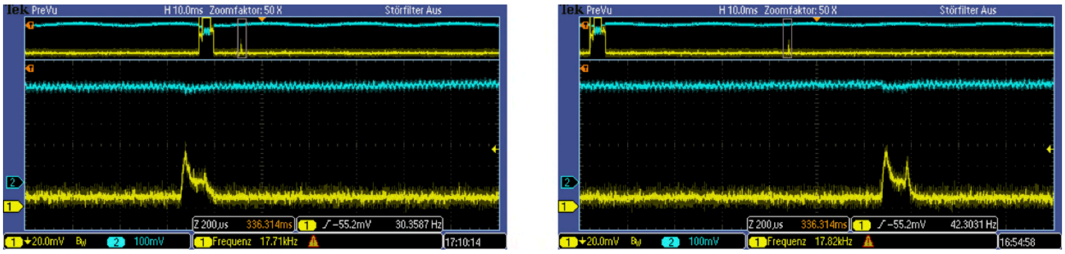


Figure 4.8: Current depending on the state of operation of the photodiode. Left: always on, Right: turned off between measurements

current consumption pin change

Depending of the state change of the tangible - wether the brightness under the light sensor changes or if the tangibles is placed on or off the screen, output pins of the micro controller are changed. These state changes are rare events compared to both the bluetooth communications and the interrupt driven wake-ups. Additionally, the MSP430 is designed for low power operations, these pin direction changes draw therefore also not much current. This current consumption is therefore neglectable.

turning the amplifier off

The operational amplifier for the photo current can either run all the time or can be switched off between measurements. In both cases (figure 4.8) the circuit draws the same amount of current. In order to prevent side effects on the measurement by turning the amplifier on and off, the amplifier is always turned on.

quiescent current

At the end the basic circuit draws almost 1,2mA quiescent current (figure 4.8). This is higher than expected. It might be caused by hidden leakage currents (e.g. because of the hand made PCB) or it is a measurement error caused by the employed measurement circuit which is not intended for such small currents.

Assuming that the quiescent current of 1,2mA represents an upper bound we will get a total current of

total current consumption

- 1,5mA for an unpaired tangible not on the table (1,2mA(quiescent current) + 243μAA(BLE) + 0,7μA(timer))
- 2,9mA for an paired tangible not on the table (1,2mA(quiescent current) + 1,7mA(BLE) + 0,7μA(timer))
- 3mA for an unpaired tangible on the table (1,2mA(quiescent current) + 1,7mA(BLE) + 62μA(comparator + analogue measurement))

As a result the tangible can be used for more than two days with a 175mAh LiPo battery before reloading. The endurance testing with the robot showed that in reality the tangible will probably last longer.

Chapter 5

Summary and future work

5.1 Summary and contributions

active sensor circuit: light pattern and scan line

In this thesis we developed an active circuit which can detect if a tangible is on a touch screen and which can utilize bluetooth low energy to send this information to the controlling system. This keeps the virtual representation of a tangible whose passive markers are filtered out at their place on the touch screen. An additional light sensor allows to determine a correct orientation if not all passive markers can be detected. In addition it allows to check if tangibles are still at their assumed place. Furthermore, each tangible can be identified with their unique bluetooth id and the id can be controlled with the response to a light pattern if necessary. Therefore, different pattern of the passive markers that allow to distinguish the tangibles are not necessary anymore. As a result, the tangibles can be made smaller and can be standardized.

low consumption

The current consumption allows a continuous operation of a tangible for more than two days even with a small 175mAh LiPo battery before reloading.

reliable detection

The sensing circuit can detect reliable if a tangible is on the screen or not. But this detection will be already triggered when the tangible is still hovering a certain distance above the screen. One remaining task is therefore to minimize the distance when a tangible detects itself on the screen. With a combination of a stable voltage source and a well adjusted circuit it seems to be possible to reduce this distance to circa two millimeter, but the corresponding endurance testing to verify this assumption still needs to be done.

