TN1571

Technical note

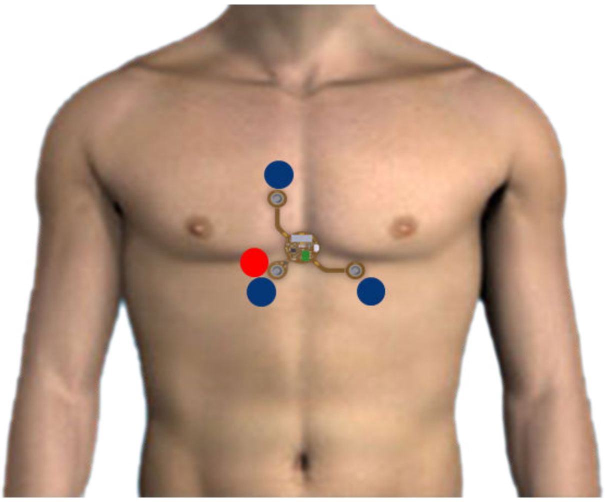
Reference design based on the ST1VAFE6AX and ST1VAFE3BX biosensors for an electronic skin patch used in cardio monitoring

Introduction

This technical note provides details of the STDES-ESP01 reference design that demonstrates the capabilities of the ST1VAFE6AX and ST1VAFE3BX to detect electrocardiography (ECG) and seismocardiography (SCG) signals using an electronic skin patch (eSP). The ST1VAFE6AX, mounted on the board, can also detect the gyrocardiography (GCG) signal enabled by the embedded gyroscope.

Specifically, this document introduces all the materials and electronic components, schematics, and layout for creating a cardio monitoring patch. Figure 1 depicts the positioning of the eSP with three terminals with snap connectors for using standard ECG electrodes. Electrocardiography, seismocardiography, and gyrocardiography biosignals are introduced in the first part of the document, while electronic skin patch functionalities and the bill of materials (BOM) are introduced in the second part of this document.

Figure 1. Electronic skin patch with three electrodes for ECG (blue) and with sensor positioning over the sternum for SCG and GCG (red)



1 Electrocardiography (ECG)

An electrocardiogram is a noninvasive medical test that measures the electrical activity of the heart. It is a valuable tool for diagnosing and monitoring heart conditions. Single-lead ECGs are a simplified version of traditional 12-lead ECGs (10 electrodes), using only two electrodes to capture electrical signals. This makes them more portable and convenient for certain applications, such as home monitoring and activity tracking.

More in general, single-lead ECGs have a wide range of applications including:

- **Home monitoring**: Single-lead ECGs can be used by individuals to monitor their heart health at home. This can help them to identify potential problems early on and seek medical attention if necessary.
- **Activity tracking**: Single-lead ECGs can be used to track heart rate variability (HRV), which is a measure of how well the heart responds to stress. HRV can be used to assess overall health and fitness and to detect early signs of stress and anxiety.
- **Athletic training**: Single-lead ECGs can be used to monitor the heart health of athletes during training and competition. This can help to prevent overtraining and to identify potential cardiovascular problems.
- **Telehealth**: Single-lead ECGs can be used for telehealth appointments, allowing patients to have their ECGs taken remotely by a healthcare provider.

1.1 ECG signal and ST1VAFE6AX sensing channel

The ECG signal is an AC signal with bandwidth of 0.05 Hz to 100 Hz, sometimes up to 1 kHz. It is in the order of amplitude of a few mV affected by several sources of noise as follows:

- High-frequency noise:
  - Motion artifacts
  - Electromagnetic interference (EMI)
  - Electromyographic signals (EMG)
- Low-frequency noise:
  - Body movement
  - Muscle contraction
  - Breathing and respiration
- Common-mode noise:
  - 50/60 Hz powerline noise
  - DC electrode offset potential

The ST1VAFE6AX in the electronic skin patch enables reading the ECG signal as indicated in Table 1, while Table 2 is focused on ST1VAFE3BX.

Table 1. **Features of ECG signal acquisition channel from the ST1VAFE6AX**

Features	
Sampling frequency	240 Hz or 120 Hz if notch filter is active
Selectable notch filter	50 or 60 Hz
High-pass filter	100 mHz high-pass first-order filter

The ST1VAFE3BX in the electronic skin patch enables reading the ECG signal up to 3.2 kHz.

