LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Department of Electrical Engineering

MASTER'S THESIS

CONCEPTUAL DESIGN OF EMBEDDED WEATHER DISPLAY

The subject of this thesis has been approved by the council of Faculty of Technology in its meeting on October 30, 2008.

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ABSTRACT

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The objective of this thesis work is to describe the Conceptual Design process of an embedded electronic display device. The work presents the following sub processes: definition of device specifications, introduction to the technological alternatives for system components and their comparison, comparative photometric measurements of selected display panels, and the design and building of a functional concept prototype.

This work focuses mainly on electronics design, albeit the mechanical issues and fields of the software architecture that significantly affect the decisions are also discussed when necessary. The VESA Flat Panel Display Measurement (FPDM) 2.0 Standard was applied to the appropriate extent into photometric measurements. The results were analyzed against the requirement standards of a customer-specific display development project.

An Active Matrix LCD was selected as the display of concept prototype, but also the excellent visual characteristics of Active Matrix OLED technology were noted. Should the reliability of the OLED products be significantly improved in the future, utilizing such products in the described application must be reconsidered.

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Tämän diplomityön tavoitteena on kuvata sulautetun elektronisen näyttölaitteen konseptisuunnitteluprosessi; järjestelmävaatimusten määrittely, järjestelmäkomponenttien teknologisten ratkaisuvaihtoehtojen esittely ja vertailu, näyttökomponenttien optiset vertailumittaukset sekä prototyyppilaitteen suunnittelu, rakentaminen ja testaus.

Työssä keskitytään lähinnä elektroniikan komponenttien valintaan, mutta myös tähän olennaisesti vaikuttavia mekaniikka- ja ohjelmistoratkaisuja on käsitelty tarvittaessa. Näyttökomponenttien optisiin vertailumittauksiin on sovellettu litteiden grafiikkanäyttöjen mittausstandardia *VESA FPDM 2.0*. Näiden mittaustulosten analysointiin käytettiin erään Vaisalan asiakaskohtaisen näyttökehitysprojektin vaatimusstandardeja.

Aktiivimatriisi-LCD valittiin konseptiprototyypin näytöksi, vaikka OLED olikin visuaalisilta ominaisuuksiltaan selvästi näyttötestin voittaja. Mikäli OLED-tekniikan heikko luotettavuus tulevaisuudessa merkittävästi paranee, sen käyttämistä diplomityössä kuvatussa sovelluksessa on syytä harkita uudelleen.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area [m^2]
I	Current [A]
I	Luminous intensity [cd]
k	Coverage factor
L	Luminance [cd/m^2]
U	Voltage [V]
u	Standard uncertainty
V	Voltage potential [V]
θ	Viewing angle [°]
A	Ampere, unit of current I
ALS	Ambient Light Sensor
ALSA	Advanced Linus Sound Architecture
AMLCD	Active Matrix LCD
AMOLED	Active Matrix OLED
ARM9	ARM architecture 32-bit RISC CPU family
ASoC	ALSA System on Chip
cd	Candela, unit of luminous intensity I
CIE	Commission Internationale de l'Éclairage
CODEC	Coder-Decoder
CPU	Central Processing Unit
CRT	Cathode Ray Tube
DAC	Digital-to-Analog Converter
DC	Direct Current
DVI	Digital Video Interface
EBI	External Bus Interface
EL	Electroluminescent
ESD	Electrostatic Discharge
FB	Framebuffer
FED	Field Emission Display
FPD	Flat Panel Display
FPU	Floating Point co-processor Unit
GPIO	General Purpose I/O
GPS	Global Positioning System

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1 INTRODUCTION

1.1 Background of the thesis

Vaisala products are generally characterized as high reliability measurement instruments. The customers are usually high technology professionals, even though the products after all provide observations for the everyday life.

As a technology oriented company, Vaisala is actively researching arising technologies for its measurement applications. The next important factor right behind the measurements themselves is providing a clear and visible indication to the user. The current Weather Display product line consists of several application specific units, and this thesis work describes a procedure of developing a single, general hardware platform concept for all of these purposes.

1.2 Research questions and objectives

The main task is to design a graphical display concept to replace the existing units which are soon to reach the end of their life. The excellent visual characteristics of the previous Weather Displays are hard, if not impossible to beat.

Without a doubt, designing a display for extensive longevity is a challenging part of this project. Speaking of a device of such long life expectancy, the decisions made in the product development phase might not live as long as the product itself, and therefore the concept once developed might need to go through some serious changes during its life. A specific focus is to be set in minimizing the probable maintenance effort caused by the end-of-life components. One cannot foresee the leading technologies in 2010. However, the new emerging technologies should be assessed in order to gain a wider view over the possible future replacements. Especially the optoelectronics as an emerging business is developing faster than ever. It is inevitable that the today's ruling display technologies will develop only until delimited by the laws of physics. The new innovations will rise and take over the lead in this billion dollar business.

A method to reliably compare display components of various technologies must be presented in order to select the best optoelectronic component to the display concept under development.

All the mentioned research aims finally to creation of a functional concept prototype, which some day could entirely replace the current line of Vaisala Weather Displays.

1.3 Structure

This thesis work is structured according to the research flow. The study starts by definition of the problem in chapter 2, given the initial design parameters and based on study of the current products. As a result, a system requirements specification is constructed.

The chapters follow each other in chronological order, the next one, chapter 2.4.2 dealing with study and selection of the appropriate technological solutions for the developed concept. Chapter 4 is dedicated to the Flat Panel Display (FPD) evaluation among the selected candidates, relative to an applicable Human Factors Design Guide.

The core objective in Chapter 5 is to describe the design and implementation process of an electronic display system that fulfills the design parameters in the best reasonable way. Engineering work and the results of the prototyping and design verification are discussed last, before the final conclusions on the thesis study and its results in paragraph 5.7.

1.4 Scope and Limitations

Within this thesis, an approach on hardware platform development is presented. The study is mainly concentrated on electronics design, albeit certain amount of platform drivers and system software architecture must be examined in order to eventually be able to produce a working prototype.

Being an extremely large-scale project for a Master's Thesis, certain parameters shall be marked out of the scope of this study. Some trivial, yet interesting branches have not been thoroughly studied, but are taken for granted. Such issues include the outer dimensions of the Embedded Weather Display, which has been straightly adopted from the preceding Vaisala Wind Display families, which conform to the standard IEC 61554 (Dimensions for Panel mounted measurement devices). The selection of processor architecture is not discussed in this thesis. Also, selection of expansion module interface together with other connectivity requirements are taken for granted. Application software is so far left undefined, though it is determined to incorporate a graphical user interface and a standard interface towards the system software.

The selection of electrical components was somewhat limited by the operating system to be used. Linux is a sophisticated software architecture even in its most embedded form and development of complicated hardware drivers is often extremely time consuming. Selection of the main system components, such as the Video Controller, Audio CODEC (Coder-Decoder) and other attached peripherals, were widely dictated by the available hardware driver support.

2 PROBLEM DEFINITION

2.1 Vaisala line of Weather Displays

There are as many opinions on the Vaisala Weather Display products as there are end-users. The generally known features however are high reliability, high quality, excellent ergonomics, and flexible connectivity and configurability. Vaisala engineers have striven for these noble qualities for several generations of Weather Display products. Figure 1 shows the line of currently produced Weather Displays.

Figure 1. **Digital Display DD50, Multichannel Wind Display WIND30 and Aviation Wind Display WIND50.**

Vaisala has been able to extend the lifespan of these Weather Display products to a decade, which is a tremendous challenge for any electronic device nowadays. The component availability over such a long period of time is never guaranteed, and some of the units have required maintenance engineering in order to keep them in production. None of these units currently fulfill the requirements of European Commission Directive 2002/95/EC, Restriction of Hazardous Substances (RoHS). Monitoring and control instruments are for the time being exempt from RoHS directive, but are likely to be included within a few years. (Huovila 2008; Goodman 2006, p.3-12)

In order to gain a broad view over the known customer problems with the preceding Weather Display products, the Vaisala Help Desk database was inspected for Display Product types WIND30, WIND50 and DD50. The findings were evaluated and listed to prevent similar problems occurring with the new hardware. Altogether 250 most recent cases were examined, resulting in 77 separate occasions where the root cause of the operational malfunction was eventually traced to an electrical defect. Table 1 shows a breakdown list of such cases. On two separate occasions, two different kinds of root causes were identified. (Vaisala 2008)

Table 1 **Preceding Product Help Desk Cases caused by electrical defects.**

Root Cause	Qty
ESD Suppressor Damaged	15
Defective LED	9
Sporadic or unknown cause	9
Incorrect electrical connection	8
EEPROM Failure	7
Switch	6
Lightning strike	6
Cooling Fan damaged	5
Analog Inputs damaged	5
Weak electrical contact	5
Assembly or Manufacturing error	3
Design change needed	1

The distribution clearly shows that the ESD (Electrostatic Discharge) suppression components are used in the product for a reason. Their possible failure mechanisms are various, but presumably the most common reason for a defect is an electrostatic discharge of higher energy than the component was rated to withstand. Regardless, in all the occasions the suppressors were the only components to break, which suggests that the design has decent protection against ESD. Supposedly, also the faulty analog input channels might have confronted shocks of similar nature, as the corrective actions on these particular occasions involved replacing faulty ESD suppressors.

The number of failures related to lightning strikes is relatively high considering the normally infrequent nature of such incidents. Proper protection against such an event is far beyond the electronics designer's decisions. As a whole, preventive measures include proper larger scale electrical installations together with passive lightning arrester equipment. What can be done by device design is to consider the phenomena of high voltage surges coupling to the low voltage power distribution network, RS-485 or Ethernet cabling. (Maceika 2003)

Incorrect electrical connection to the DC power supply, using either inverted polarity or voltage out of the unit's acceptable range has caused several operational failures. This is not only an issue of improving the Instruction Manual and education, but these cases also can be reduced by a different design approach. Instead of a protection diode across the voltage supply setting off the fuse, another diode in series with the fuse should be utilized in order to prevent service need in unfortunate occasion of inverted polarity. The drawback of this solution is the voltage drop across the diode which might affect meeting the low input voltage rating, and cause increase in power dissipation under normal operation conditions.

2.2 Market Demand pushing for Improvements and Flexibility

The Vaisala products have been utilizing serial communications successfully for decades. As the Ethernet has proved to be a rugged and reliable network topology for industrial applications, there is also a need to transfer the serial measurement data over Ethernet in addition to previous leased line modems and serial protocols.

The old, but widely approved serial communication standards such as RS-232C and RS-485 have been challenged by new, improved technologies, like CAN (Controller Area Network), a serial multi-drop bus originally developed by Bosch for automotive applications. Despite the growing number of advanced serial protocols, numerous devices on the field still support communication on these classical serial protocols. Their number is still so substantial, that they simply cannot be ruled outside of the concept. (Hölttä 2008; Hyvättinen 2008)

Generally speaking, each application area typically has its own serial communication standard. CAN is characteristic for automotive industry, SDI-12 is widely approved among active hydrological sensor manufacturers (Hölttä 2008), and optical fibers are needed in some installations to prevent trouble caused by differences in ground potential at opposing ends of the transmission line. To properly overcome the need for numerous different ways of communication in a single product, a modular expansion interface must be utilized.

The nature of embedded devices is changing as well. More often the operational capabilities of such a device need to be modified according to the customer requirements. Sophisticated, layered software architecture is needed to achieve this functionality. The factory loaded system software layer must offer the basic software framework for the core system. The application software in turn must be able to easily build up and plant on top of this basic layer, without the software developer writing any hardware-specific code.

In addition, today's customer applications need to incorporate many different stimuli before the display device is able to produce the information it is intended to present. For example, a maritime wind display application must be able to provide accurate wind speed and direction measurements both in absolute values and relative to the vessel course (Huovila 2008). This requires an input from a GPS (Global Positioning System) receiver to obtain the ship's velocity and direction of travel. By throwing in an electronic compass input, the system would become able to determine the leeway, the deviation from vessel's intended course due to the drifting.

2.3 Applicable Standards

Any successful product takes into account the customer needs and demands in addition to the compulsory ones demanded by legal provisions. Characteristically, Vaisala instruments are used in environmentally, electrically and electromagnetically harsh conditions. Thus the customers tend to require the products to fulfill a wide variety of harmonized standards, yet some application specific requirements may be needed. Typically the products are tested against not only the common European standards, but also the US military and NATO standards to comply with governmental customers' requirements in the US market.

Electrical standards applicable to Vaisala Weather Displays are presented in Table 1. They were used as a baseline for the design of the new display concept.

Table 2. Applicable Standards (Lyömiö 2008).

Applicable Standard	Description
MIL-STD-461F	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-810G	Test Method standard for Environmental Engineering Considerations and Laboratory Tests
HF-STD-001	The Human Factors Design Standard (and its amendments and amendment drafts)
IEC 60945	Maritime navigation and radio communication equipment and systems - General requirements - Methods of testing and required test results
CISPR 22, Class B (EN 55022)	Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement
CISPR 24 (EN 55024)	Information technology equipment - Immunity characteristics - Limits and methods of measurement

The Human Factors Design Standard HF-STD-001 (HFDS) was selected as a design reference, since it was previously used in a customer-specific display development project.

2.4 The Product Specification

2.4.1 Modularity

Due to the long expected life span of the product, extra thought was given to the future expandability and design maintainability. In order to gain such product qualities, the new concept was determined to be designed for maximum modularity: isolate the unsteady components in easily replaceable modules to reduce the R&D effort needed to replace end-of-line components.

For example, fast developing optoelectronics is likely to become obsolete several times during the long life span of the product in question. Whenever a display product reaches its end-of-life, or a new and better display panel is introduced to the market, it's trivial to change the display adapter card design when all the display specific hardware is bound to a single module.

2.4.2 Outcome

The device was required to operate on two common battery voltages, 12 and 24 V. Based on expected DC voltage variation of +30/-10 %, the input voltage was specified to fluctuate between +9 and +36 VDC (IEC 60945:2002, p.49). The audio features were dictated by the need to produce spoken messages to the user.