5.2 Ongoing work

fine adjustment: Constant voltage source

As before mentioned the active circuit design with a stable voltage source and well adjusted voltage divider for a small hovering distance has to be tested. This work is conducted at the moment. First tests with a constant voltage source showed also some kind of loading characteristic, the distance will increase over time at the beginning. This has to be researched further.

motorized tangible

In the same layout with the constant voltage source a connector for a serial connection from the bluetooth module is also integrated. This allows the extension of the tangible with additional functionality like a connection to a motor controller board to move the tangible by the controlling computer system. Florian Busch develops such a system at present.

software toolkit

At the moment René Linden reworks the software of controlling system in order to simplify the usage of the active tangibles in applications.

applications

With these theses in progress more demonstrator applications will be build and reworked: For example the air hockey application is already used as an every time ready demo and will be more and more refined, while other applications will be developed.

textile hull

The passive marker system can be replaced by a textile hull, where conductive marker and their connections are embroidered. The benefits will be that the construction is simplified, and the textile will clean the touch table. An easy replacement of the textile counters the challenge of pollution of the textile. The embroidery allows an optimization of the marker form - nowadays a rectangular form is used for technological reasons, but other might be better for functionality (e.g. circular). Alternatively more artistic pattern for the markers can also be pursued.

5.3 Future work

In future these tangibles can be used in more applications: For example an exhibit like the peace of aachen can use these tangibles. Furthermore applications like tabletop games and learning environment can be extended with these tangibles.

remove MSP430

Looking at the hardware side it will be interesting to remove the MSP430 since the bluetooth module can also fulfill the same functionality. The resulting tangible will be slightly cheaper (less components) and can be made smaller, but on the likely cost of a slightly higher power consumption (the active BLE module draws more current than the MSP430, on the other hand the quiescent current of the MSP430 is removed).

replace BLE112 by PAN1740

For a mass production by machine it might be interesting to replace the BLE112 with the PAN1740 - this module draws less current and is smaller, but not solderable by hand. For production by machine the photodiode has to be changed - in the current design the diode is placed upside down in a hole, which is not feasible with standard pick and place machines.

replace BLE112 and MSP430 by QN9021

The NXP QN9021 has also lower power consumption than the BLE112 module. It integrates a M0 micro controller with comparator and analogue measurement. Therefore, it is suitable to replace also the MSP430. It's has the same QFN32 package as the MSP430, so instead of adding a whole BLE module only the antenna circuit has to be added, reducing space requirements.

loading circuit

For an exhibit it might be interesting to either charge the tangible inductively or even use a solar cell to power the circuit.

orientation dependent timing

Finally, the detection method also can be changed: Since the screen scans the table from one side to the other the scan line of a capacitive touch table arrives at different markers of a tangible at different times dependent on their position on the screen (figure 5.1). Therefore, the orientation can also be determined by sensing the induced voltages at each pad. Since the peaks in figure 5.1 consist of several singular voltage peaks the analogue measurement has to be fast enough to conduct several measurements within such a singular peak (4μs). Furthermore, such an evaluation circuit has to identify the time when the scan line is below the marker independently from noise and induced minor maxima. As an additional challenge, the signal strength depends highly on the coupling to the touch screen: Small contact variants might result in a changed voltage pattern.

position depending on impulse distances

On the microsoft surface one can distinguish two different impulse pattern: One is applied on all transmitter lines at the same time - resulting in a strong impulse - the other scans all transmitter lines successively (figure 5.2). Therefore, the latter gets a slower rising and falling pattern with a slightly lower amplitude in total.

We can distinguish both signals depending on the different form. Since the table scans the whole table line after line, the distance between the calibration peak and the measurement peak is proportional to the position of the sensor electrode on the screen. Therefore, we can at least determine one coordinate of a tangible with this method.

Both methods require a relatively high amount on analogue measurements, which might be interesting for future academic research.