Table 2. **Features of ECG signal acquisition channel from the ST1VAFE3BX**

Features	
Sampling frequency	800 Hz, and up to 3200 Hz when using vAFE channel only
Selectable notch filter	50 or 60 Hz
Programmable gain amplifier	x2, x4, x8, and x16

Further details are available in the product datasheets.

2 Compensating motion artifacts

Correction or compensation algorithms can use the motion information from the ST1VAFE6AX and ST1VAFE3BX, provided by the accelerometer or inertial measurement units (IMUs) to detect and reduce motion artifacts in the ECG signal.

Motion artifacts are undesired electrical signals that can be introduced into a biopotential measurement such as the electrocardiogram (ECG) recording due to user movement. These artifacts can obscure the normal ECG waveform that is in the range of 0.5 mV to 5 mV, making it difficult to interpret and potentially leading to misdiagnosis. Motion artifacts can be caused by a variety of factors, for example in ECG recording they include the following:

- **Breathing**: The expansion and contraction of the chest during breathing can generate electrical signals that mimic the ECG waveform.
- **Muscle movement**: Muscle contractions, such as those caused by walking, talking, or coughing, can also generate electrical signals that interfere with the ECG recording.
- **Body movements**: Any movement of the patient, such as fidgeting or rolling over, can introduce motion artifacts into the ECG recording.

There are two main types of motion artifacts such as high-frequency artifacts (HFA) and low-frequency artifacts (LFA). HFAs are caused by rapid movement and appear as spikes or sawtooth waves on the ECG recording, while LFAs are caused by slow movement or tremors and appear as a wavy or blurred baseline on the ECG recording.

There are several techniques that can be used to detect and reduce motion artifacts in ECG recordings. These include:

- Filtering: Electronic filters can be used to remove high-frequency noise from the ECG signal.
- Adaptive filtering: Adaptive filters can adjust their filtering parameters in real time to minimize the effects of motion artifacts.
- Artifact-removal algorithms: Artifact-removal algorithms can identify and remove motion artifacts from the ECG signal.

3 Seismocardiography (SCG) and gyrocardiography (GCG)

The ST1VAFE6AX system-in-package inertial measurement unit (IMU), featuring a 3-axis digital accelerometer, and the ST1VAFE3BX, featuring a 3-axis digital accelerometer as well, can be used for running seismocardiography tests.

Seismocardiography (SCG) is a noninvasive medical technique that measures the vibrations produced by the heart. These vibrations, called seismocardiogram (SCGs), are caused by the heart's mechanical activities, such as the pumping of blood and the opening and closing of valves. SCGs can be used to assess the overall health of the heart, including its size, function, and structure.

SCG involves placing a small accelerometer on the chest wall. The accelerometer measures the vibrations produced by the heart and converts them into an electrical signal. This signal is then amplified and processed to create an SCG waveform. The SCG waveform is analyzed to identify any abnormalities in the heart's mechanical activity.

SCG has the potential to be a valuable tool for diagnosing and monitoring a wide range of heart conditions, including:

- Heart failure: SCG can be used to assess the severity of heart failure and monitor the response to treatment.
- Valvular heart disease: SCG can be used to assess the function of the heart valves and identify any abnormalities.
- Hypertension: SCG can be used to assess the stiffness of the arteries and monitor the response to treatment.
- Atrial fibrillation: SCG can be used to detect atrial fibrillation, a type of irregular heartbeat.

SCG has several advantages over heart imaging techniques, such as echocardiography and magnetic resonance imaging (MRI). These advantages include:

- Noninvasive: SCG is a noninvasive procedure that does not require the use of radiation or needles.
- Portable: SCG systems can be portable and used in a variety of settings, including clinics, hospitals, and even the home.
- Real-time monitoring: SCG can be used for real-time monitoring of the heart's function.
- Continuous monitoring: SCG can be used for continuous monitoring of the heart's function over time.