The automatic display brightness adjustment offers a way to enhance the readability in dark conditions by limiting the display contrast to a comfortable level. This is further discussed in paragraph 4.3. Requirement for temperature sensing enables the unit to self-diagnose probable overheating issues, as mentioned in paragraph 5.3. The connectivity and environmental requirements were taken for granted. As a result, the general requirements for the device are presented in Table 3.

Table 3. Product Specification.

Area	Specification	
Mechanics	IEC 61554 Compatible panel mounting	
Display	Graphical, at least QVGA resolution and 4 distinctive colors	
Audio	Able to reproduce 100Hz - 10kHz wave audio	
Software Platform	Linux 2.6, Graphical User Interface	
User input	Sufficient to operate Graphical User Interface	
Product Life Span	10 years	
Other services	Automatic display brightness adjustment	
	Temperature sensing	
Connectivity	Ethernet 10/100 Mbit/s	1
	USB 2.0 Host	1
	USB 2.0 Device	1
	Memory Card Slot	1
	RS-232C	1
	RS-485	1
	Vaisala TAMI Module slot	1
Environmental	Operating temperature	0 ºC … 60 ºC
	Storage temperature	-40 ºC … 80 ºC
	MTBF[1]	> 20000 hours

[1] Mean Time Between Failure

3 TECHNOLOGY STUDY

3.1 Overview

The first step in the design process was to find the most suitable technological solutions for an Embedded Weather Display. The environmental requirements demand extremely tolerant decisions for temperature and lighting conditions. This chapter will discuss the selection methods for the most important components of the system.

In order to find a reasonably priced and competent enough solution for a given subsystem, some of them have been assigned several options. The final selection is presented later on in Chapter 5, covering the design process and the prototype.

Linux 2.6 as an Operating System (OS) was predetermined as a requirement. This turned out to be an extremely significant issue to consider when making the architectural decisions concerning the electronics. Available Linux device driver support widely dictated selection of system components such as Video Driver IC (Integrated Circuit) and Audio CODEC.

3.2 Processor Module

Vaisala R&D had already evaluated an ARM9-based processor module ECO920 from Garz & Fricke GmbH. The card provides a wide variety of peripheral functions on a small-footprint module, including SDRAM and NAND Flash memories together with Ethernet physical layer transceiver, oscillator, and reset circuits (Garz & Fricke 2008).

Figure 2. Selected Processor Module, Garz & Fricke ECO920 (Garz & Fricke 2008).

To limit the scope of this thesis work, the choice of ECO920 processor module was taken for granted.

3.3 Optoelectronic Components

Probably the most demanding component for a display unit is the screen itself. Surely, the time of the cathode ray tube is long gone in applications such as small embedded displays. The development has led to digital flat panels, which rule the market in their numerous variations. However, there are still plenty of different technologies for a comparative analysis. In this study, only multi-color dot matrix displays are discussed.

The selection of the best (or several good candidates) is discussed in this chapter. A look will also taken to the emerging technologies being currently developed in the laboratories. These will most certainly be competing with the leading TFT LCD (Thin Film Transistor Liquid Crystal Display) some day.

3.3.1 Application Restrictions

As the physical dimensions of the unit were dictated by the standard for panel mounted equipment, it also affected the selection of suitable display panels. The device was required to be mounted on square 138 mm panel cutout. There are no restrictions set for the depth of the bezel protruding from the panel, but the maximum size of the bezel is limited to 144 by 144 mm. There are no limitations for device overall depth either. (IEC 61554:1999)

3.3.2 Current Graphical Display Technologies in the Market

The vast majority of the today's display technologies are based on electronically manipulated liquid crystals. These LCD panels have taken giant leaps since the first consumer applications back in 1970s. Today the panels incorporate an embedded driving circuitry implemented using an active transistor matrix produced on thin film technology. These TFT LCDs still remain undefeated with their fairly good image quality combined with low prices. A typical TFT, also called an Active Matrix LCD (AMLCD) cell, is illustrated in Figure 3. (AAPM 2005)

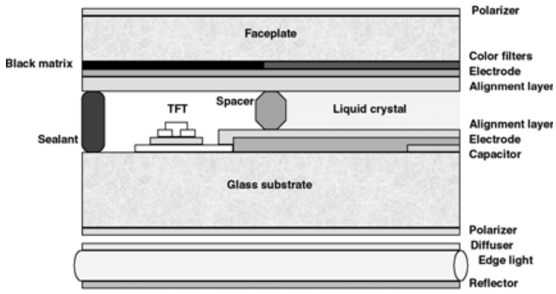

Figure 3. Typical cross section of an AMLCD (AAPM 2005, p. 22).

On the contrary to the LCD, which merely modulates the backlight passing through the liquid crystal cells, an alternative technology is the emissive EL (Electroluminescent) display. The phenomenon of electroluminescence is non-thermal conversion of electrical energy into luminous energy. The most familiar type of EL is based on electron-hole recombination near a p-n junction, utilized in LED (Light Emitting Diode) and OLED (Organic LED) devices. The traditional EL displays take advantage of thin film phosphor materials, which emit light when set in a large enough electric field. These TFEL (Thin Film Electroluminescent) panels are also referred as high field TFEL, due to the electric field used to produce the emission. A typical TFEL cell structure is presented in Figure 4. (King 2003; Badano 2004)

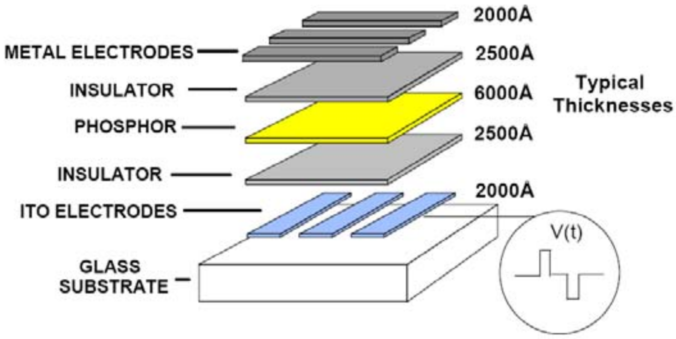

Figure 4. **Illustration of conventional TFEL structure.**

High field TFEL Displays have been superior to any other display when it comes to visual characteristics and mechanical strength. The downsides include relatively high pricing. Five to ten fold unit price compared to similar TFT panels made the TFEL displays lose the competition in the consumer market. However, TFEL displays have found their way into applications of more professional nature, such as in medical, mining and machinery industry.

3.3.3 Promising future replacements

FED (Field Emission Display), is a yet another attempt to produce a totally flat CRT (Cathode Ray Tube) display. Instead of a heated cathode, the electrons are emitted by an array of microscopic tip emitters and accelerated be a voltage across a vacuum gap towards the phosphorous material. Despite the great potential of the technology, no commercial FED products have launched, and severe luminance non-uniformity together with reliability issues have been reported for prototype designs. A typical FED cell is presented in Figure 5. (AAPM 2005)

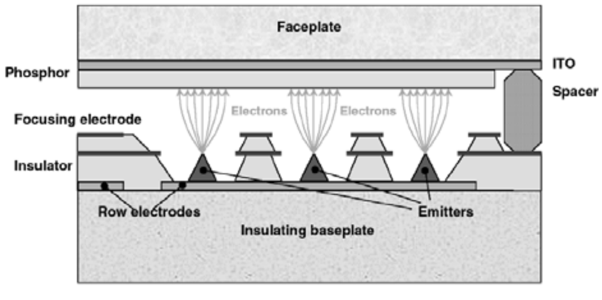

Figure 5. **Cross section of a typical FED (AAPM 2005, p. 23).**

The latest emissive electroluminescent display technology is based on OLED, which has proved capable of providing high luminous efficiency and wide viewing angle. Also the straightforward construction and fairly simple manufacturing process have given promises of competitive pricing compared to ruling TFT Displays. Some problems still exist with OLED technology, such as low yield and reliability together with license fees and patents protecting many methods vital for OLED manufacturing.

The first OLED Displays are already in the market, yet the process limits the mass producible panel size to roughly 3 inches diagonal. The first commercial 4.3" panel targeted for mass production was introduced in Display Taiwan exhibition, June 2007 by Taiwanese Chi Mei Electroluminescence Corporation (CMEL 2007).

3.3.4 Digital Video Interfaces

Unfortunately, not a single interfacing standard exists for communication between an embedded processor and the panel itself. Instead, most of the Digital displays on the market have adapted a popular interfacing scheme from early Sharp AMLCDs.

The best conceivable, widely recognized and supported interfaces for graphics displays are IBM's VGA (Video Graphics Array) and its successor DVI (Digital Visual Interface) (AAPM 2005). These internationally standardized graphics interfaces however pose a demand for very high signaling speeds, thus presenting a problem when considering the minimal resolution required for the concept. In addition, the conversion to any higher level standardized graphics format would have unnecessarily obfuscated the unit design. For these reasons, the Embedded Weather Display needs an alternative display connection.

Despite the diverging practices, the Digital RGB (Red-Green-Blue) interfaces in the many displays closely resemble each other. The basic ideas behind every panel controller chip are very similar. Commonly, the data is transferred in parallel digital format in the rhythm of a Pixel Clock signal (PCLK). The beginning of every new field (frame) is indicated by a Vertical Synchronization Pulse (VSYNC) and an upcoming new Horizontal Line by a Horizontal Synchronization Pulse (HSYNC). The usage of these synchronization signals is derived directly from the preceding analog CRT driving signals.

Back in CRT technology, the display data was usually transferred to the screen in so called Fixed Timing Mode, in which the timely gap between the end of the line data and beginning of the synchronization pulse (Front Porch), as well as the gap between the end of the HSYNC pulse and the beginning of the line data (Back Porch) was precisely predefined. Inability to follow these strict timing rules resulted in image dislocation on the screen. This was not considered as a major issue in the analog TV receiver, as the picture was nevertheless adjusted to span slightly outside the active screen area. Moreover, CRT required a special *horizontal blanking interval*, during which the scanning beam was turned off and returned back to the beginning of the next scan line. (AAPM 2005, p.16)

Most of the driving ICs integrated into various FPDs still automatically detect and obey the former Fixed Timing scheme. However, a more flexible Pixel Data Enable (DE) signal has replaced the HSYNC signaling in many modern, digital applications. The DE signal distinctly indicates the arriving horizontal line data, therefore totally overruling the need for a HSYNC signal.

3.3.5 TFT LCD Technology

Even though the liquid crystals have been researched for decades and most of the phenomena around them are very well known, the biggest challenge in common for all of the LCD technologies is the fact the liquid crystals' light conducting characteristics are heavily polarized and dependent on the light wavelength. Thus the brightness and contrast change with viewing angle. (AAPM 2005)

Unfortunately these disadvantages tend to have very complicated dependencies on each other. Many manufacturers have compensated for these inconsistencies using different filtering films on top of the display panel, but due to the complicated nature of the problem, all the TFT LCD panels available are more or less trade-offs between their visual characteristics, such as viewing angle, brightness, contrast capabilities, and color reproduction.

3.3.5.1 LCD Panel Properties

A typical TFT LCD provides the best visual characteristics on viewing angles on the horizontal plane. This is a drawback of the TN (Twisted Nematic) effect, but also derived from the common ergonomics; a human observer is more likely to move in horizontal direction than in vertical. LCD panels are usually built in a way, that the grayscale reproduction performance is optimized for viewing along the screen normal. Due to the convoluted relation of liquid crystals and polarizing filters, the vertical viewing angles other than perpendicular usually provide either of two unwanted properties; an excessive contrast where the lightest shades of gray blend to black or a phenomenon called grayscale inversion where dark colors appear brighter than the light ones. Depending on the application needs, this is usually selectable simply by rotating the panel by 180 degrees. (AAPM 2005; Ishikawa et al. 1995; NEC 2005)

3.3.5.2 Backlight

Property of brightness is based on the background lighting of the vitreous LCD panel. The contrast is then generated polarizing the liquid crystals according to the display data and thus forming images on the polarizing filter film covering the screen, as was presented in Figure 3. The major drawback of this mechanism is the limited ability of the liquid crystals to block the backlight, and on the other hand the luminous flux attenuation caused by filtering and polarizing films together with the LCD substrate. Therefore the LCD suffers from poor contrast performance, which is heavily dependent on the viewing angle. The self-luminous technologies, such as OLED easily achieve contrast ratio of more than 100:1 over the whole hemispatial space.

The backlight is the most important component of an LCD display when it comes to the reliability prediction. The LCD panel itself is virtually everlasting compared to the backlighting. Due to the materials used and construction, CCFL lamps are highly sensitive to mechanical stress and vibration whereas LEDs can withstand continuous vibration and impacts and acceleration forces of several hundred Gs.

CCFL tubes provide more luminous flux compared to available LEDs, but their emission spectrum is neither linear nor continuous, and does not span over the whole color gamut of human eye either. White LED backlight emits more linear spectrum, but suffers also from limited gamut, spanning typically a mere 50% compared to the NTSC color space (de Vaan 2007).

White LED backlights for LCDs are typically constructed using Gallium Nitride (GaN) or Indium Gallium Nitride (InGaN) LED material. These are employed for blue or green LEDs. The junction is then coated by a phosphorous layer to shift some of the emitted power to a broader spectrum band. This produces light that resembles white to human eye, but consists mainly of blue and green components. (Anandan 2008)

Using tricolor RGB LED as the backlight source enables white balance adjustment and fully saturated colors (de Vaan 2007). Although the undisputable benefits in the color reproduction characteristics, the White LEDs are still used in the LCD panels because of the better availability, simpler control circuitry and more versatile packaging options (Park & Lim 2007).

