T-eyeglasses

Project Abstract

The promising global impact of wearable health electronics makes it one of the most attractive areas of today's research. Innovation in miniaturization, power consumption and signal processing has been the focus for the development of such systems. However, these devices have not reached the mass market yet. The development of a versatile system, which is easily adaptable for any kind of application and assures high performance, but also is unobtrusive to wear and comfortable to use, could revolutionize this domain. According to the T-eye team's experience, everything is at hand to develop such a platform, based on TI's embedded processors, wireless communication solutions and highly-customized analog front-ends. As a proof of concept, the T-eyeglasses integrate the MSP430 architecture, the CC2541 BLE SoC and two of TI's analog front ends in a comfortable and aesthetic manner. This system measures biopotential signals, inertial signals as well as heart rate and communicates with handheld devices. In this project multiple hardware and software disciplines, going from hardware testing to system design and from signal processing to app development are cleverly combined into one successful wearable system.

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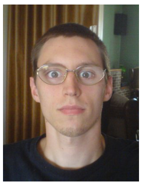

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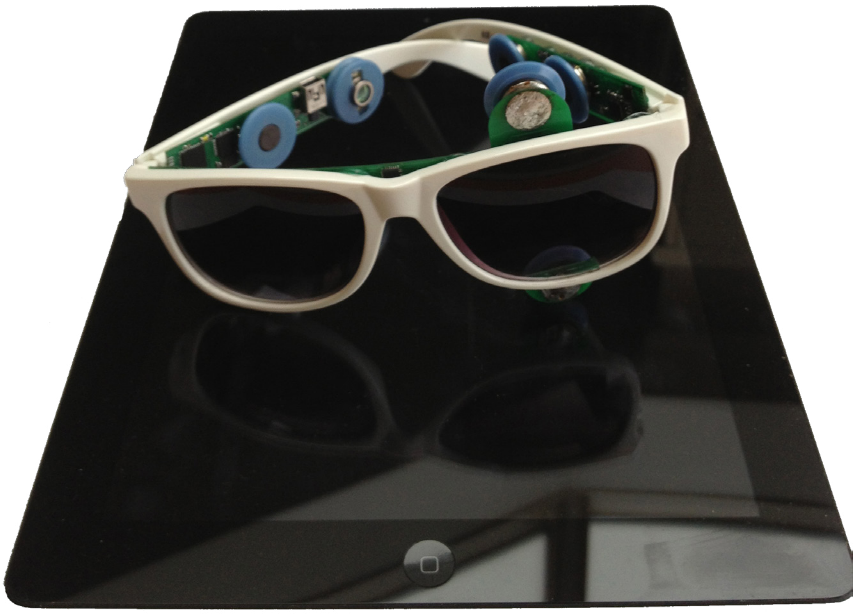
Teye System



Teye Components

ADS1292(1), AFE4490(1), CC430F5137(1), CC2541F256(1), OPA333(4), LM3658(1), TPS62233(1), PCF8574(1)

Introduction

Emerging technologies such as cloud computing and Internet of Things have made a world, which is increasingly connected. The constant progress in the field of vital signal acquisition will take this prevalent trend to the next level. These ubiquitous, intelligent devices will help athletes to break records, patients to be more aware of their disorders, gamers to have a better virtual experience and employees to develop their career. A recent study even found that users of this technology feel more intelligent, self-confident and in control of their lives. Yet, on one hand, a signal acquisition system is only as good as the data it delivers, on the other hand, wearable technology will only achieve acceptance in the mass market if it is unobtrusive and fits as a natural extension of the human body. Therefore, these devices need to be designed for both function and fashion. To reach this level of comfort, such a system needs to be seamlessly integrated in mundane attire such as glasses, shoes, gloves, hats or watches; and communicate with handheld devices that are already omnipresent, such as smartphones and tablets. As an illustration, we designed the T-eyeglasses, a vital signal acquisition system integrated into ordinary sunglasses, which can be remotely controlled by an iOS app. To satisfy the quality requirements as well, we made use of TI's highly optimized, integrated analog front ends and its power-efficient MSP430 architecture.

System Overview

The T-eyeglasses contain three sensor modules, which are managed by a performance-rich and power-efficient microcontroller of the MSP430 platform. This MCU also exhibits elementary signal analysis software to extract physiological parameters out of the recorded vital signals. The first analog front end measures the gaze direction of the eye. And, withal, our intention to measure this parameter justifies the selection of sunglasses as a carrier for our wearable device. Next, electronics are included to measure one of the most important vital signals, namely, heart rate. This signal is mostly obtained by acquiring the electrocardiogram. Yet, we selected an alternative method, which is more conveniently incorporable in the T-eyeglasses. Lastly we went for a recently popular wearable sensor, the inertial measurement unit, to measure head motion. The inclusion of the Bluetooth Smart protocol makes it possible to interface with a smartphone or tablet. This wireless link can be used to communicate the raw vital signals as well as the extracted physiological parameters or to adjust acquisition specifications. Furthermore, power management circuitry is included to optimize autonomy. Fig 1 shows a block-level schematic of the architecture of the glasses. This report will discuss the performance of the selected analog front ends, treat the communication to an iOS handheld device and elaborate about the encountered challenges during system integration. Because wearable devices only are as useful as the purpose they serve, we will finally give an overview ofapplications that can benefit from the T-eyeglasses.