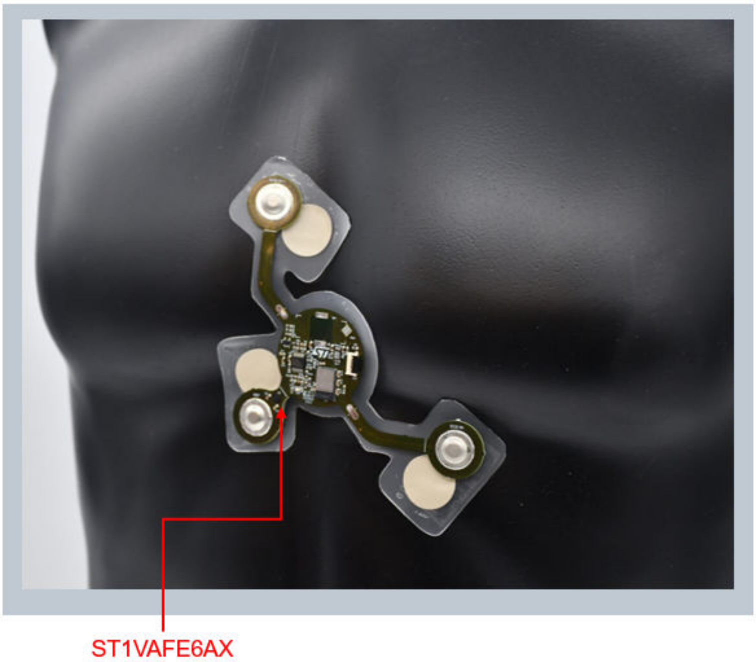
The ST1VAFE6AX and ST1VAFE3BX in the electronic skin patch enable running the SCG. The recommended positioning of the sensor is to stay as close as possible to the sternum as depicted in Figure 2.

Gyrocardiography (GCG) is a new noninvasive technique for assessing heart motions by using a sensor of angular motion (a gyroscope) attached to the skin of the chest. This technique is implementable using the embedded gyroscope provided by the ST1VAFE6AX sensor as well.

Refer to the following article for further details or contact ST sales and marketing.

Jafari Tadi, M., Lehtonen, E., Saraste, A. *et al.* Gyrocardiography: A New Non-invasive Monitoring Method for the Assessment of Cardiac Mechanics and the Estimation of Hemodynamic Variables. *Sci Rep* **7**, 6823 (2017). https://doi.org/10.1038/s41598-017-07248-y

Figure 2. Sensor positioning over the sternum for SCG and GCG detection

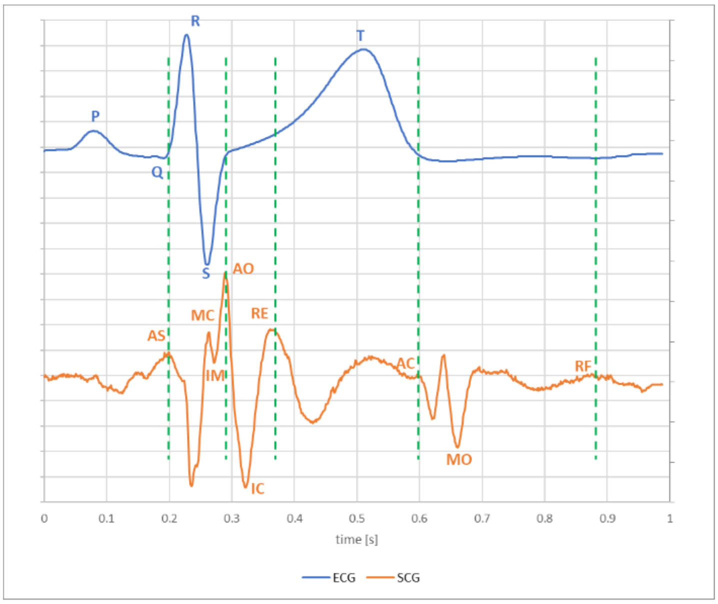


4 Synchronization of ECG and SCG and context-aware vital signs monitoring (VSM)

ECG and SCG channels can be run in parallel, enabling the computation of healthy indicators on single channels, or heart conditions based on the parameters extracted using both channels.

Figure 3 is an example of synchronized acquisition of ECG and SCG with all the annotated points labeled. The ST1VAFE6AX is positioned over the sternum as indicated in Figure 1 (red circle).