3.3.6 Thin Film Electroluminescence

For over two decades, TFEL displays have proved to be the best and often the only solution for demanding applications in harsh environments. The visual characteristics are excellent in all areas except the color reproduction, which is typically limited to a single color. The latest innovations have brought up TFEL panels with a 4 bit RG (Red-Green) color space, which is able to produce 16 different shades of red, green and yellow. Extremely wide operational temperature range from -50 to +85 ºC, rugged construction and long lifetime makes this panel unquestionably the best option for applications where the reliability is appreciated over the low unit price. (Planar 2007)

3.3.7 Active Matrix Organic LED

The first OLED device was introduced by Tang and Van Slyke (1987). Ever since, the growing interest has driven the OLED development towards a commercialized mass product. The OLEDs are composed with two or more organic layers sandwiched with a cathode and an anode for charge carrier injection (Salaneck et al. (2001). p.525). An illustration of a typical OLED structure is shown in Figure 6.

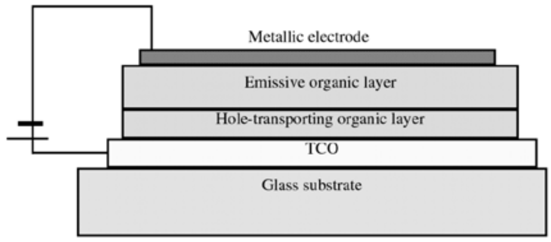

Figure 6. **Structure of a typical polymer emissive material in OLED display device (AAPM 2005, p. 24).**

Regardless of the promising research results, the organic materials have suffered from fast degradation, especially the blue color has been problematic, and the lifetime of the hole transport layer in the usual OLED configurations has been limited to less than 1000 hours (Salaneck et al. 2001, p.576; Lääperi et al. 2007).

Many market analysts have been guessing the future of OLED technology. However, it still seems to confront insuperable problems, as the commercialized units limit in rather small-size panels. Display manufacturer Kyocera has announced mechanical and interface specifications for an upcoming 5.7" AMOLED (Active Matrix OLED) panel in November 2007, and CMEL lately reported having solved all the ageing issues of the materials, and advertises lifetime expectancy of 20 000 hours. However, no credible proof of products fulfilling such promises has been presented.

3.3.8 Selecting the Flat Screen Displays for evaluation

The display candidates were selected among the selection of commercially available panels. Undeniably, the most extensive selection of different displays represented the numerous available LCD panels. As the image quality was the main concern, the selection was limited to active matrix technologies, such as TFT. Being a popular size category among the medical industry, automation control system and vending machine vendors, the variety of displays measuring 5.5" and 5.7" diagonal was still vast. The focus was then turned to panels, which were primarily designed to be daylight readable. This enabled cutting the number of candidates into three, which all were of transmissive type.

The EL display selection was straightforward, as the low number of available products in the size-category was efficiently limiting the possibilities. A suitable colored industrial grade 4.9" EL panel was selected from Planar. The traditional TFT participated in the competition with three panels, in two background lighting flavors; high luminosity 5.5" CCFL backlighted display from NED and two 5.7" LED backlighted units from Optrex and PVI (Prime View). The last panel was selected for curiosity, the lately released CMEL 4.3" AMOLED, mainly intended for consumer applications.

3.4 Processor architectures

The software platform was specified outside this thesis - the hardware was required to run Linux 2.6. This excluded virtually all 16-bit processor architectures, and the demand for MMU (Memory Management Unit) finally turned the focus on a selection of compact 32-bit SoC (System on Chip) Application Processor ICs.

The ECO920 processor module was taken for granted for the concept. It carries an Atmel AT91RM9200 RISC microcontroller, which is capable of controlling most of the peripherals required for the product. Only Video, Audio and Analog to Digital conversion peripherals require external controller ICs to meet the requirements

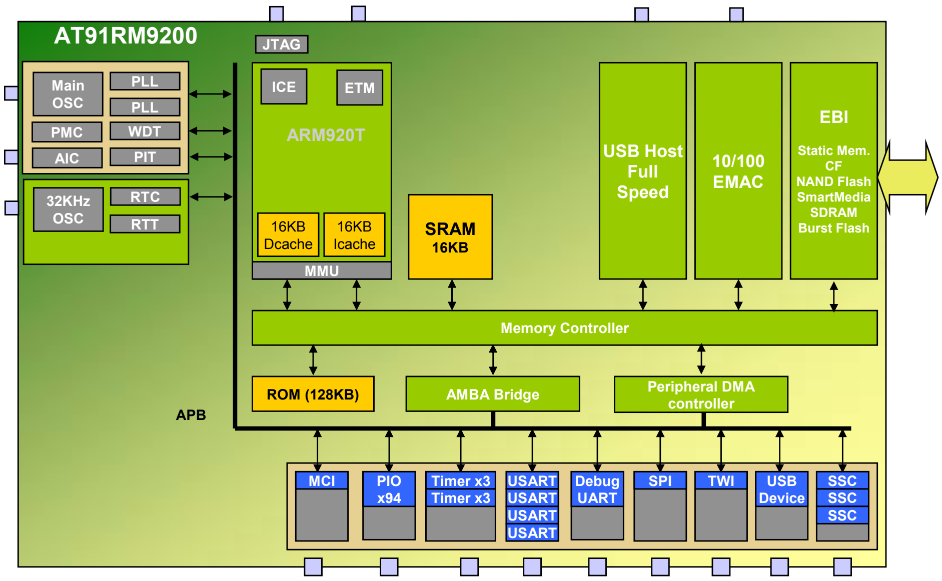

Figure 7. Block diagram of the application processor AT91RM9200. (Samuelsson 2008)

EBI (External Bus Interface) is used to connect and map the video driver IC to the processor's address space. SSC (Synchronous Serial Controller) is used to connect an audio CODEC chip to the system. It takes care of providing PCM (Pulse Code

Modulation) coded audio data to the DAC (Digital to Analog Converter), which in turn converts it to an analog voltage signal, synchronously with the Bit Clock and Frame Synchronization signals provided by the CODEC.

3.4.1 Processor Module Life Cycle

Despite the fact that the Application Processor IC in question is an old product and potentially at the end of its life, it is still recommended for new designs by the manufacturer. This is mainly due to the chip implementation on the obsolescent 0.18-micron manufacturing process. Atmel has also terminated their ARM 920T Processor Core license, which indicates that no development whatsoever can be anticipated. (Samuelsson 2008)

In the Atmel line of compatible application processors, there are possible replacements, which could potentially take the place of AT91RM9200 application processor. Migration to another chip is always a sensitive issue, but for this reason a modular processor platform has been chosen for the concept. This decision was made in the first place to isolate all the processor dependent hardware, such as Flash and SDRAM memory chips, reset logic and oscillator circuits on a single module. This kind of independent entity is relatively simple to replace with an updated unit, without further changes on the product hardware design. It is even anticipated that the migration process could be carried out by the module supplier, in case the market demand still exists.

3.4.2 CPU Performance

This thesis does not cover the selection process of the CPU (Central Processing Unit) Chip. Neither does it deal with Application Software, as the primary focus is on electronics design. However, certain application performance related features should be discussed.

A typical Vaisala Weather Display Application is definitely mission-critical, but by no means a processor-intensive, even though it poses a need for accurate floating point calculations. AT91RM9200 does not include a Floating Point co-processor Unit (FPU) in addition to the ARM 920T Processor Core and therefore the processing of floating point operations must be emulated using fixed point calculation. There are several ways of implementing such behavior on software; either by using special library calls to solve floating point calculations or embedding this functionality directly into OS kernel code. When it comes to Embedded Linux, the latter solution is more often used, despite the severe performance issues related to such a method. In terms of accuracy and software consistency, this is however considered generally affordable. For this reason, an extra thought must be given when developing the Software Framework.

3.5 Software Architecture

A typical PC (Personal Computer) consists of more or less standardized components, which all function uniformly from a computer to another. To achieve such a harmony, a set of different expansion buses have been defined and standardized.

Unlike the desktop computer, an embedded system usually incorporates a vast selection of different, often rather exotic peripherals and communication buses. Figure 8 illustrates a typical embedded device built upon an embedded SoC device, containing several interfaces not common in the PC world, such as Flash Memory, LCD Controller and push buttons and LEDs directly attached to the chip's I/O (Input/Output) lines.

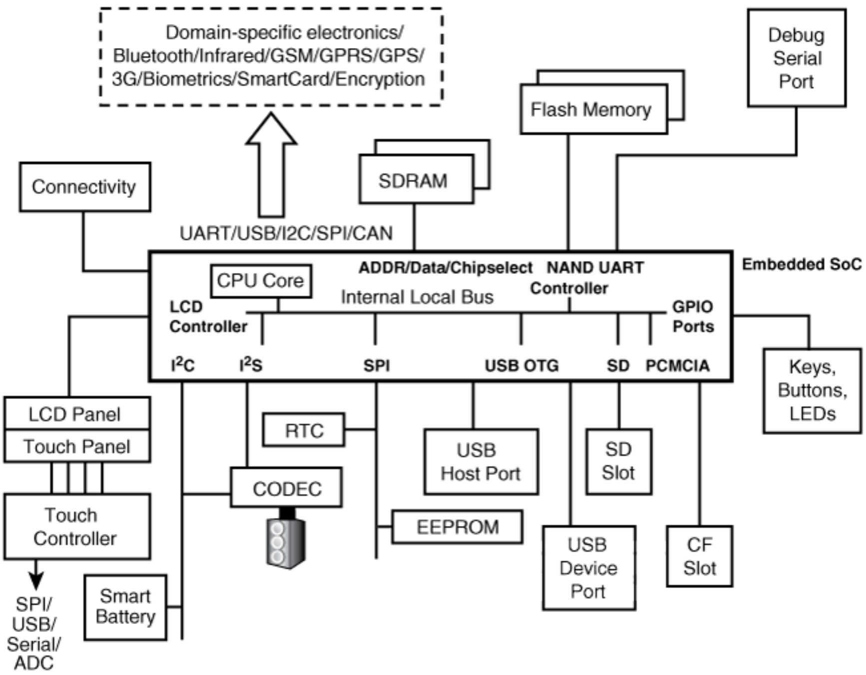

Figure 8. Hardware block diagram of a typical embedded system. (Venkateswaran 2008, p.92)

In order to achieve the layered software structure mentioned in paragraph 2.2, a Graphical User Interface (GUI) framework was destined to be implemented to assure painless application software development. According to Ala-Fossi (2008), Qt Software's cross-platform application framework, Qt, has proved to be a rugged and flexible foundation for development of GUI Applications. In order to maintain software portability to other systems and hardware platforms, Qt was selected to the concept project. Qt's dual licensing policy enables proprietary development under commercial license. (Qt 2008a)

A GUI software package called Qt for Embedded Linux version 4.4 was found to be perfectly suitable for the display concept under development. It was completely compatible with the Qt based desktop applications, already running on ARM9-powered Linux hardware, and supported rather straightforward Linux Framebuffer (FB) driver architecture as a software interface towards the Video Controller. As an input, it accepted any device recognized by the *tslib* universal Touch Screen Library. (Qt 2008b; Venkateswaran 2008, p.359, 228)

Qt for Embedded Linux is ignorant about the system audio capabilities. For this purpose, an additional User Interface and Application Platform package, Qt Extended, would have been used to obtain complete support for multimedia, games, and cellular communications - just to mention a few of 19 available modules. However, this was considered overkill for such a simple device, and the sound output was destined to be handled separately from the Qt framework. (Qt 2008c)

The Advanced Linux Sound Architecture (ALSA) provides an open source SoC framework, which enables reuse and free combining of drivers for embedded system components, like I^2S peripheral of a processor or Audio CODEC chips. Since the selected processor family, Atmel AT91, was already supported by the ALSA SoC (ASoC) framework, it was selected as the audio driver for the concept under design. The audio interface towards the application software is provided by *salsa-lib* library, intended for embedded systems. The LGPL (Lesser General Public License) policy does not prohibit developing proprietary software utilizing the open source library (ASoC 2008). Figure 9 illustrates a simplified software architecture block diagram.

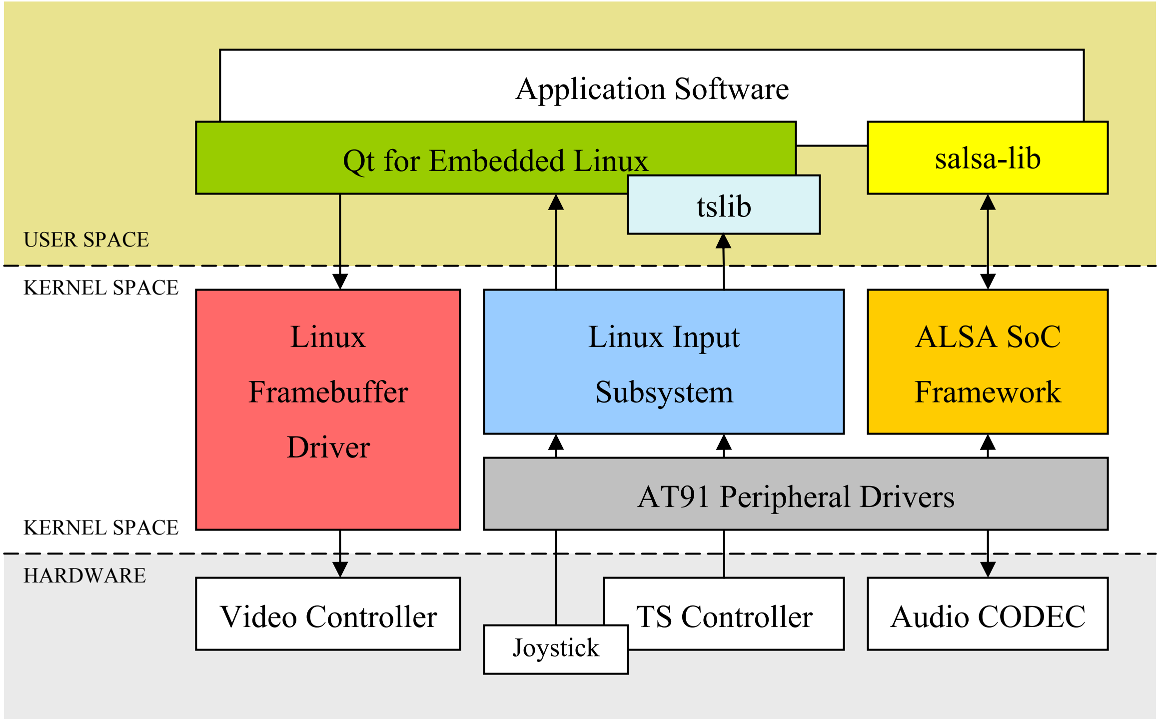

Figure 9. Block diagram of Embedded Weather Display Software Architecture.