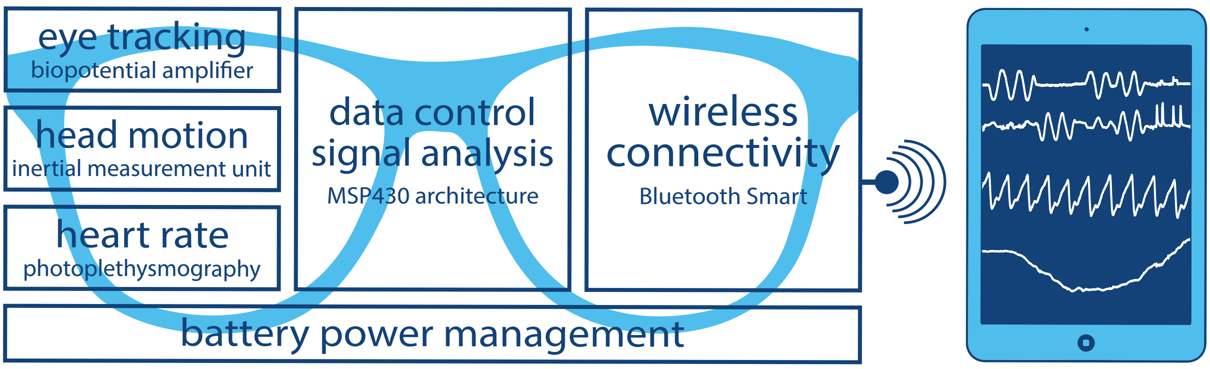
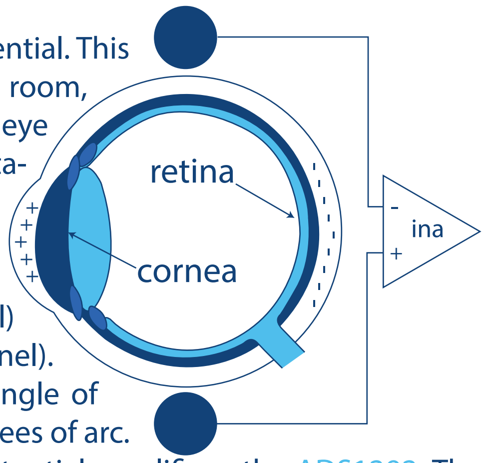


Fig 1: A block-level schematic of the T-eyeglasses

Eye Tracking by Recording Bioelectric Potentials



The eyes are the origin of a steady corneal-retinal potential. This voltage, which is about 6mV in a normally illuminated room, produces a dipole field that can be used to measure eye position. As the eye moves, the dipole changes orientation, causing alterations in the potential field. The electrooculogram (EOG) is the signal measured between two pairs of electrodes, commonly placed above and below the midline of one of both eyes (vertical channel) and on the left and right temple (horizontal channel). There is an almost linear relationship between the angle of gaze and the EOG output up to approximately 30 degrees of arc.

Our system makes use of one of TI's integrated biopotential amplifiers, the ADS1292. The high signal-to-noise ratio and the 24-bit resolution of the on-board A/D-converter enable acquisition of EOG signals, which have an amplitude in the range of hundreds of µV. The amplifier's moderate voltage gain and the integrated right leg drive give the system the capability to deal with drift, which is a common issue in EOG acquisition. Before integrating this component in the T-eyeglasses, its properties are extensively reviewed, using the ADS1292 Demonstration Kit. Fig 2 shows raw EOG data recorded by the T-eyeglasses with a data rate of 125sps. As notable, the systems 50Hz rejection ratio is extremely high. This is not only due to the high CMRR of the ADS1292, but also because of the system itself. The amplifier is placed near the electrodes and is battery powered, as a result, long electrode connections are avoided and power supply interference is minimized. The signal pattern in fig 2 contains three subsequent 10s-intervals in which the subject moves his eyes from left to right, up and down and circularly, and one last interval in which eye blinking is visualized. These are 4 easily recognizable eye gestures that can be used for eye tracking applications.

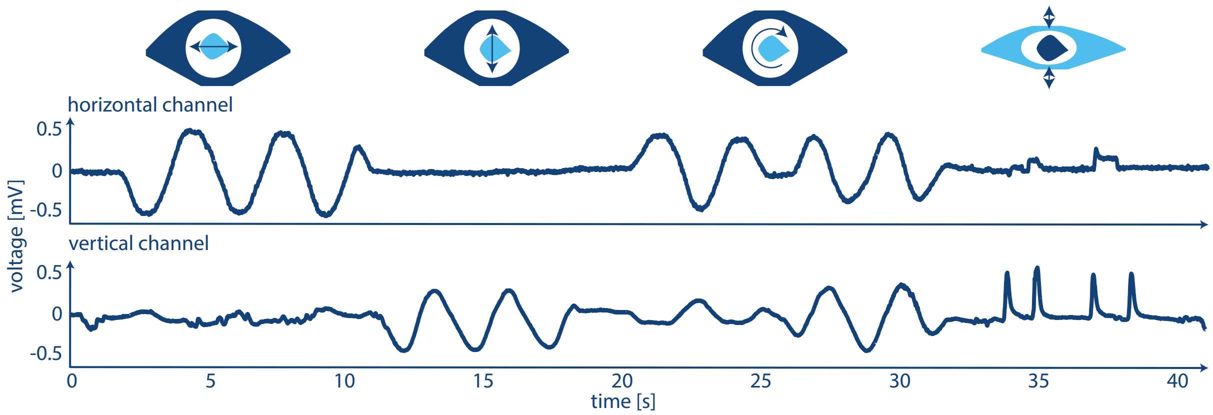


Fig 2: A raw EOG recording with four easily recognisable eye gestures (DR=125sps, G=12).