Figure 3. **ECG and SCG filtered signals acquired in parallel by the ST1VAFE6AX**



AS: Atrial Systole
MC: Mitral valve Closure
IM: Isovolumic Moment
AO: Aortic valve Opening
IC: Isovolumic Contraction
RE: Rapid ventricular Ejection
AC: Aortic valve Closure
MO: Mitral valve Opening
RF: Rapid diastolic Filling

The parallel and synchronized acquisition of both channels by the same device on the same timing enables:

- Recording the single-lead ECG
- Extracting heart condition indicators such as heart rate and heart rate variability by processing the ECG signal
- Recording the SCG
- Extracting heart condition indicators by processing the SCG signal
- Extracting heart condition indicators based on both channels with high accuracy
- Using motion information for compensation and correction purposes
- Using motion sensors for context-aware measurements of vital signs

Regarding the context-aware measurements of vital signs, you can refer to the following application notes:

- AN6120 ST1VAFE6AX: biosensor with vAFE (vertical analog front-end) for biopotential signals and 6-axis IMU (inertial measurement unit) with AI and sensor fusion
- AN6155 ST1VAFE6AX: finite state machine
- AN6161 ST1VAFE6AX: machine learning core
- AN6160 ST1VAFE3BX: biosensor with vAFE (vertical analog front-end) for biopotential signals and ultralow-power accelerometer with AI and antialiasing
- AN6207 ST1VAFE3BX: finite state machine
- AN6208 ST1VAFE3BX: machine learning core

Some examples of context-aware functionalities include:

- ECG, heart rate, and heart rate variability interpretation based on user activity
- ECG healthy or status indicators used for triggering other kinds of measurements (for example, a heart rate increase triggers the user activity detection)

- Event-based measurements:
  - ECG acquisition and analysis at a periodic number of human steps
  - Increase the ECG analysis frequency depending on the detected user activity (for example, bicycling)
  - Free-fall detection triggers continuous ECG recording and analysis

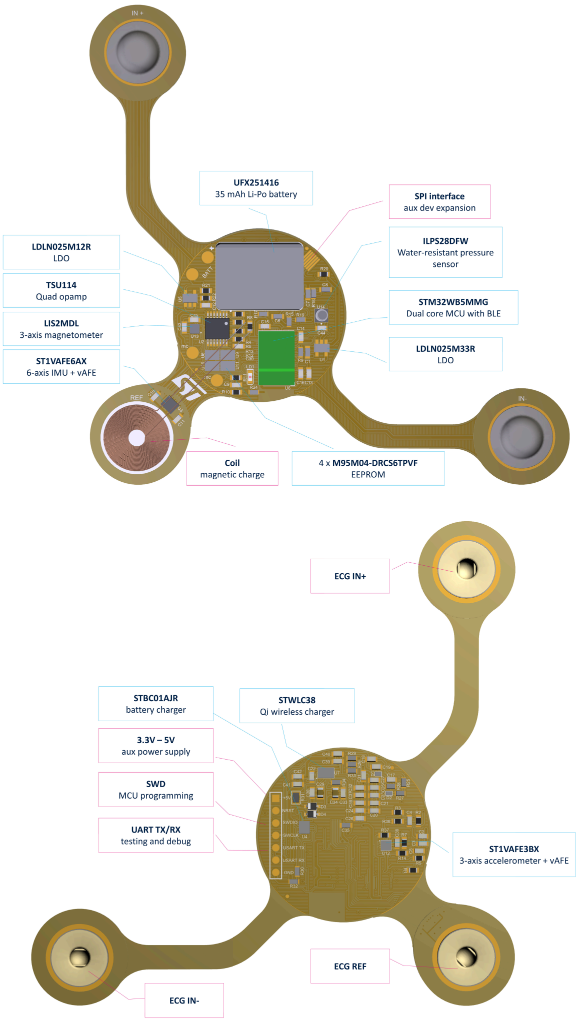
Contact ST sales and marketing for further details.

5 eSP system architecture

Figure 4 illustrates the system layout with key components as follows:

- STM32WB5MMG, an ultralow-power, dual-core, and small form factor certified 2.4 GHz wireless module
- ST1VAFE6AX, biosensor embedding a vAFE channel to detect biopotential signals and a 6-axis IMU featuring a high-performance 3-axis digital accelerometer and 3-axis digital gyroscope for motion tracking.
- ST1VAFE3BX, biosensor embedding a vAFE channel to detect biopotential signals and a 3-axis digital accelerometer
- TSU114, ultralow-power consumption operational amplifiers (op-amp)
- LIS2MDL, ultralow-power high-performance 3-axis magnetic sensor
- ILPS28DFW, ultracompact piezoresistive absolute pressure sensor
- LDLN025M33R and LDLN025M12R, ultralow noise LDO
- M95M04, electrically erasable programmable memory (EEPROM)
- STWLC38, integrated wireless power receiver
- STBC02AJR, integrated power management device
- UFX251416, lithium-ion polymer battery