3.6 Video Controller

Means to generate the digital RGB signal to the display component was required. Unlike many competing SoC devices, AT91RM9200 does not incorporate an embedded LCD driver. The generation of these signals using the processor's data bus and general purpose I/O signals was considered way too troublesome. A discrete Video Controller IC was to be selected.

A video chip from Solomon Systech, SSD1906, was evaluated for the application. It soon turned out, that the missing driver support was the major obstruction for utilizing this chip. Also, the limited amount of Display RAM on the chip did not allow increasing the screen resolution in the future. Due to these drawbacks, the IC had to be discarded.

Fortunately, a suitable Video Controller chip already had Linux support. An Epson S1D13742 Mobile Graphics Engine Linux Framebuffer driver was released by the manufacturer in February 2008, and the chip was selected to provide the video capabilities of the concept design. (Epson 2008)

For the time being, an improved SSD1961 Display Controller IC has been launched by Solomon Systech, and it incorporates 675 kilobytes of video memory, and thus supports future upgrade to VGA resolution. This chip is worth evaluating in case the concept is decided to be developed further. (Solomon 2008)

3.7 Input devices

Typically Vaisala Weather Displays are running continuously from the first day of implementation. Despite the long-term active states, the input controls are not as critical components as one could assume. The main duty of the Weather Display device is to present valid, measured data to the user, and the most important factors, such as wind speed and direction needs to be displayed at all times. Often the device needs operator intervention only at the installation time or when some setup parameters need to be changed.

Taking this into account, the prototype unit was decided to include only a cheap joystick, which on the one hand was well more affordable than any touch sensing technologies, but on the other hand introduced the necessary three degrees of freedom to fully operate a menu-based interface.

In case a need arose in the future for such a touch panel, it was desired to remain optional. For this purpose a quick research was conducted, and it soon turned out that the availability of many advanced touch panel technologies were unreachable due to the small size of the application. The only widely available type was an affordable resistive touch panel, which on the downside reduces the display luminance by 20 percent[2]. Also, placing any extra layer on top of the TFT screen might throw up unpredictable reflections, glare, among other unwanted effects on display contrast and readability. These issues are not covered by this thesis.

[2] This indicative attenuation figure was measured by placing a Fujitsu N010-0554-T009 touch panel in front of a white TFT screen.

A standard touch panel construction is shown in Figure 10. Vertical and horizontal films, which both present a set of parallel linear resistive wires, are placed one upon the other on top of the display. These films are set up in a way that they do not touch each other, but there is a small gap in between them. Whenever a user touches a point on the springy outermost film, resistive wires create a galvanic connection and the touched vertical position can be read by placing a measurement voltage V_m across the Y-axis film. Now, recording the potential of X-axis film from either end yields a relative position when compared to the measurement voltage V_m:

$$y_{rel} = \frac{U_y}{U_m}. \tag{1}$$

The position x_{rel} can be read in a similar manner, applying the measurement voltage V_m over the horizontal film and measuring the vertical film potential.

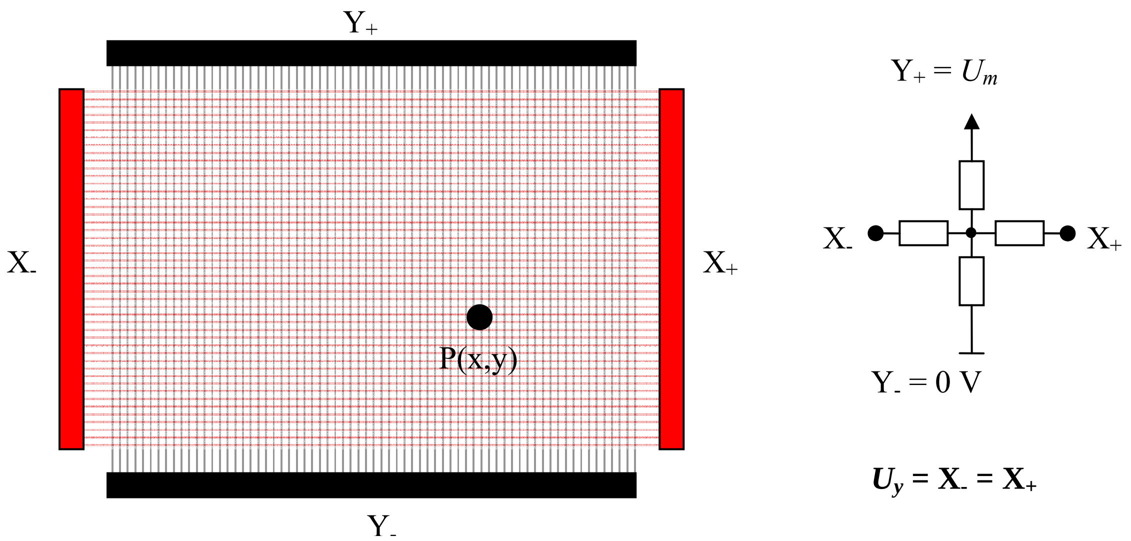

Figure 10. Typical Touch Panel construction and measurement circuit to obtain Y-value.

Determining user input on a resistive touch panel requires an Analog to Digital Conversion. For this purpose, a simple touch screen controller chip was selected among the devices supported by Linux. Texas Instruments ADS7846 takes care of analog to digital conversion of both axes, notifying the host system upon a touch event through a hardware interrupt signal, storing the measured coordinates, and sending the data to the host whenever queried through SPI (Serial Peripheral Interface) bus.

3.8 Audio CODEC

In order to be able to output wave audio, the device was necessary to include a digital to analog converter. A Wolfson Microelectronics WM8510 Audio CODEC was selected due to the decent software support provided by the chip manufacturer. The chip incorporates a 24-bit serial Sigma Delta DAC with conversions rates up to 48 kHz, together with 800mW speaker driver. (Wolfson 2008)

4 FLAT PANEL DISPLAY MEASUREMENTS

To achieve reproducible comparison between the opponent panels, a method for reliable measurement of the visual characteristics of the display components was developed. The most interesting key figure with regard to any human readable optoelectronic component is information visibility, and more precisely, a quality best described by the term *readability*.

In this study, the display panels were put on a race against each other. The components were evaluated through measuring the panel visual characteristics.

4.1 Photometric Measurements

The most important photometric measure when assessing qualities of flat panel display is luminance. It is defined as the radiated intensity per unit area on a plane perpendicular to the given direction, and is an objective, scientific replacement to the subjective quantity known as brightness. For display measurements, a Luminance Meter Minolta LS-110 was used. It provides an optical acceptance angle of ⅓° and dynamic range from 0.01 to 999 900 cd/m^2 when set to *FAST* or 0.01 to 499 990 cd/m^2 when set to *SLOW* response time.

The device is equipped with an optical filter to achieve spectral response close to the one of a human eye, described by standard $V(\lambda)$ function. This was first introduced by the Commission Internationale de l'Éclairage (CIE) in 1924, and it's still used as a representation of the spectral sensitivity curve of an ideal standard human observer. (Ware 2004, p. 81)

The device used was not traceably calibrated. The objective of this measurement was not to determine any absolute luminance values, but more like relative qualities, such as contrast ratio. For this kind of comparative measurements, the meter manufacturer has provided following relative, short-term repeatability characteristics:

Table 4 **Luminance Meter LS-110 Short Term repeatability (Minolta 1987)**

Luminance range	Accuracy
0.01 - 9.99 cd/m2	±0.2% ±2 digits
10.00 - 999900 cd/m2	±0.2% ±1 digits

The luminance meter is also reported to have influence of lens flare effect less than 1.5% (Minolta 1987).

4.2 Luminance and Viewing Angle

An ideal flat panel display could be characterized by a perfect Lambertian emitter. This means that the optimal display surface radiates equally into a hemisphere.

According to Lambert's Cosine Law, the transmitted luminous intensity I_θ from a surface element *dA* is dependent on the observing angle *θ*. This is because the area of *dA* exposed towards the observer is diminished in proportion to the cosine of *θ* when compared to the perpendicular situation, where intensity is I_0:

$$I(\theta) = I_0 \cdot \cos(\theta) \tag{2}$$

Luminance is defined as the radiated intensity from surface element *dA* per unit area of the element projected on a plane perpendicular to the given direction. As the apparent area of *dA* decreases in proportion to cosine of *θ*, the luminance equation of *dA* can be written as follows:

$$L(\theta) = \frac{I(\theta)}{A(\theta)} = \frac{I_0 \cdot \cos(\theta)}{dA \cdot \cos(\theta)} = \frac{I_0}{dA}. \tag{3}$$

Assuming that the surface is uniform over the measurement area, the luminous intensity I_0 increases proportionally as *dA* increases. Thus, luminance *L* is constant and independent of *dA*. Ideally, in case of a Lambertian surface, luminance measurement should yield equivalent results irrespective of the observation angle. (VESA FPDM:2001, p.256)

4.3 Typical Requirements for Display Visual Characteristics

The Human Factors Design Standard was selected as the design reference in paragraph 2.3. The requirements state that the most challenging conditions for display readability appear in an Air Traffic Control Tower environment, where illumination is stated to vary from approximately 10 to 65 000 lux (par. 5.1.6.1). The darkest scenario corresponds roughly to illumination produced by a candle on a table. This sets demand for display backlight control in the low end of the LED brightness. The worst case scenario from the display's point of view scales to the magnitude of horizontal illumination level outdoors on a clear day. For reference, direct sunlight can achieve illumination of 100 000 lux.

In addition, the recommended contrast ratios for various tasks are listed on a Chapter 8 of the Human Factors Design Guide. Table 5 lists these suggestions collected from various US federal sources. According to HFDS, the contrast ratio greater than 3:1 is required on all lighting conditions and viewing angles, though 7:1 is preferred. (Ahlstrom & Kudrick 2007, par. 5.1.6.14)

Table 5. Display contrast ratio requirements for various conditions (Ahlstrom & Longo 2001)

Condition	Contrast Ratio
Bright ambient illumination	> 7:1
Dark ambient illumination	3:1 to 5:1
Dynamic data	> 8:1
To attract attention	> 7:1
Continuous reading	3:1 to 5:1

The requirements also state that all areas of the display surface shall be readable from within at least 40 degrees of the centered normal on the screen (par. 5.1.4.2). (Ahlstrom & Kudrick 2007)

In addition to the panel visual characteristics and backlight brightness control, color selection also affects the visible contrast ratio. Using different tonal values of the same color can provide useful means to decrease the contrast ratio visible to the user. This must be considered when designing the application software and appearance and coloring of the GUI.

4.4 Measurement

The contrast ratio was measured using a sample data of alternating full screen black and white in cycles of 8 seconds. The measurement point was set in the middle of the display area, and luminance values for both black, L_b and white L_w were recorded for each viewing angle from -80º to +80º, using steps of 5º.

The measuring setup was planned using VESA FPDM 2.0 Flat Panel Measurement Standard as a reference. Not all the repeatability conditions were met, as some of the equipment needed to reliably verify fulfillment of these requirements were not available to be used in this study. Most of the requirements for measuring and documenting the environmental conditions were discarded, since the comparative measurements were conducted in the same room within a relatively small time frame.

4.4.1 Arrangement

The panels were measured in a dark room. The display under measurement was attached to a goniometer using a special fixture, which allowed setting the panel azimuth relative to the luminance meter. The center point of the display active area was laid on the axis of rotation.

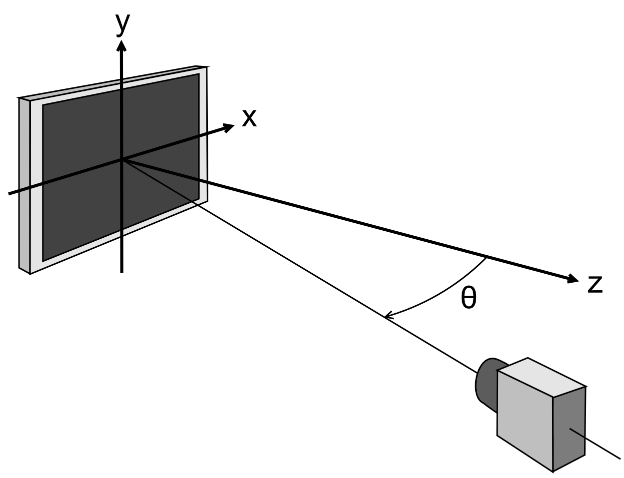

Figure 11. Measurement setup.

The display stand and the luminance meter were fastened to a breadboard laboratory table and the distance between the goniometer axis and the luminance meter outer lens was set to 1200 mm.

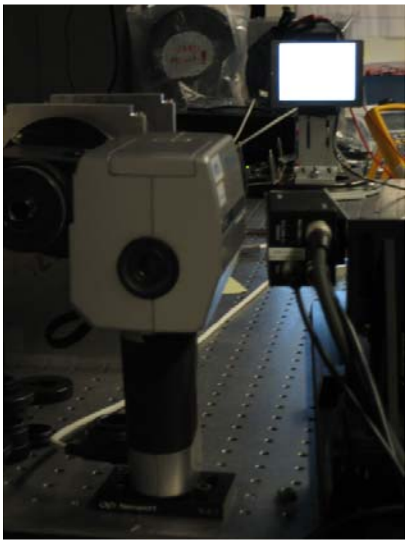

Figure 12. Measurement setup built on a laboratory table.

The zero-azimuth was set by aiming the luminance meter viewfinder to the center point of the display, and attaching a parallel semiconductor laser over the luminance meter lens mount. A paper with a vertical line was attached to the front of the luminance meter lens and the laser beam was directed to a piece of key steel on top of the display panel. The brush finish of the steel spread the beam into a fan beam, which in turn was used to adjust the goniometer to a position perpendicular to the laser. A similar calibration procedure was performed for each of the measured panels.