A powerful advantage of EOG-based eye trackers over current video-based systems is that they require very low computational power. The following signal processing algorithm was first implemented and tested in Matlab, and subsequently embedded in the MSP430 architecture. During an initialization phase the test subject is asked to move his eyes in order to determine the range of possible EOG voltages on each channel. This range can vary among individuals due to anatomical differences. During the eye tracking phase, the horizontal and vertical channel value represent, respectively, the X and Y coordinates of the eye position. Fig. 3 shows the performance of the software, while the test subject was moving his eyes over a predefined circular trajectory. Note that the subject blinked at 1s and 7s, which caused artifacts on the vertical channel and transient deviations from the circular trajectory.

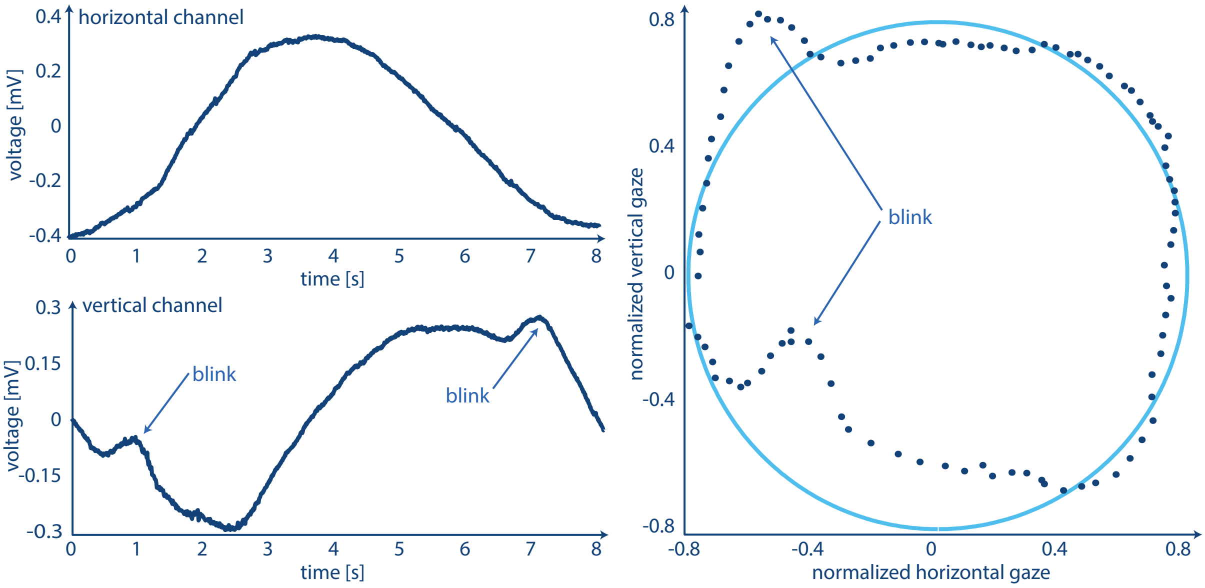


Fig 3: EOG signals and eye tracking, while the subject was following a predefined circular trajectory.

Motion Capture with an Inertial Measurement Unit

Motion interface technology is becoming a prominent part of today's consumer electronics, such as gaming systems, smart TV remotes, step counters and sports monitors. Following this trend, highly accurate, low cost inertial measurement units (IMU) have already found their way into the wearables market. The T-eyeglasses includes an MPU6000 MEMS device of Invensense, which combines a 3-axis accelerometer and a 3-axis gyroscope on the same silicon die. This 6 degrees of freedom motion processing solution can extend our eye tracking algorithm with head motion capturing as well. Also for this sensor we developed a lightweight algorithm, tested in Matlab and optimized to be integrated into the MSP430 architecture. The algorithm smartly combines the double integral of the accelerometer data and the integral of the gyroscope data to extract position. Fig 4 shows the result of the motion capturing technique. In this example the test subject made a slow, circular movement with his head, following a predetermined, circular trajectory displayed on a screen. The IMU was positioned on top of the spectacles, in between both eyes. The two graphs at the left illustrate respectively the three axis of acceleration and the three axis of rotational speed.