Figure 4. Front and back of the electronic skin patch with key components



5.1 Encapsulation process and electrodes

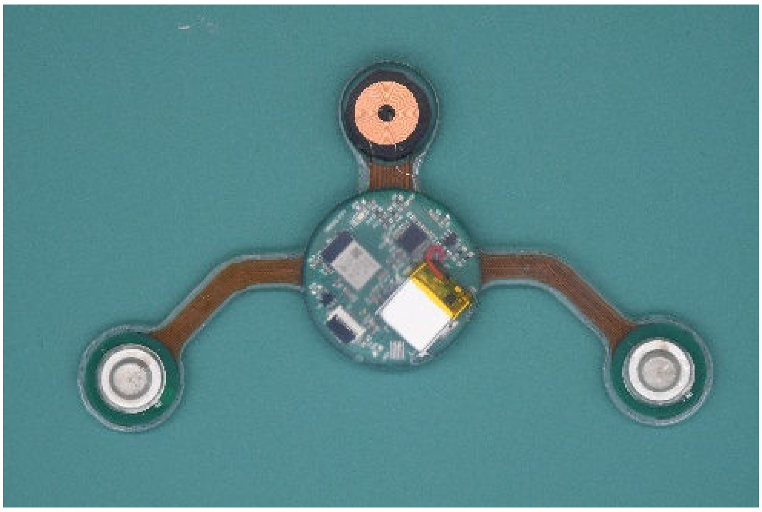
In the electronic skin patch, either dry or gelled ECG electrodes can be used to read the ECG. Gelled electrodes are made of a conductive material that is coated in a conductive gel. The gel helps to improve conductivity by providing a low-resistance path between the electrode and the skin. Dry electrodes are made of a conductive material, such as silver or silver-plated stainless steel that is attached directly to the skin. They do not require any additional gel or paste to improve conductivity. The following table summarizes the main differences between these two types of electrodes.

Table 3. **Dry vs. gelled electrodes**

Feature	Dry electrodes	Gelled electrodes
Requires gel	No	Yes
Skin impedance	Higher	Lower
Motion artifact susceptibility	Higher	Lower
Skin irritation	Lower	Higher
Comfort	More comfortable	Less comfortable

The electronic skin patch is encapsulated to be water resistant, more flexible, and resistant to sustain human body movements without compromising the ECG signal with motion artifacts. Figure 5 shows the board encapsulated by liquid silicone rubber using materials and processes made by DuPont^{TM} Liveo^{TM}.

Figure 5. **Encapsulated electronic board**



The silicon rubber encapsulated board is connected to a *skin adhesive layer* developed and manufactured by DuPont™ Liveo™ Healthcare. The adhesive layer integrates snap electrodes based on DuPont™ Liveo™ Soft Skin Conductive Tape 1-3150 technology and other adhesive materials selected from a broad range of Liveo™ PSA (pressure sensitive adhesive) and SSA (soft skin adhesive) DuPont proprietary technologies to adapt to various skin conditions and wearing times. The skin adhesive layer with three dry electrodes integrated is currently in prototype phase (Figure 6).

Figure 6. Skin adhesive layer with conductive tape

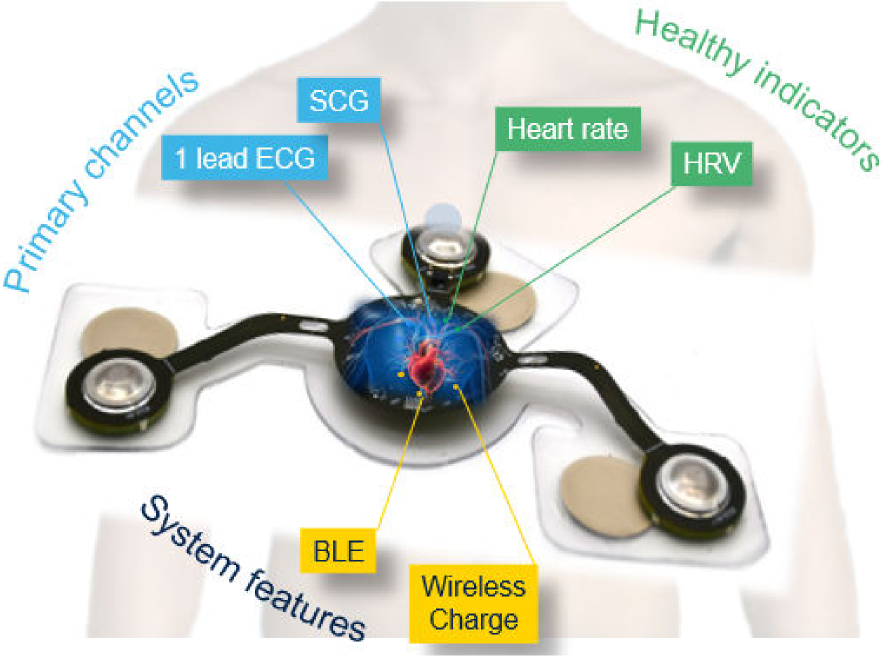
The electronic board can be used with any type of electrodes such as gelled electrodes, hard dry conductive electrodes, and dry flexible electrodes as well.