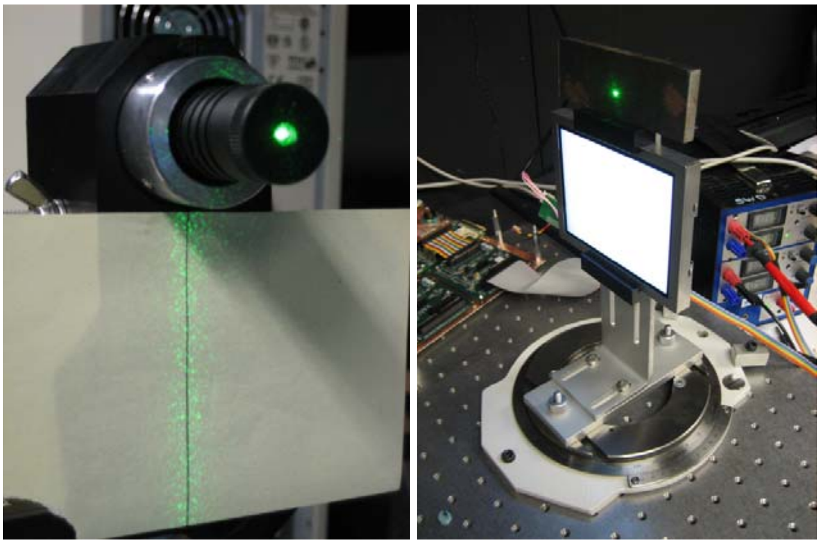

Figure 13. Adjusting the zero-azimuth.

As the properties of the LCD backlights tend to vary over their normal temperature range, they display units were allowed a 60-minute warm up period before any measurements were recorded. Self luminous displays, such as Planar EL and CMEL OLED are also affected by the operating temperature. Distinctive from the backlit LCD, their temperature dependence is of different nature. The pixel luminance deteriorates with the rising temperature, which can be noticed, for example, by viewing a high-contrast picture for some time, and then changing the view to a full screen white. The previously brightly lit pixels have produced heat and warmed up, while the dark pixels have stayed cooler. Now, when the screen turns all white the previous picture can be distinguished as a dim shadow figure until the pixel temperature again becomes uniform over the screen surface.

It was obvious that in order to achieve the best and steadiest result, all of the displays should be driven using the same periodical measurement sample data during the warm up period as was used during the actual measurements.

The display luminance was continuously measured and recorded through the serial data transmission line into a spreadsheet program on a PC computer. The luminance meter was set to slow response speed, which approximates to integration time of 1.5 second. A rather long integration time is needed to avoid inaccuracies induced by the screen flickering.

4.5 Results

The measurements were recorded only in horizontal plane, as all the panels could not be mounted in upright position to the fixture. In the case of most LCD screens, the horizontal viewing angles are directly comparable to each other, and thus the most interesting. Figure 14 illustrates the measured contrast ratios of the selected display components.

The black and white luminance graphs are presented for comparison in appendices I-II. The measurement records for each display are presented in appendices IV-VIII. In addition, a set of digital photographs of each display was recorded using different viewing angles. These pictures were digitally perspective corrected, and geometrically transformed back to zero-azimuth to comparably illustrate the contrast degradation along the viewing angle. A summary is presented in appendix III.

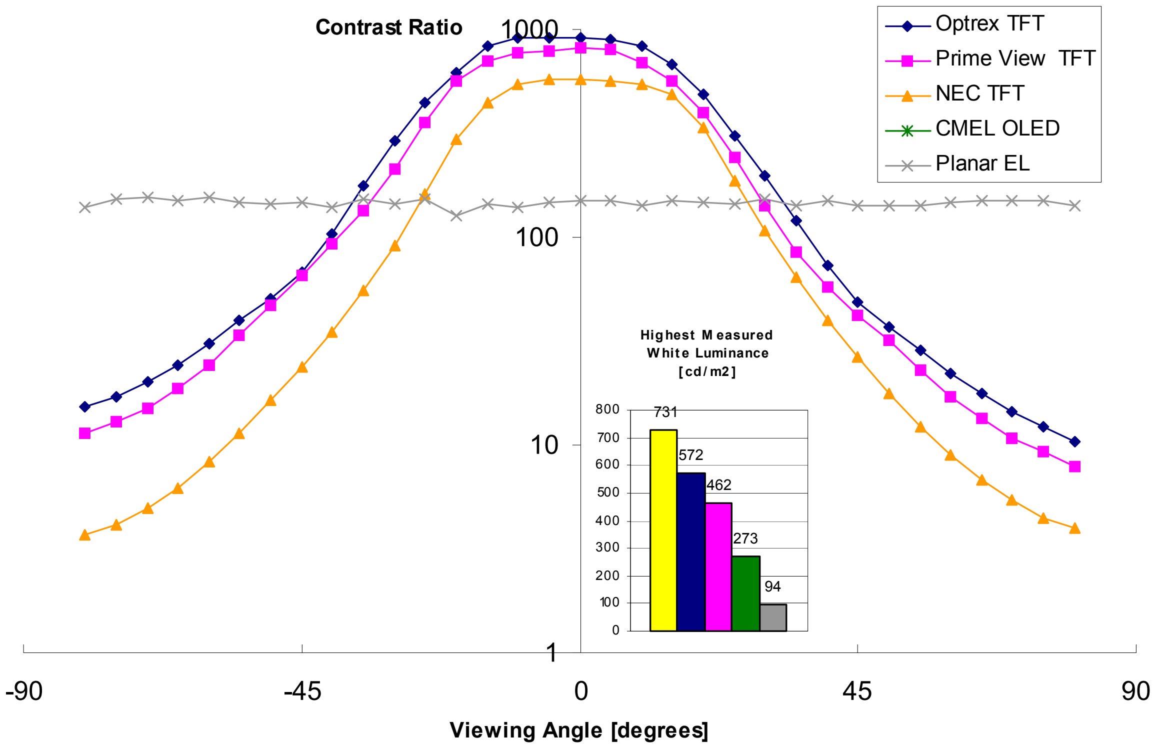

Figure 14. **Contrast ratios of displays presented as a function of viewing angle. Contrast ratio is presented in logatihmic scale.**

Determining the CMEL OLED panel contrast ratio was not possible using the luminance meter utilized. The low-end dynamics of the instrument was not sufficient to measure the black luminance of the display, resulting in zero luminance readings. These results were judged as void. As the OLED panel proved to be able to deliver white luminance more than two times greater than the Planar EL at all viewing angles, it is justified to state that the wide viewing angle incorporated to the fairly good luminance and excellent contrast characteristics makes it visually the best display of the comparison. However, this applies only to dark room environment.

The average contrast ratio on the boundary of the 40° viewing angle recommended by the Human Factors Design Guide is presented in Table 6. The average contrast ratio for all displays is well beyond the required 7:1. (Ahlstrom & Longo 2001)

Table 6. Contrast ratios at the perimeter of required viewing angle.

Display	Contrast Ratio $CR(-40^\circ)$	Contrast Ratio $CR(+40^\circ)$	Average Contrast Ratio $\overline{CR}(\pm 40^\circ)$
Optrex TFT	104	73.0	88.7
Prime View TFT	92.2	58.1	75.1
NEC TFT	35.1	39.9	37.5
Planar EL	140	149	144

As a result, it is observed that the actual LCD panels are far from the Lambertian emitter behavior. However, EL and OLED have a quasi-Lambertian emission, like CRT. (AAPM 2005, p.22)

The objective of these measurements was to assess the readability of the Flat Panel Displays. The dark room measurements were selected due to the simple arrangement and few instruments needed to conduct. The user of a Weather Display, the ultimate target of all this study, is hardly ever located in such an awkwardly lighted environment. As stated by the Human Factors Standard, the ambient illumination is expected to vary from extremely dark to highly bright conditions.

Due to the complex nature of the display contrast ratio degradation along the increasing stray light conditions, there is no known acceptable way of analytically approximate the relevance of these dark room results to any other kind of environment. To achieve reliable information on display daylight readability, a method suggested by Kelley et al. (2006) could be utilized. (Kelley et al. 2006)

4.5.1 Measurement Uncertainty

In uncertainty calculations, it is assumed that the instrument vendor has reported the relative accuracy using expanded uncertainty $R_m = U/L$ with a coverage factor of $k = 2$, or so to say, confidence level of 95 %. The standard uncertainty can be written as follows:

$$U = ku \Leftrightarrow u = \frac{R_m}{k} L . \tag{3}$$

As the main interest was in the contrast ratio measurements, the short-term repeatability may be used to form error estimate. The relative uncertainty of the contrast measurement equals the square sum of black and white standard uncertainties:

$$u_c^{\,2}(L_w, L_b) = u_w^{\,2}(L_w) + u_b^{\,2}(L_b) . \tag{4}$$

Ignoring the additional error sources, the standard uncertainty of a several short-term measurements would be given by the equation

$$u(L) = \sqrt{\left(\frac{R_m}{k} L\right)^2 + (\delta L)^2} , \tag{5}$$

where $R_m L$ is the component of uncertainty related to the short term accuracy drift and δL the component of uncertainty associated with the last digit readout. δL is not considered to follow normal distribution, and thus is used as such.

The luminance meters are known to suffer from contamination of the measurement by lens flare between the lens elements. Influence of lens flare for the instrument used is reported to be less than 1.5 %. Assuming that this value corresponds to an expanded relative uncertainty of $U_l / L = 1.5$ % with a coverage factor of k = 2, equation 5 can be rewritten:

$$u(L) = \sqrt{\left(\frac{R_m}{k} L\right)^2 + \left(\frac{R_l}{k} L\right)^2 + (\delta L)^2} \ , \tag{6}$$

Table 7 illustrates the uncertainty components used when calculating the final results in appendices IV-VII. The accuracies reported by the instrument vendor are listed in Table 1. (VESA FPDM:2001, p. 212)

Table 7. Components used to calculate the total short-term luminance measurement uncertainties

Luminance L range [cd/m^2]	Relative expanded short-term measurement uncertainty R_m [%]	Relative expanded uncertainty due to lens flare R_l [%]	Readout uncertainty δL [cd/m^2]
0.01 – 9.99	0.2 %	1.5 %	0.02
10.00 – 99.99	0.2 %	1.5 %	0.01
100.0 – 499 900	0.2 %	1.5 %	0.1

Above mentioned short-term uncertainties are not applicable to absolute luminance measurement results. According to the Minolta LS-110 Instruction Manual, a ±2 % relative uncertainty accounts to the errors in factory calibration. This accuracy has been used in results of appendix VIII. Even larger drift is anticipated in luminance measurement accuracy due to aging of the instrument. This must be considered when interpreting the absolute luminance values in appendices IV-VII.

4.5.2 Further Error Sources

As previously mentioned, the sensor noise was not taken into account in error estimate calculations, because this uncertainty was not reported by the luminance meter manufacturer nor could it be reliably detected. It is likely that the low luminance uncertainties are too optimistic. An alternative form of equation 6, with respect to the noise uncertainty component s_n would have been

$$u(L) = \sqrt{\left(\frac{R_m}{k} L\right)^2 + \left(\frac{R_l}{k} L\right)^2 + (\delta L)^2 + s_n^{\,2}} \qquad (7)$$

4.5.3 Conclusions on error

In case the lens flare had proven to be a source of significant error, it could have been minimized by using a frustum of cone between the display and measuring device as suggested by VESA FDPM 2.0. The frustum prevents any luminance outside the meter's area of acceptance interfering with the result. (VESA FPDM:2001, p. 188-191)

Inability to meet the uncertainty goal of FPDM Standard set for zero-azimuth (perpendicular to screen ±0.3º) resulted in minor asymmetry of the contrast ratio graphs. This was linearly compensated when assessing the ±40º contrast. For other interpretations on the results, this must be considered.

5 ENGINEERING AND PROTOTYPING

Based on the earlier results, a prototype unit was designed and assembled. The main goal was set to the functionality rather than exactly following the given and concluded design requirements.

5.1 Selection of the display component

5.1.1 Reliability

Reliability of an electronic device is generally characterized through MTBF (Mean Time Between Failure), a statistical property of the device, which describes its average lifetime. MTBF calculations assume a constant failure rate, which is not the case with units wearing out, and thus cause the failure rate to increase over time. When it comes to display units, lifetime is usually defined as the period of time in which the luminance is degraded to half of the original. For LCD devices, the dominating quality is the lifetime of the backlight.

Planar reports only 15% luminance degradation after 100 000 hours of operation at maximum luminance output. Also an MTBF of more than 50 000 hours is anticipated on 90% confidence level. CMEL announces lifetime of 20 000 hours for their OLED, which is not comparable, since it assumes output level of mere 30% of the maximum luminance.

CCFL tubes' lifetime varies usually from 10 000 to 50 000 hours. NEC reports lifetime of 40 000 hours for their CCFL backlight module. The LED backlight lifetime expectancy is generally a little shorted, even though some manufacturers have been promising as long as 60 000 hours lifetime for their LED backlights. Prime View reports 20 000 hours, while Optrex reports 15 000 hours.

5.1.2 Result

Based on the measurement results presented in Chapter 4, the CMEL AMOLED was the bright winner. However, due to the doubts on the reliability and availability of the product, it was considered as way too recent for the developed concept.

The race between TFT and TFEL was finally decided in TFT's favor, as the five fold pricing was considered too expensive for the application.

LED backlighting was preferred over CCFL due to the simpler driving electronics and competing reliability. CCFL backlight requirements for high voltage power supply were considered demanding, even though the LED was slightly losing in the luminance comparison. This left only two units to compare, LED backlighted 5.7" TFT units from Optrex and PVI.

Based on the slightly better contrast performance in laboratory tests, the Optrex TFT was selected for the concept prototype. The difference to the PVI was not significant, but Optrex's adequate QVGA resolution together with slightly lower unit price was preferred over the PVI's more expensive VGA alternative. However, it must be noted that PVI offers a drop-in replacement for Optrex in case the requirements for resolution performance change or availability issues arise.