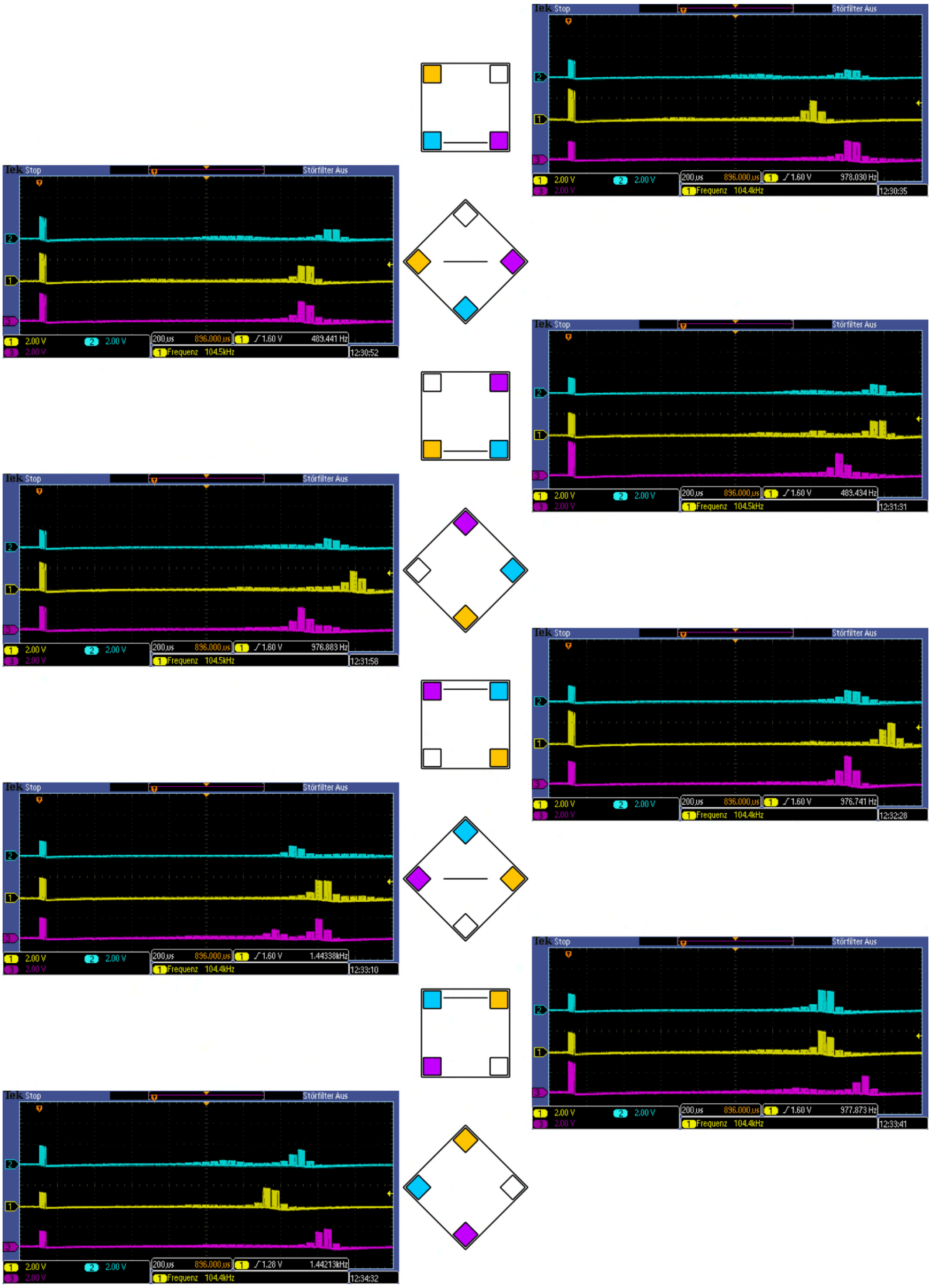


Figure 5.1: A scan line arrives at different time for each pad depending on the orientation on the screen. Middle: Orientation of the pads on the screen, in the same row on the left or right side: Oscillator picture of the signal detected at each pad.