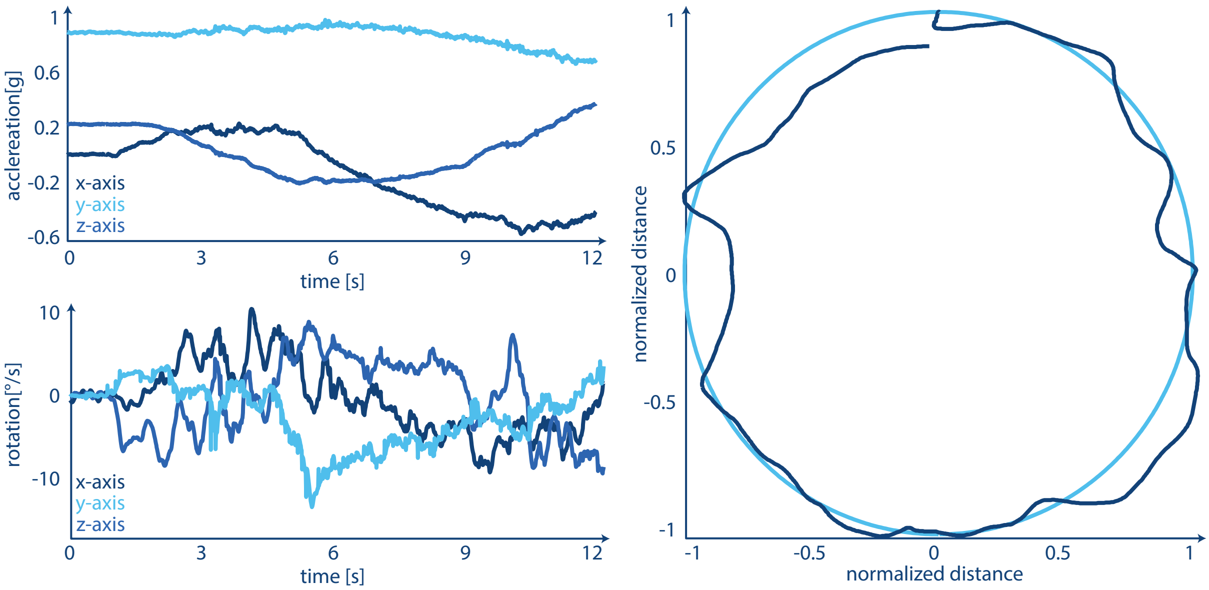
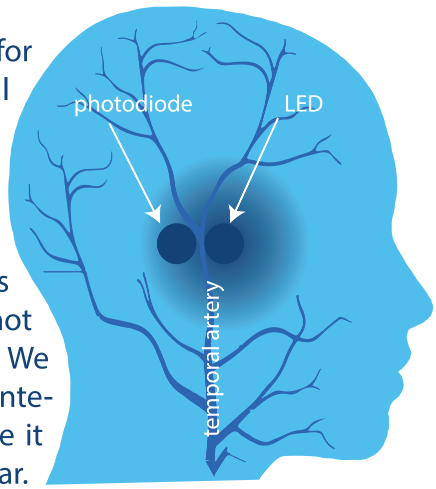


Fig 4: Inertial signals and head tracking , while the subject was following a predefined circular trajectory.

Heart Rate Detection using Photo Plethysmography



In Q1 of 2013, TI introduced the first integrated front end for photometry, the AFE4490. By illuminating a slim peripheral limb and recording the amount of transmitted light, this component can determine the changes in blood volume caused by the cardiac cycle and can thus be used for photoplethysmograph-based heart rate detection. Conventional transmittive photoplethysmography (PPG) goes accompanied with finger cuffs or ear clamps, which are not applicable for long-term, unobtrusive measurements. We developed a sensor, based on reflective PPG. The sensor is integrated into the right temple arm of the spectacles, where it illuminates the superficial temporal artery in front of the ear. The AFE4490 integrates the full photometry front end but leaves us enough configuration freedom to optimize signal quality as well as to reduce power usage. Since we are only interested in heart rate, we used a modest sample rate of 100sps. We fine-tuned the other acquisition parameters, such as the gain and filter values of the receiver channel and the power and timing settings of the LEDs, by using the AFE4490 evaluation module together with its commercially available finger cuff. Next, we selected an off-the-shelf photodiode and LED to be integrated into the T-eyeglasses. In this evaluation phase, we opted for a red LED, but in a later stage a switch to an IR emitter will make this sensor less notable. Fig 5 depicts three PPG signals. These signals are obtained using the T-eyeglasses in combination with the off-the-shelf finger cuff placed around the left index finger, a homemade cuff using the selected photodiode and LED, fixed around the same finger and the homemade reflective PPG sensor, located in front of the right ear. The two latter graphs also contain illumination data, which was not available for the finger cuff. To reduce baseline variations, the signals were high pass filtered. The transmittive signals have a high signal-to-noise ratio. The two peaks, the larger one related to systolic pressure, the smaller one related to aortic valve closure, are clearly visible. As expected, the reflective signal is smaller in amplitude and is deformed. Nevertheless, heart rate can still easily be derived. To estimate this parameter, we developed an algorithm to detect the upper peaks from the PPG, and to compute the rhythm using the average of the peak-to-peak distances of the last ten detected spikes.