5.2 Block Diagram

Given the product specifications and component decisions made in Chapters 2 and 3 respectively, a block diagram illustrated in Figure 1 was formed. As anticipated in paragraph 2.4.1, a separate modular adapter interface was to be designed for display interconnection. It incorporates the routing of digital video signals to a connector component specific to the display module, a switching regulator circuit to power up the backlight, and the optional Touch Screen Controller. Only the adapter module needs redesigning in case the display panel is changed.

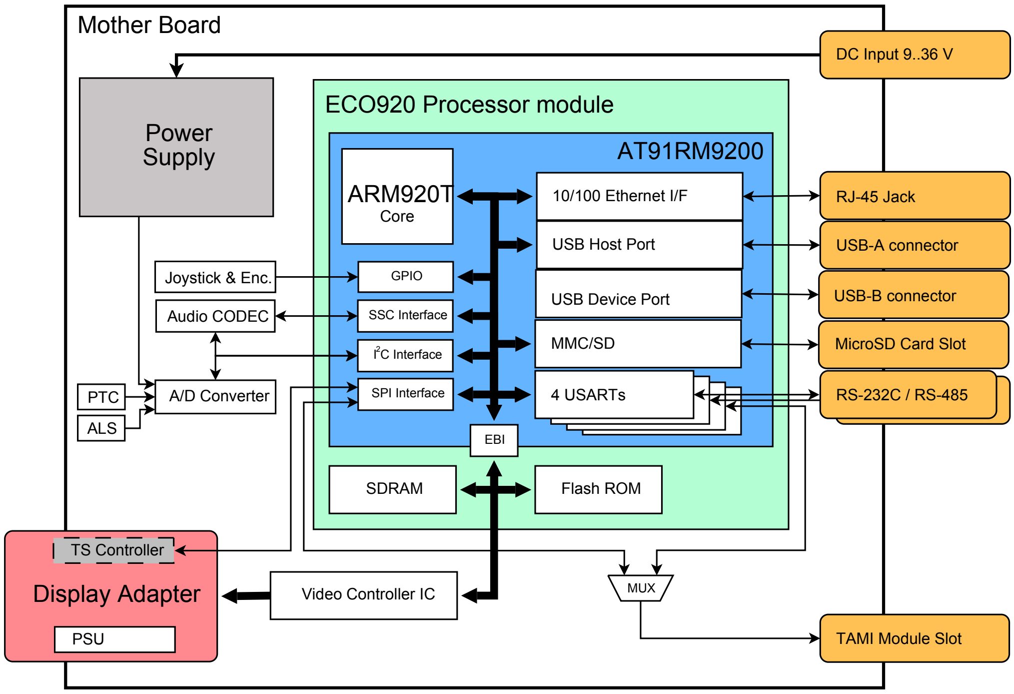

Figure 15. Electrical Block Diagram of the Embedded Weather Display.

The joystick and incorporated rotary encoder are interfaced to the GPIO (General-Purpose I/O) unit of the processor. Audio data is fed to the CODEC through the SSC controller, and the CODEC control is implemented through I^2C (Inter-Integrated Circuit) interface, as well as the connection of generic 8-bit ADC (Analog to Digital Converter) IC. The main function of the ADC is to provide supervisory over input voltage and several main regulator voltages for diagnostic purposes, in addition to the ALS (Ambient Light Sensor) and temperature sensing NTC (Negative Temperature Coefficient) resistor. The optional touch screen controller on the Display Adapter board is connected to an SPI channel.

The Vaisala TAMI (Transmitter Add-On Module Interface) module can communicate through an SPI or an USART (Universal Serial Synchronous-Asynchronous Receiver Transmitter) interface. This choice is module-dependent, and thus a multiplexing circuit was added. (TAMI 2008)

5.3 Thermal Design

Without further calculations, the expected power dissipation was estimated rather low compared to the physical dimensions of the device, and thus considered insignificant in terms of mechanical construction and heat transfer. The overall heat production was also assumed to be evenly distributed between numerous components and spread over the circuit board. Based on this assumption, a non-analytic approach was selected to save effort and avoid complicated and often inaccurate calculations. The unit was planned to be reviewed using a thermographic camera once the prototype unit was assembled.

In PCB (Printed Circuit Board) design, sufficient cooling was achieved by providing minimal thermal resistance from heat sources to the ground plane spanning over the entire circuit board. This was carried out by placing extra thermal vias from the power components' ground pads to the ground plane.

In order to be able to self-diagnose possible problems with insufficient heat transfer, two temperature sensing NTC resistors were to be installed on circuit board, nearby the presumably greatest sources of power dissipation, the switching power stage, and the processor module.

5.4 Power Supply

One of the most challenging tasks in the project was defining and designing the power supply stage for the unit. Considering the harsh nature of battery powered and battery back-upped low-voltage distribution networks, it was expected to withstand high voltage transient surges in addition to the requirements for noise immunity and considerable voltage drift.

High power efficiency was considered a fairly important feature in order to reduce excessive heat dissipation. The wide input voltage range on the other hand made selection of a good converter scheme extremely important. High input voltage excluded virtually all the linear regulators, as well as many of the switching regulator ICs. Only a minority of switching regulators on the market was able to handle input voltages as high as 60 V, and the component selection was dictated mainly by this feature.

The wide variety of peripherals created a need for several voltages. Main power supply was dictated by the 3.3 V logic level used, but for instance USB Host feature needed a regulated 5 V power supply.

Acknowledging the fact that cascading several converter stages increases the possibility of the control drifting out of regulation, this was initially considered a topology to avoid. The overall power efficiency of parallel converters was also considered better than the cascading topology could ever achieve, but as a drawback this decreased the number of suitable regulator chips, increased the required voltage rating of the input capacitors and thus inevitably was going to raise the total component cost.

The Vaisala Transmitter Add-on Module Interface specification defines two distinct input voltages to be supplied by the host device. The module is allowed to draw a mere 10 milliamperes from the 3.3 volt main logic supply. A special pre-regulated supply voltage with a wider range of +9..15V, V_S, which allows the module to independently create necessary supplies for its possible high-power functions. Some modules are also capable of powering up the host device via V_S line, but for this application a diode was added in series, in order to prevent current flowing from module to the host.

Some of the Vaisala TAMI modules also support remote firmware update. These units provide a Flash programming voltage to the host device, but using this option was considered rather impractical in a computer system of this complexity, and this voltage supply was not connected. (TAMI 2008)

The assessed TFT panels required higher voltages for LED backlighting, and they were intended to be driven using a constant current source.

Voltage for backlight LEDs in the panels was typically roughly 12V in room temperature. The LED forward voltage decreases as the junction temperature rises, and this causes degradation in display luminance, thus heavily affecting the visual characteristics of the display. To properly overcome this, the LED power supply should have been designed to deliver constant power rather than constant current. However, this was considered too sophisticated and complicated driving scheme, and the backlight power supply was designed to limit the LED current to the maximum rating of the panel. For preventing the high voltage from causing damage to the power supply components in a no-load condition, a feedback circuit was designed to limit the converter output voltage to maximum of 15 volts.

5.5 Electromagnetic Compatibility

As referenced by CISPR 24, immunity of the developed equipment against ESD, radiated interference, fast transient bursts, transient surges, and conducted interference are to be tested according to methods described in EN 61000-4-2, -3, -4, -5, and -6, respectively.

A device intended to be used in industrial environment shall withstand 1 kV line-to-line and 2 kV line-to-ground transients surge to its DC lines. The I/O lines expected to extend more than 30 meters in length, such as RS-485, are tested using 1 kV common mode voltage surge and test waveforms defined by EN 61000-4-5. These tests approximate the average coupled voltages caused by a lightning strike in long cabling. The aspect was taken into account by using Transient Voltage Suppression (TVS) diodes in DC lines and ceramic transient protection components across the I/O lines.

ESD tolerance is tested using 4 kV contact and 8 kV air discharge. The developed device must be able to tolerate such shocks, and it can be achieved by offering a safe path for high voltage to pass the electronics without causing remarkable potential differences within the electronics. This is best done by means of mechanical design and electrical protection similar to the voltage surge suppressors.

Neither of these violent tests was run on the device, because it would have compromised the functionality of the prototype unit. A larger amount of prototypes must be assembled in order to be able to assess the level of achieved protection for ESD and voltage surge. However, a radiated interference test was run. Figure 16 illustrates the results of the test, showing also the magnitude limits defined by the followed test standard.

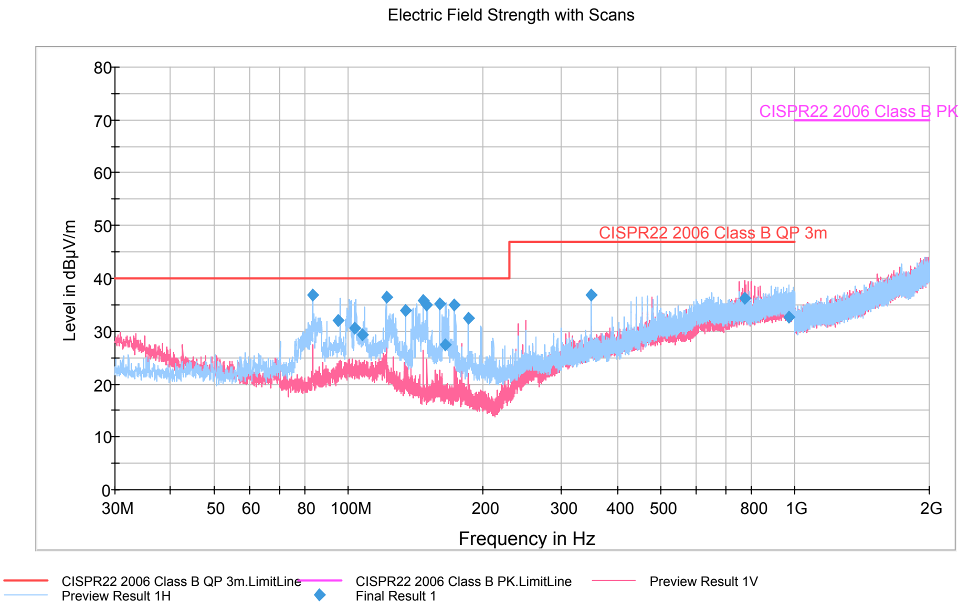

Figure 16. **Measured radiated emissions according to CISPR 22 Class B.**

5.6 Thermal analysis

Thermographic imaging was utilized to assess the thermal performance in normal room operating temperature. Figure 17 shows the temperature distribution of the device after running continuously for 60 minutes. For testing purposes, the LCD panel LED backlight was running on constant 180 mA current. The device was attached in upright position to a sheet of cardboard, which has low heat capacity and provides good insulation from surrounding thermal masses. The measurements were recorded using AGEMA 590 Thermal Camera, which was set to emissivity factor of 0.95.

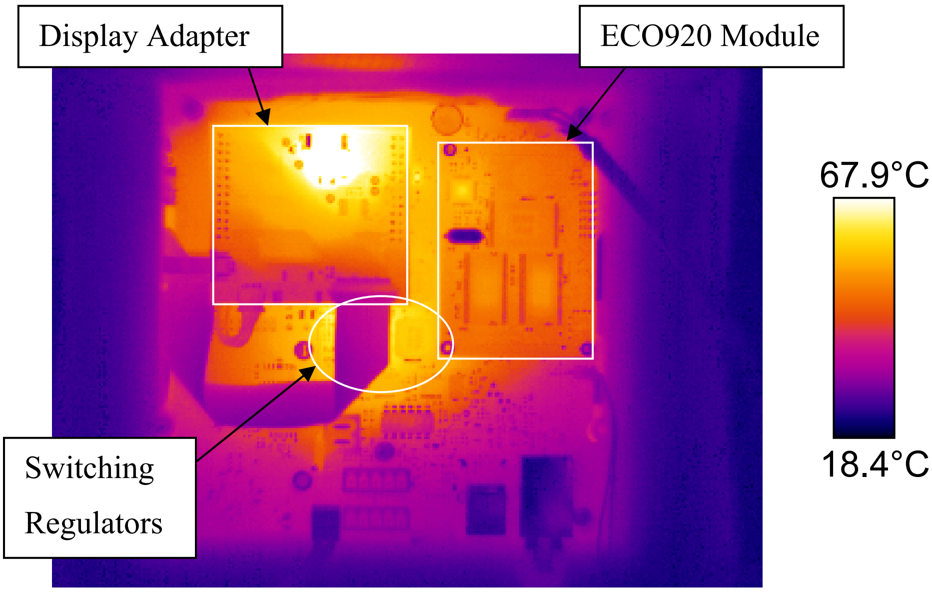

Figure 17. Temperature distribution obtained using thermal imaging.

As observed from the Figure 17, excessive overheating is present on the Display Adapter board. Otherwise the heat conduction from components to the PCB ground plane and furthermore to the aluminum frame seems quite efficient, since there are no visible sharp temperature gradients along the path. In a real-world case, most of the conducted heat energy should be eventually transferred to the mounting panel. A portion of it also is planned to be removed by natural convection through back cover ventilation holes and from the front panel.

In order to isolate the source of excessive heat, a more detailed close-up image was recorded. The result can be seen in Figure 18. Turned out that the switching regulator controller feeding the LED backlight was not able to transfer enough heat energy to the circuit board ground plane due to the mistake in PCB layout; there isn't a single thermal via below the switching chip.