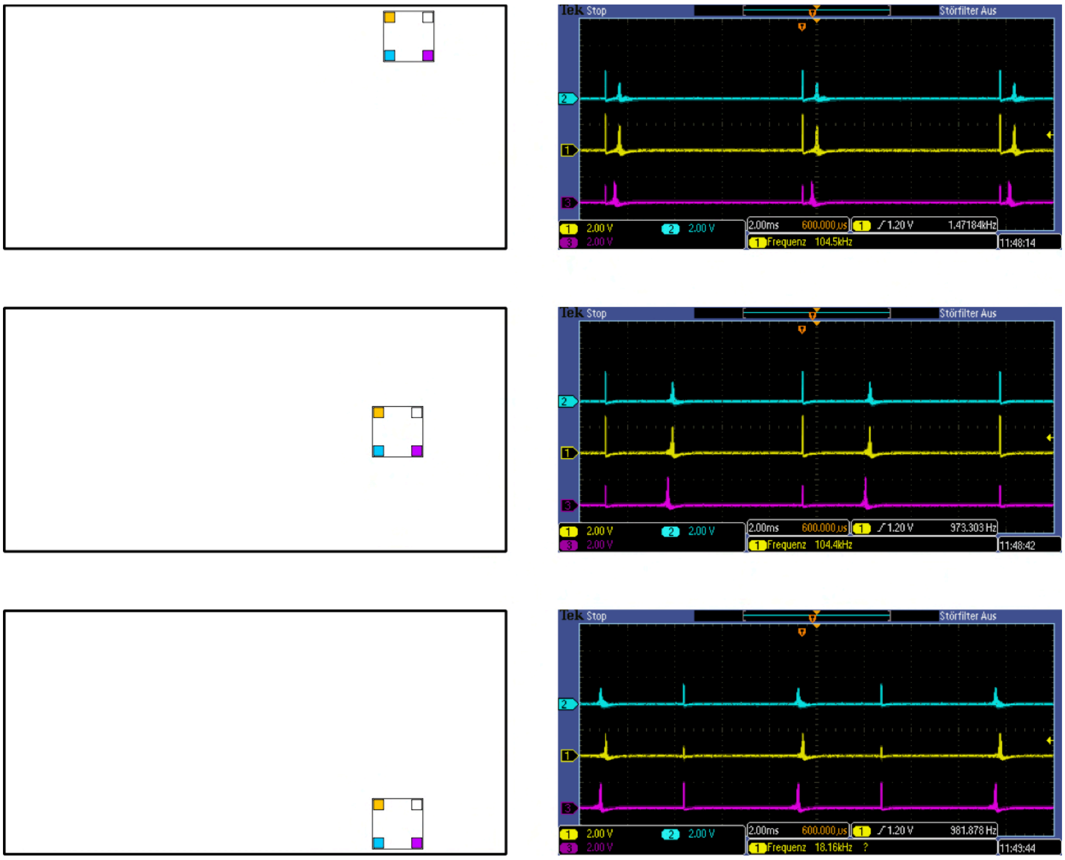


Figure 5.2: The microsoft surface first scans all lines in parallel (calibration), then one after another. The first one results in a stronger rise and fall and a higher peak than the other. The distance between these two peaks corresponds to the position on the screen.

Appendix A

Layouts, Schematics and Software

APUC/PERC schematics and layouts[a]

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[a] http://hci.rwth-aachen.de/public/folder/Research Projects/MACS/PERC/Hardware

APUC/PERC source code MSP430 and BLE112[a]

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[a] http://hci.rwth-aachen.de/public/folder/Research Projects/MACS/PERC/Software

Schematics, design and software of the testing robots[a]

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[a] http://hci.rwth-aachen.de/public/folder/Research Projects/MACS/PERC/Testing Robot

Thesis[a]

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[a] http://hci.rwth-aachen.de/public/folder/Research Projects/MACS/Publications/Thesis Jan Thar

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