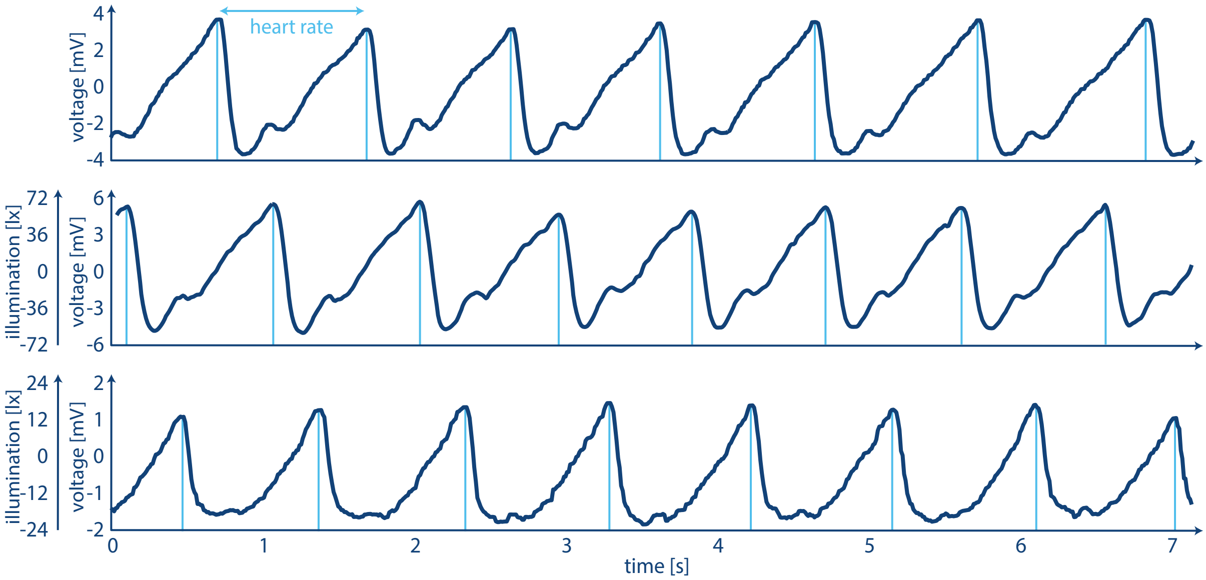


Fig 5: PPG signals of respectivly the commercial finger cuff, the home made finger cuff and reflecitve sensor.

Connecting to the World

Today, apps are getting extended by things you can throw, hold, measure or wear. These so-called appcessories are set to become one of the biggest growth areas of the decade. It's an evolution where devices, carried about by people, are connecting to things in their environment. Nokia already postulated in 2001 that the world could evolve to have a web of a billion phones and a trillion connected devices. This idea re-emerged recently, since Bluetooth Smart, the latest version of the Bluetooth standard, is getting integrated in a multitude of smartphones, tablets and laptops, and is finding it's way into battery powered peripherals. This wireless protocol has specifically been designed to allow all sorts of devices to be connected up to your phone. TI plays an essential role in this evolution by being the industry leader in highly integrated wireless connectivity solutions. One of these solutions, the CC2541 system on chip, is the market's most flexible and cost-effective Bluetooth Smart solution. Moreover TI's SensorTag in combination with the SensorTag App is designed to shorten the design time for Bluetooth Smart app development. To make the T-eyeglasses appcessory-ready, this platform is used as a reference to develop a dedicated iOS app. The T-eye app comprises three screens. The settings screen makes it possible to adjust certain acquisition parameters, the raw data screen shows the measured vital signals and the parameters screen visualizes the extracted information. This screen exhibits a fish in a fish tank, which can be controlled by eye gestures, and shows heart rate. Fig 6 shows screenshots of this app, developed with iOS7 and installed on an ipad mini. While the sensor tag is devel- oped to directly target phone app developers, the CC2541 mini development kit, in combi- nation with BTool and Smart RF Studio, helps hardware engineers to get a better insight into the Bluetooth Smart protocol and the CC2541 system on chip. In case of the T-eyeglasses, the CC2541 is configured as network processor, while the on-board MSP430 MCU, which is much more optimized for low-power solutions, manages the sensor data and contains the profile and application layer. The communication between both devices is handled by means of vendor-specific HCI commands over an SPI interface. We designed and imple- mented a variety of GATT-based profiles and services using the examples given by TI's BLE stack to handle the T-eyeglasses sensors. Because Bluetooth Smart is intended for light duty cycle devices that support small data throughput, the light-weight signal processing algo- rithms, described in the previous chapters, have been integrated into the MSP430 micro- controller. In this way only the relevant, processed data needs to be sent to the master device and the low-power features of the BLE standard can be used to the full.

Fig 6: Screenshots of the T-eye app, designed with iOS7 and installed on an iPAD mini.