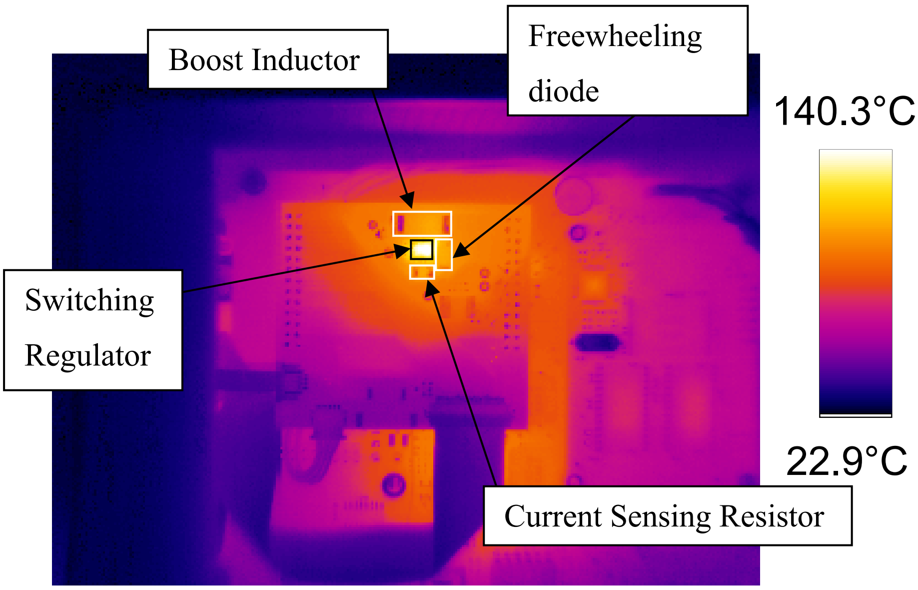

Figure 18. Close-up thermal scan of the TFT backlight regulator.

The results of these measurements shall be considered only suggestive, and their purpose was simply to bring out possible power dissipation issues, just like now happened. More accurate measurement and environmental tests are required in order to properly analyze the thermal performance of the device in all environmental situations.

5.7 Prototyping Results

Even though the prototype was not explicitly required to meet all the design guidelines listed in chapter 2, it seemed to cope with them rather well for a totally new design. All the requirements set for the prototype in paragraph 1.2 were met, except that the final concept software was not developed, and the fully functional Embedded Weather Display prototype was not achieved. However, the hardware platform functionality was able to be verified using other software solutions.

The future considerations for continuing the product development include a new revision of the Display Adapter PCB design to improve the poor thermal performance detected in paragraph 5.6. Also, the mother board was noted to have a couple of missing traces, few mistaken component footprints and some flaws concerning the component orientation. Also, the mechanical design is worth reconsidering together with the ergonomics.

Figure 19. The Embedded Weather Display Prototype mounted on an instrument panel.

6 CONCLUSIONS

A Display Panel based on TFT LCD technology is by far the best choice for a described product concept. However, the promising OLED technology should definitely be monitored, and should there be significant improvements to the current production techniques and product reliability, the results of this study should be questioned and revaluated.

A similar approach of comparative photometric measurement is worthwhile applying to selection process of any optoelectronic component. It can provide an R&D engineer with valuable objective data in addition to mere visual assessment. Nevertheless, an optoelectronic component should never be evaluated based solely on measurements, as they likely to pose some amount of error and furthermore, are not able to detect and distinguish many complex phenomena as a human eye. However, a more sophisticated measurement arrangement and metrics are needed in order to reliably assess the actual daylight readability, like the one suggested by Kelley et al. (2006).

The objective of the prototype was not to be a finished product, but a demonstrative example of the technologies selected for the concept. This target was achieved and on some points even, as the unit was successfully used to demonstrate the flexibility of the created concept. It also provides a decent cost estimate, a starting point for a future full-scale productization process. In addition, plenty of valuable information on available components and products on the market was successfully gathered, and a broader view gained over the suitable technologies for the concept described.

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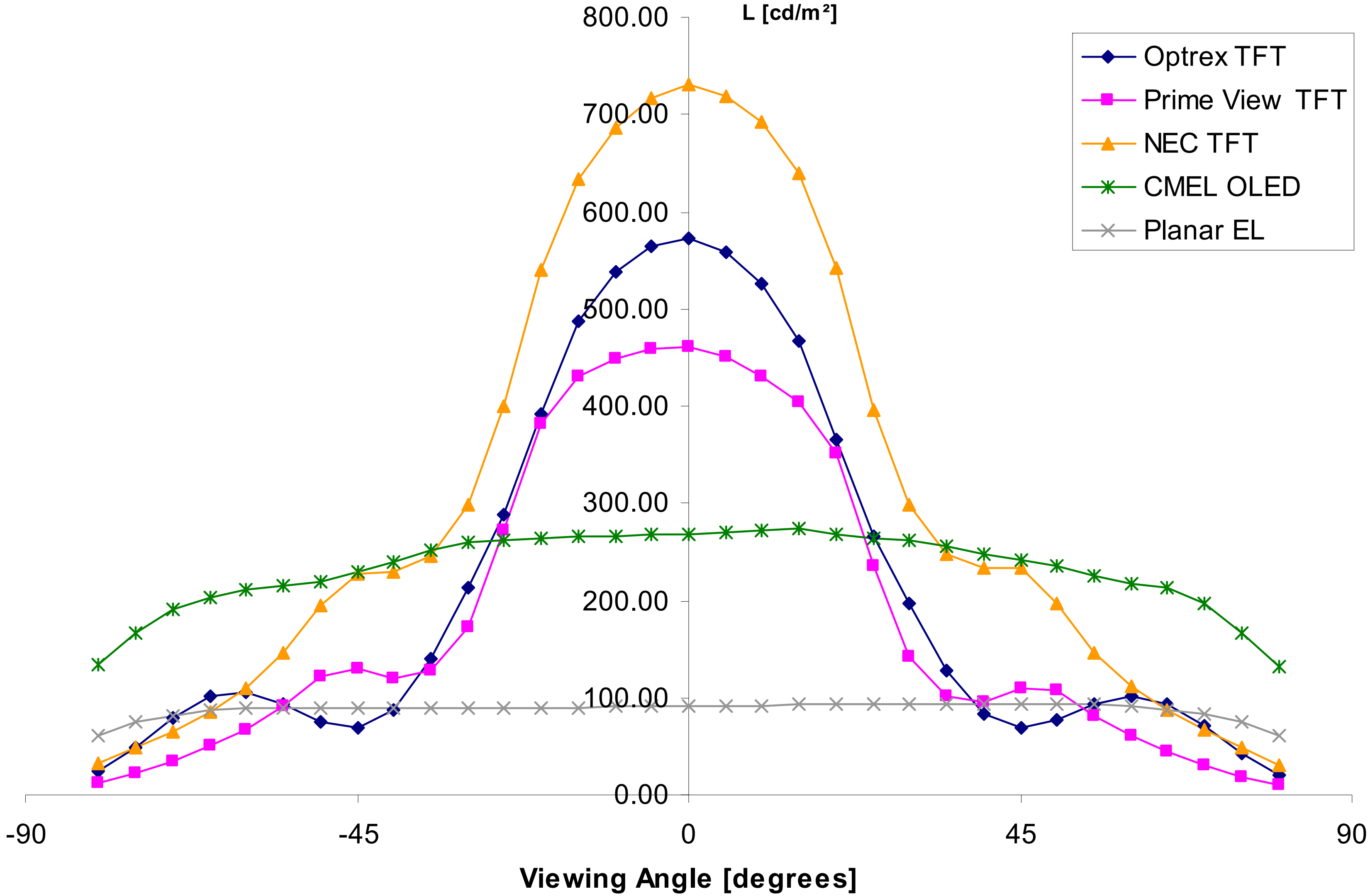
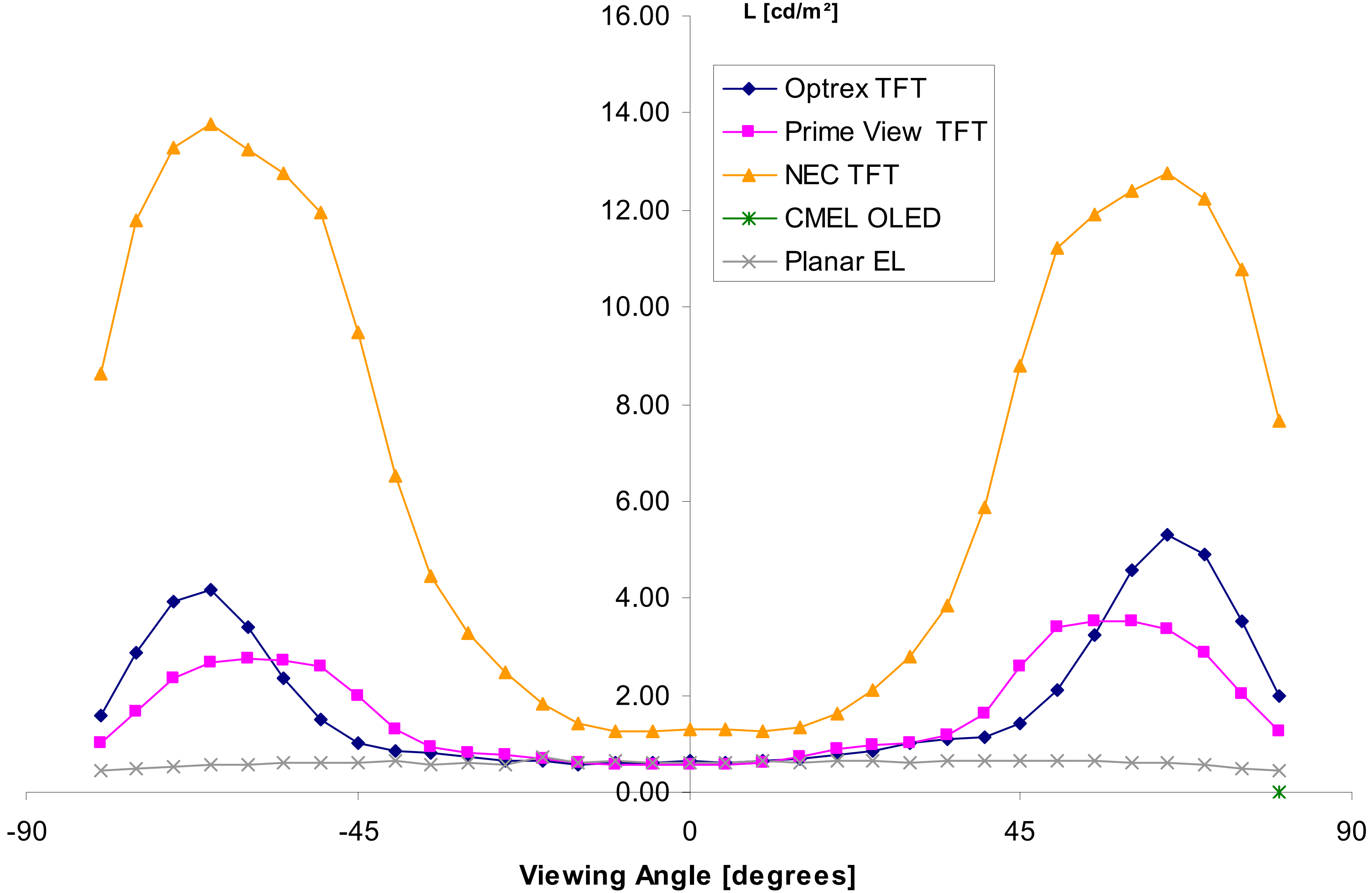
APPENDICES

Appendix I.	Measured white luminance relative to viewing angle
Appendix II.	Measured black luminance relative to viewing angle
Appendix. III.	Display image perception relative to viewing angle using perspective corrected photographs.
Appendix IV.	Measurement record for Optrex TFT
Appendix V.	Measurement record for Prime View TFT
Appendix VI.	Measurement record for NEC TFT
Appendix VII.	Measurement record for Planar EL
Appendix VIII.	Measurement record for CMEL OLED

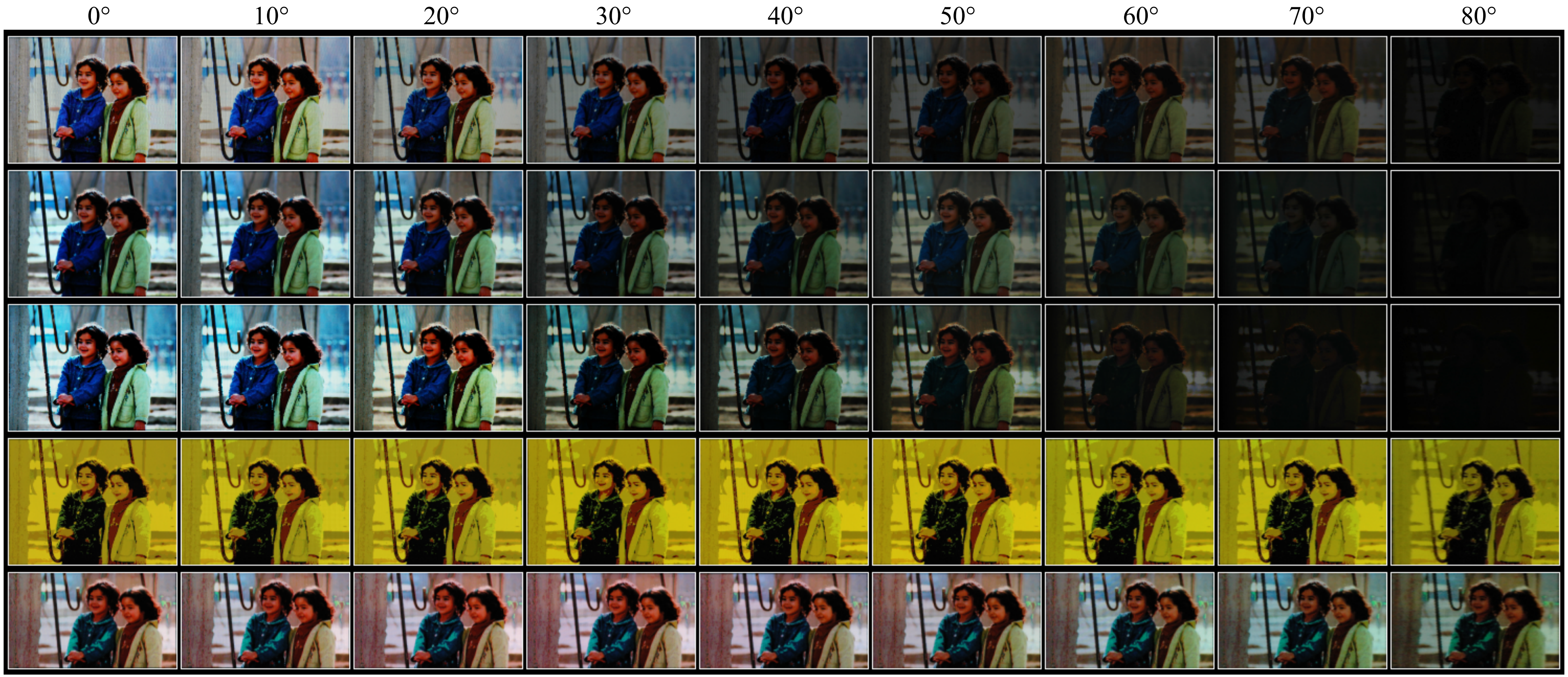
Appendix I. Measured white luminance relative to viewing angle.