Design of the T-eyeglasses

Recently, discrete analog implementations are progressively being replaced by application-specific, integrated analog front ends. These single-chip solutions not only tremendously improve the system's footprint and power consumption but also reduce the time to market by avoiding time-consuming simulations. Moreover, thanks to TI's broad range of well-documented evaluation modules and the E2E-community, their AFEs are straightforward to work with. The design challenges of the T-eyeglasses are, therefore, mainly situated at the system level as will be discussed next. To fit the acquisition system into the spectacles the circuitry is distributed over three printed circuit boards (PCB). One PCB is placed above the frame and serves as a communication bus between the two other PCBs, which are attached to the temples. This frame-PCB (17cmx7mm) also contains the IMU and the top electrode of the vertical EOG channel. The bottom electrode of this channel is attached below the left lens. The left temple-PCB (7.5cmx25mm) consists of the EOG acquisition unit, the left electrode of the horizontal channel, the common-mode feedback electrode and the Bluetooth Smart interface. The right temple-PCB (7.5cmx25mm) includes the reflective PPG sensor and acquisition unit, the power management circuitry, the right electrode of the horizontal channel and the central MCU. Fig 7 illustrates a circuit-level schematic and indicates the used TI components. Because BLE is designed to send small chunks of data instead of signal streams, we chose the CC430F5137 to be our data management MCU. This microcontroller combines the MSP430 architecture with a state of the art CC1101 sub-1-GHz RF tranceiver core. The beauty of this transceiver is that, while it has a highly configureable baseband modem, supporting sophisticating network protocols, such as SimpliciTI, it can also be used for low-level data streams, which is very convenient during testing and development. Also the CC2541 can be used for proprietary RF applications, but because of our positive experience with CC430 we chose it to be merely a Bluetooth network processor.

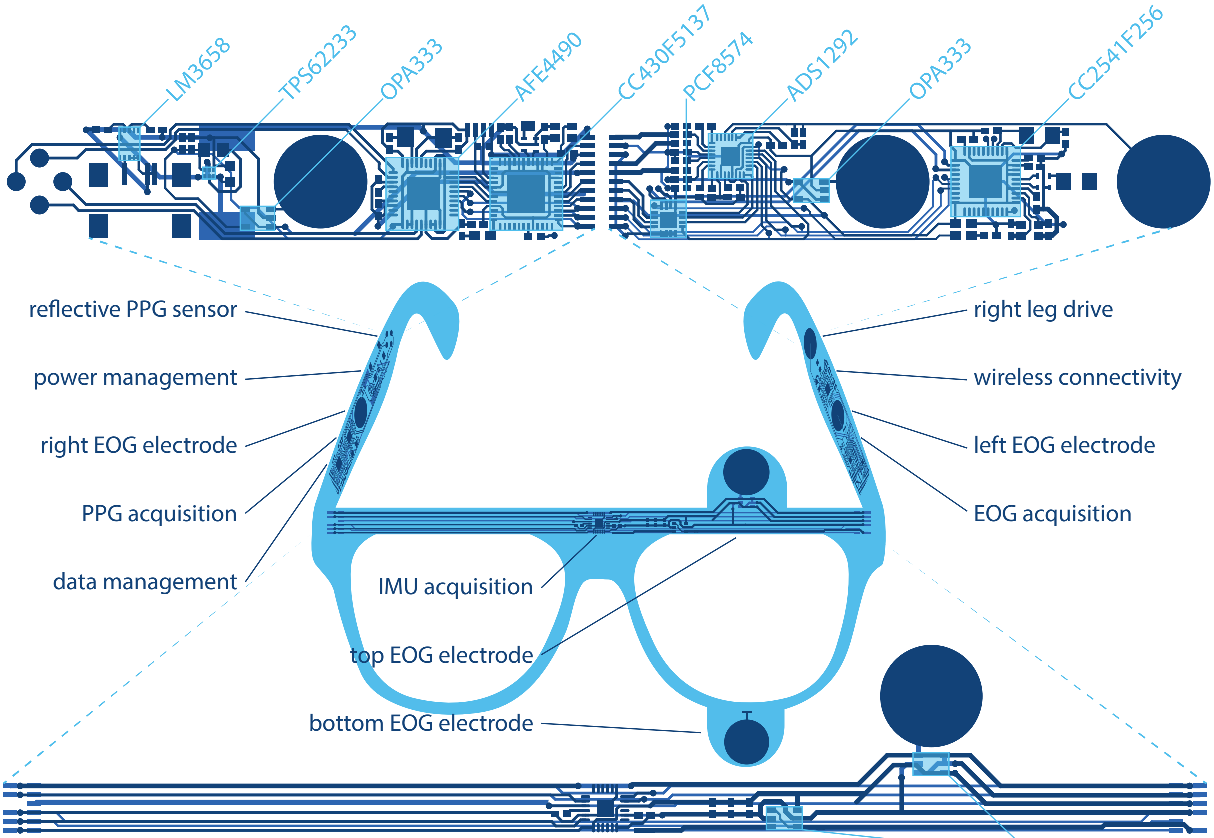


Fig 7: A circuit-level schematic of the T-eyeglasses

The software running on the MCU is written using CCS v5 and is designed in a very modular fashion, such that it is easily adaptable to future appcessory projects. Next to the BLE profile and application layer, it contains a custom made hardware abstraction layer, sensor layer and signal processing layer. The latter contains the different signal processing algorithms. A lot of effort is put in minimizing current consumption by utilizing the MSP430 ULP architecture to the full. The MCU communicates to all peripherals using SPI. The data and clock lines can be shared among all devices, but additionally each device needs a separate chip select and interrupt line. Moreover, the ADS1292 has extra digital pins that need to be linked to the MCU. To limit the number of connections between both temple-PCBs, a PCF8574 I/O-expander is added. This component needs an I2C interface and interrupt line but replaces 8 other I/Os. This device also provides the possibility to easily add new sensormodules in the future. The inputs of a biopotential amplifier have commonly an ultra-high impedance to deal with skin-electrode impedance mismatch and are consequently extremely sensitive to extraneous noise. Therefore, it is highly recommended to keep the digital lines as far as possible from the analog input signals of the ADS1292. In case of the T-eyeglasses, however, we don't have the luxury to do so. We only have one narrow communication bus, containing both analog and digital signals. To cope with this, we implemented OPA333 buffers near each biopotential input electrode to make these lines less susceptable to digital noise. The T-eye- glasses are powered by a rechargeable li-ion polymer battery, GM061752, providing 300mAh@3.7V. This battery seamlessly fits between the right temple and its PCB. The minimum overall supply voltage is 3V, therefore, we use a TPS62233 dc-dc converter, optimized for battery powered portable applications, to reduce the supply voltage. This converter also reduces the current load of the battery during RF communication and thus guarantees a more stable voltage and an increased effective battery life. Lastly, a LM3658 battery charger and a mini usb-connector are added to the design, such that it is possible to recharge the battery using a USB port. Fig 8 shows the finalized T-eyeglasses with its PCB's.

Fig 8: The finalized T-eyeglasses and the three assembled printed circuit boards

A Multitude of Applications

Assistance of physically disabled people is a first field of applications that comes to mind when talking about detecting eye gestures. In the last decade there have been several studies conducted that aimed at helping people with severe motor disorders, such as guiding wheelchairs, facilitating verbal communication and replacing keyboard and mouse functions by using EOG. Also head motion can be used as an input for such brain-computer interfaces. Additionally, heart rate detection can identify risky situations and warn nurses or people close to the patient.

Moreover **automotive** applications can benefit from the T-eyeglasses. Studies have shown that sleepiness can impair driving performance as much or more so than alcohol. Therefore, several car manufacturer studies are focusing on driver drowsiness. Eye and head motion tracking could be used in this case to indicate if the driver is attentive to the road, while heart rate can measure the stress status of the automobilist. This information can be fed back to the chauffeur or can be used to modify ambient conditions such as temperature, lighting and music volume.

EOG is frequently the method of choice for recording eye movements in **sleep research** as well. This signal can be used in order to detect sleep stages such as REM and NREM. In combination with more advanced clinical measurements, such as the electrocardiography and respiration recording, it can help to automatically detect sleep apnea in the hospital. But also commercial sleep applications in a home environment can use our system. Today several apps exist, for instance, to detect the best moment to wake up a person. If we integrate our system into a sleeping mask we can use the data of the three sensor modules to have a quite accurate impression about the person's sleep condition.

Recently, a lot of attention has been given to systems that can improve **gaming** experience by using vital signals as an input. Wii for example introduced the first succesful applications controlled by user's movements. The success of these applications relies in the fact that they do not require extra devices that are foreign to the gamer. Likewise, obtrousive heart rate detection can detect the excitement level of the user and can alter the game accordingly. Eye tracking and head motion detection can be used to adjust the camera angle in the game to the position where the gamer is looking. This will improve the experience of the player by "introducing" him in the game itself.

For **sport applications,** especially the photoplethysmogram can be useful. Heart rate is the most used parameter to indicate the status of athletes. Moreover, our system is easily extentable to measure the arterial oxygen saturation as well. This is another important vital parameter for a sportsperson.

Last but not least, we can use our system for **educational** purposes. Several T-eye members are involved in an annual educational project that introduces children to the world of science in a playful manner. In this workshop, the participants are taught to program a game, which uses their own EOG signals as an input. The T-eyeglasses concept originated from these workshops. The futuristic character of controlling something with your eyes or head and of measuring heart rate with a light source fascinates students and makes it easer to enthuse them to become electrical engineers.

Moreover, because the T-eye glasses are merely a case study and because of its modular mindset, our system can effortlessly be metamorphosed into another appcessory, covering an entire fresh range of applications.

Conclusions

With this project we have demonstrated that vital signal acquisition units can be made more comfortable without losing quality. This is feasible by intelligently integrating the wearable electronics, provided by TI, into existing garments. Moreover, because we anticipate a fully connected world, we adapted our system to be an appcessory, epitomizing the simplicity of the TI SensorTag. While our spectacles themselves are already usable for a diverse range of applications we consider our modular approach during the design phase to represent the paramount innovation in our project. With the MSP430 architecture and the CC2541 BLE interface being the quintessence of wearable technology, our platform can quickly be adapted to multifarious cutting-edge, seamlessly integrated, health appcessories in the future. Our team, being really multifaceted, covers a broad range of hardware as well as software skills. This gives us the opportunity to successfully integrate a mulititude of technology aspects and to present you a promising wearable system: the T-eyeglasses.