Appendix II. Measured black luminance relative to viewing angle.



Appendix III. Display image perception relative to viewing angle using perspective corrected photographs.



Displays compared: 1. line: Optrex TFT, 2. line: Prime View TFT, 3. line: NEC TFT, 4. line Planar EL, 5. line CMEL OLED

Appendix IV. Measurement record for Optrex TFT.

Display type	Optrex TFT
Part Number	T-55265GD057J-LW-AAN
Backlight	LED
BL Drive	Constant current I=180 mA
Measured values	I=180,29 mA, U=12.6 V

Viewing Angle *θ* [º]	**White Luminance *Lw* [cd/m2]**	**Black Luminance *Lw* [cd/m2]**	**Contrast Ratio CR**	**Short-term White Luminance Uncertainty uw [cd/m2]**	**Short-term Black Luminance Uncertainty ub [cd/m2]**	**Total Expanded Contrast Uncertainty *Uc* with coverage factor k=2**
80	20.53	1.99	10.3	0.16	0.025	0.32
75	42.85	3.52	12.2	0.32	0.033	0.65
70	70.27	4.90	14.3	0.53	0.042	1.07
65	93.65	5.30	17.7	0.71	0.045	1.42
60	102.00	4.59	22.2	0.78	0.040	1.56
55	93.30	3.26	28.6	0.71	0.032	1.41
50	77.79	2.11	36.9	0.59	0.026	1.18
45	69.29	1.43	48.5	0.52	0.023	1.05
40	82.48	1.13	73.0	0.62	0.022	1.25
35	128.9	1.08	119	0.98	0.022	1.96
30	197.5	1.00	198	1.5	0.021	3.00
25	266.4	0.87	306	2.0	0.021	4.04
20	364.5	0.75	486	2.8	0.021	5.52
15	466.6	0.69	676	3.5	0.021	7.06
10	525.5	0.63	834	4.0	0.021	7.95
5	557.5	0.62	899	4.2	0.021	8.44
0	571.7	0.63	907	4.3	0.021	8.65
-5	564.1	0.62	910	4.3	0.021	8.54
-10	537.8	0.59	912	4.1	0.020	8.14
-15	486.6	0.58	839	3.7	0.020	7.37
-20	392.3	0.63	623	3.0	0.021	5.94
-25	288.1	0.65	443	2.2	0.021	4.36
-30	212.6	0.73	291	1.6	0.021	3.22
-35	140.6	0.80	176	1.1	0.021	2.14
-40	87.70	0.84	104	0.66	0.021	1.33
-45	69.17	1.01	68.5	0.52	0.021	1.05
-50	75.59	1.50	50.4	0.57	0.023	1.14
-55	93.03	2.33	39.9	0.70	0.027	1.41
-60	105.90	3.42	31.0	0.81	0.033	1.62
-65	101.50	4.16	24.4	0.77	0.037	1.55
-70	79.00	3.94	20.1	0.60	0.036	1.20
-75	49.48	2.88	17.2	0.37	0.030	0.75
-80	24.47	1.60	15.3	0.19	0.023	0.37

Appendix V. Measurement record for Prime View TFT.

Display type	Prime View TFT
Part Number	PD057VT1
Backlight	LED
BL Drive	Constant current, I=240 mA
Measured values	U=10.2 V

Viewing Angle *θ* [º]	**White Luminance *Lw* [cd/m2]**	**Black Luminance *Lw* [cd/m2]**	**Contrast Ratio CR**	**Short-term White Luminance Uncertainty uw [cd/m2]**	**Short-term Black Luminance Uncertainty ub [cd/m2]**	**Total Expanded Contrast Uncertainty *Uc* with coverage factor k=2**
80	10.08	1.27	7.94	0.08	0.02	0.16
75	18.86	2.04	9.25	0.14	0.03	0.29
70	31.09	2.87	10.8	0.24	0.03	0.47
65	44.95	3.37	13.3	0.34	0.03	0.68
60	60.06	3.51	17.1	0.45	0.03	0.91
55	81.25	3.52	23.1	0.61	0.03	1.23
50	107.7	3.40	31.7	0.82	0.03	1.64
45	109.3	2.60	42.0	0.83	0.03	1.67
40	94.6	1.63	58.1	0.72	0.02	1.43
35	100.6	1.19	84.5	0.77	0.02	1.54
30	142.5	1.01	141	1.08	0.02	2.17
25	235.8	0.97	243	1.79	0.02	3.57
20	351.4	0.88	399	2.66	0.02	5.32
15	403.4	0.72	560	3.05	0.02	6.11
10	430.5	0.62	694	3.26	0.02	6.52
5	450.8	0.56	805	3.41	0.02	6.82
0	461.9	0.57	810	3.50	0.02	6.99
-5	458.9	0.58	791	3.47	0.02	6.95
-10	449.4	0.58	775	3.40	0.02	6.80
-15	430.8	0.61	706	3.26	0.02	6.52
-20	382.0	0.67	570	2.89	0.02	5.78
-25	271.5	0.76	357	2.06	0.02	4.11
-30	173.6	0.81	214	1.32	0.02	2.63
-35	127.0	0.94	135	0.97	0.02	1.93
-40	119.9	1.30	92.2	0.91	0.02	1.83
-45	130.7	2.00	65.4	0.99	0.03	1.99
-50	122.2	2.61	46.8	0.93	0.03	1.86
-55	92.20	2.72	33.9	0.70	0.03	1.40
-60	67.42	2.77	24.3	0.51	0.03	1.02
-65	50.18	2.69	18.7	0.38	0.03	0.76
-70	35.25	2.35	15.0	0.27	0.03	0.54
-75	21.57	1.67	12.9	0.16	0.02	0.33
-80	11.64	1.03	11.3	0.09	0.02	0.18

Appendix VI. Measurement record for NEC TFT.

Display type	NEC TFT
Part Number	NL3224BC35-22
Backlight	CCFL NEC 55PW131 CCFL
BL Drive	Inverter
Measured values	U=12.002 V

Viewing Angle *θ* [º]	**White Luminance *Lw* [cd/m2]**	**Black Luminance *Lw* [cd/m2]**	**Contrast Ratio CR**	**Short-term White Luminance Uncertainty uw [cd/m2]**	**Short-term Black Luminance Uncertainty ub [cd/m2]**	**Total Expanded Contrast Uncertainty *Uc* with coverage factor k=2**
80	30.32	7.65	3.96	0.23	0.061	0.48
75	48.34	10.78	4.48	0.37	0.082	0.75
70	66.27	12.22	5.42	0.50	0.093	1.0
65	87.40	12.77	6.84	0.66	0.097	1.3
60	111.7	12.39	9.02	0.85	0.094	1.7
55	146.5	11.92	12.3	1.1	0.091	2.2
50	197.9	11.21	17.7	1.5	0.085	3.0
45	232.7	8.79	26.5	1.8	0.069	3.5
40	233.8	5.86	39.9	1.8	0.049	3.5
35	247.6	3.83	64.6	1.9	0.035	3.8
30	298.4	2.78	107	2.3	0.029	4.5
25	396.1	2.11	188	3.0	0.026	6.0
20	542.1	1.62	335	4.1	0.023	8.2
15	640.3	1.32	485	4.8	0.022	9.7
10	691.4	1.26	549	5.2	0.022	10.5
5	718.9	1.28	562	5.4	0.022	10.9
0	730.8	1.28	571	5.5	0.022	11.1
-5	717.6	1.25	574	5.4	0.022	10.9
-10	686.0	1.27	540	5.2	0.022	10.4
-15	634.2	1.43	443	4.8	0.023	9.6
-20	539.3	1.83	295	4.1	0.024	8.2
-25	400.6	2.46	163	3.0	0.027	6.1
-30	298.2	3.28	90.9	2.3	0.032	4.5
-35	245.1	4.46	55.0	1.9	0.039	3.7
-40	229.2	6.53	35.1	1.7	0.053	3.5
-45	226.5	9.47	23.9	1.7	0.074	3.4
-50	195.4	11.93	16.4	1.5	0.091	3.0
-55	146.1	12.76	11.4	1.1	0.097	2.2
-60	110.2	13.26	8.31	0.84	0.101	1.7
-65	85.58	13.76	6.22	0.65	0.105	1.3
-70	65.65	13.28	4.94	0.50	0.101	1.0
-75	48.23	11.77	4.10	0.37	0.090	0.75
-80	31.79	8.62	3.69	0.24	0.068	0.50

Appendix VII. Measurement record for Planar EL.

Display type	Planar EL
Part Number	EL320.240 FA3
Backlight	none
BL Drive	n/a
Measured values	U=12.002 V

Viewing Angle *θ* [º]	**White Luminance *Lw* [cd/m2]**	**Black Luminance *Lw* [cd/m2]**	**Contrast Ratio CR**	**Short-term White Luminance Uncertainty uw [cd/m2]**	**Short-term Black Luminance Uncertainty ub [cd/m2]**	**Total Expanded Contrast Uncertainty *Uc* with coverage factor k=2**
80	61.49	0.43	143	0.47	0.02	0.93
75	74.62	0.50	149	0.56	0.02	1.13
70	82.98	0.55	151	0.63	0.02	1.26
65	87.93	0.59	149	0.67	0.02	1.33
60	90.90	0.62	147	0.69	0.02	1.38
55	92.70	0.65	143	0.70	0.02	1.40
50	93.35	0.66	141	0.71	0.02	1.41
45	93.60	0.66	142	0.71	0.02	1.42
40	93.65	0.63	149	0.71	0.02	1.42
35	93.95	0.66	142	0.71	0.02	1.42
30	93.90	0.61	154	0.71	0.02	1.42
25	93.88	0.65	144	0.71	0.02	1.42
20	93.48	0.63	148	0.71	0.02	1.42
15	92.73	0.62	150	0.70	0.02	1.40
10	92.35	0.65	142	0.70	0.02	1.40
5	92.05	0.61	151	0.70	0.02	1.39
0	91.65	0.61	150	0.69	0.02	1.39
-5	91.08	0.62	147	0.69	0.02	1.38
-10	90.60	0.65	139	0.69	0.02	1.37
-15	90.08	0.62	145	0.68	0.02	1.36
-20	89.48	0.71	126	0.68	0.02	1.35
-25	88.88	0.58	153	0.67	0.02	1.35
-30	88.38	0.61	145	0.67	0.02	1.34
-35	88.48	0.58	153	0.67	0.02	1.34
-40	88.35	0.63	140	0.67	0.02	1.34
-45	88.43	0.60	147	0.67	0.02	1.34
-50	88.93	0.62	143	0.67	0.02	1.35
-55	89.33	0.61	146	0.68	0.02	1.35
-60	88.50	0.57	155	0.67	0.02	1.34
-65	86.30	0.58	149	0.65	0.02	1.31
-70	81.75	0.53	154	0.62	0.02	1.24
-75	74.31	0.49	152	0.56	0.02	1.13
-80	61.42	0.44	140	0.46	0.02	0.93

Appendix VIII. Measurement record for CMEL OLED.

Display type	CMEL OLED
Part Number	P0340WQLC-T
Backlight	none
Measured values	U=+5.001 V
	U=-5.002 V

Viewing Angle *θ* [º]	**White Luminance *Lw* [cd/m2]**	**Black Luminance *Lw* [cd/m2]**	**Contrast Ratio CR**	**Short-term White Luminance Uncertainty uw [cd/m2]**	**Short-term Black Luminance Uncertainty ub [cd/m2]**
80	132.2	0	n/a	1.66	3.31
75	165.8	0	n/a	2.07	4.15
70	196.8	0	n/a	2.46	4.92
65	212.3	0	n/a	2.66	5.31
60	218	0	n/a	2.73	5.45
55	225.3	0	n/a	2.82	5.64
50	236	0	n/a	2.95	5.90
45	242	0	n/a	3.03	6.05
40	248.3	0	n/a	3.11	6.21
35	256.8	0	n/a	3.21	6.42
30	262.3	0	n/a	3.28	6.56
25	264.1	0	n/a	3.30	6.61
20	267.7	0	n/a	3.35	6.70
15	273.4	0	n/a	3.42	6.84
10	271.4	0	n/a	3.39	6.79
5	271	0	n/a	3.39	6.78
0	269	0	n/a	3.36	6.73
-5	267.7	0	n/a	3.35	6.70
-10	266.4	0	n/a	3.33	6.66
-15	266.7	0	n/a	3.34	6.67
-20	264.6	0	n/a	3.31	6.62
-25	262.4	0	n/a	3.28	6.56
-30	259.6	0	n/a	3.25	6.49
-35	251	0	n/a	3.14	6.28
-40	240.6	0	n/a	3.01	6.02
-45	229.4	0	n/a	2.87	5.74
-50	219.7	0	n/a	2.75	5.50
-55	214.5	0	n/a	2.68	5.37
-60	210.7	0	n/a	2.64	5.27
-65	203.5	0	n/a	2.55	5.09
-70	190.5	0	n/a	2.38	4.77
-75	167.4	0	n/a	2.09	4.19
-80	133.5	0	n/a	1.67	3.34