Future Work

There are three main points that should be addressed in order to improve the commercial impact of our product. First of all, in this early stage, we built a proof of concept of a wearable acquisition system. Our main focus was hardware and software engineering: selecting the most suitable components, testing the different subblocks, analysing the recorded signals and designing a system which has the abiltiy to be integrated into spectacles. But because aesthetics is paramount in wearable systems, our focus will need to shift to industrial design: making our device easy-to-use, invisible and comfortable to wear. Secondly, at this moment, our product relies on the use of commercially available, wet electrodes. In the future, dry electrodes need to be included, which potentially also has consequences for the data acquisition circuitry. Finally, the MSP430-architecture is designed for ultra-low power and offers the perfect mix of peripherals for sensor acquisition and data managment. Applications that require more robust signal processing techniques, such as eye tracking systems, could benefit from an ARM Cortex-M3/M4 processor, which is the industry-leading processor for highly deterministic real-time applications, delivering high performance.

Acknowledgements

We would like to thank our research groups, ESAT-MICAS and ESAT-STADIUS, for allowing us to pursue this project and grant us access to their facilities for the development of our printed circuit boards, the design of the software, and the measurement of our finalized designs.

Bill of Materials

Name	Component	Description	Mouser Code
MSP	CC430F5137	MSP430 MCU with RF Core	TI free sample
B101	balun 433MHz	433 MHz balun for cc1101	0433BM15A0001E
X101	crystal 26MHz 10ppm	RF clock	732-TX325-26F09Z-AC3
R101	resistor 0402 56kΩ	bias RF current	667-ERJ-XGNJ563Y
R102	resistor 0402 47kΩ	pull-up reset	667-ERJ-XGNJ473Y
C101	capacitor 0402 470nF	decouple Vcore	81-GRM155R61A474KE5D
C102,C103	capacitor 0402 13pF	load capacitor crystal	81-GRM1557U1H130GZ1D
BLE	CC2541F256	BLE system on chip	TI free sample
B201	balun 2.45GHz	2.45GHz balun for CC2541	609-2450BM15A0002E
ANT	antenna 2.45GHz	2.45GHz antenna	609-2450AT18A100E
X201	crystal 32MHz	RF clock	732-FA128-32F20X-K3
X202	crystal 32.768kHz	low power clock	815-ABS07-32.768KHZT
R201	resistor 0402 56kΩ	bias RF current	667-ERJ-XGNJ563Y
C201	capacitor 0402 1μF	decouple Vcore	810-C1005X7S1A105K
C202,C203	capacitor 0402 13pF	load capacitor crystal	81-GRM1557U1H130GZ1D
C204,C205	capacitor 0402 18pF	load capacitor crystal	581-04025A180F
EOG	ADS1292	analog front-end for EOG	TI free sample
OPA1-OPA4	OPA333	buffer	TI free sample
R301	resistor 0402 1MΩ	RLD LPF	667-ERJ-XGNJ105Y
R302-R305	resistor 0402 56kΩ	anti aliasing LPF	667-ERJ-XGNJ563Y
C301	capacitor 0402 1.5nF	RLD LPF	581-0402YC152JAT2A
C302,C303	capacitor 0402 1μF	analog bypass	810-C1005X7S1A105K
C304	capacitor 0402 100nF	decouple reference	810-C1005X7R1H104K
C305	capacitor 0603 10μF	decouple reference	810-C1608X5R1E106M
C306-C307	capacitor 0402 47nF	decouple PGA	810-C1005X8R1C473KEP
C308-C311	capacitor 0402 47pF	anti aliasing LPF	581-04025A470J
EL1-EL5	electrodes	hard plastic wet electrodes	[hospital]
PPG	AFE4490	analog front-end for PPG	TI free sample
X401	crystal 8MHz	internal clock	ABM3-8.000MHz-D2Y-T
C401,C402	capacitor 0402 27pF	load capacitor crystal	581-04025A270J
C403	capacitor 0402 2.2μF	decouple reference	810-C1005X7S1A225K
C404	capacitor 0402 2.2μF	decouple reference	810-C1005X7S1A225K
LED401-LED402	LED 0603 red	PPG LED	604-APT1608SURC
DET401	photodiode	PPG detector	78-BPW21R
IMU	MPU6000	inertial measurement unit	[invensense]
C501	capacitor 0402 100nF	filter capacitor	810-C1005X7R1H104K
C502	capacitor 0402 2.2nF	charge pump capacitor	581-04025C222K
IO-EXP	PCF8574	I/O expander	TI free sample
DCDC	TPS62233	step down converter	TI free sample
CHRG	LM3658	LM3658	TI free sample
USB	USB mini connector	USB mini connector	649-10033526N3212MLF
R601	resistor 0402 10kΩ	pull-down TS	667-ERJ-XGNJ103Y
R602	resistor 0402 10kΩ	bias charge current	667-ERJ-XGNJ103Y
L601	inductor 0805 2.2μH	dc/dc coil	MLZ2012N2R2L
C601	capacitor 0603 10μF	decoupling	810-C1608X5R1E106M
C701-C704	capacitor 0402 100nF	decoupling	810-C1005X7R1H104K
C705-C708	capacitor 0402 1μF	decoupling	810-C1005X7S1A105K
C709-C710	capacitor 0402 2pF	decoupling	581-04025U2R0BAT2A
C711	capacitor 0603 10μF	decoupling	810-C1608X5R1E106M
LED1,LED2	LED 0603 white	indictation LED	720-LWL283Q1R23K8L1Z
R801,R802	resistor 0402 1kΩ	LED bias	667-ERJ-XGNJ102Y
BATT	300mAh Li-ion cell	battery	[powerstream]