Contact STMicroelectronics and DuPont for more details and information.

6 System features

The eSP offers a microcontroller with embedded BLE connectivity feature and wireless charging.

Figure 7. **esP offering primary channels, system features, and healthy indicators**



Regarding the BLE, the STM32WB5MMG is used as an ultralow-power, dual-core, and small form factor certified 2.4 GHz wireless module. BLE is used for connecting the patch with a client (for example, a mobile phone) able to run commands on the eSP itself:

- Either for real-time data transfer
- Or for downloading the ECG or SCG raw data, extracted features, or system information stored in the microcontroller flash memory in the client application

BLE commands from the client are even used for changing the operating modes (continuous ECG monitoring, periodic ECG monitoring, on-demand monitoring, event-driven monitoring) or other configurations of the system features.

Double-tap detection over the patch (chest) by the ST1VAFE6AX is used for activating the BLE pairing. The eSP activates the BLE pairing for a predefined time window. If there are no clients that can establish a BLE connection, then the BLE pairing mode is closed, otherwise the connection is established, and the commands are sent from the client to the server (patch).

Finally, regarding wireless charging (WC), the STWLC38 is used as an integrated wireless power receiver suitable for wearable/hearable and smartphone applications.

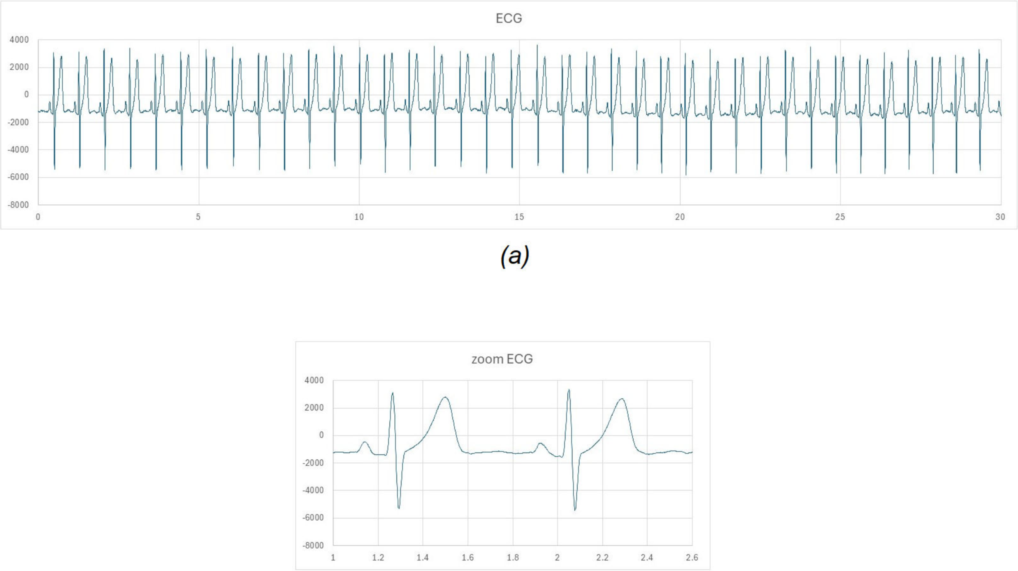
The role of WC is fundamental because patches very often are designed without any means for battery charging through connectors and wires.

The STDES-WBC86WTX reference design based on the STWBC86 for wireless power transmitter application can be considered as a WC power station.

7 ECG signal

ECG signal acquisition using the electronic skin patch with ST1VAFE6AX enabled is illustrated in the following figure.

Figure 8. **(a) ECG signal acquired by ST1VAFE6AX; (b) zoom of ECG signal**



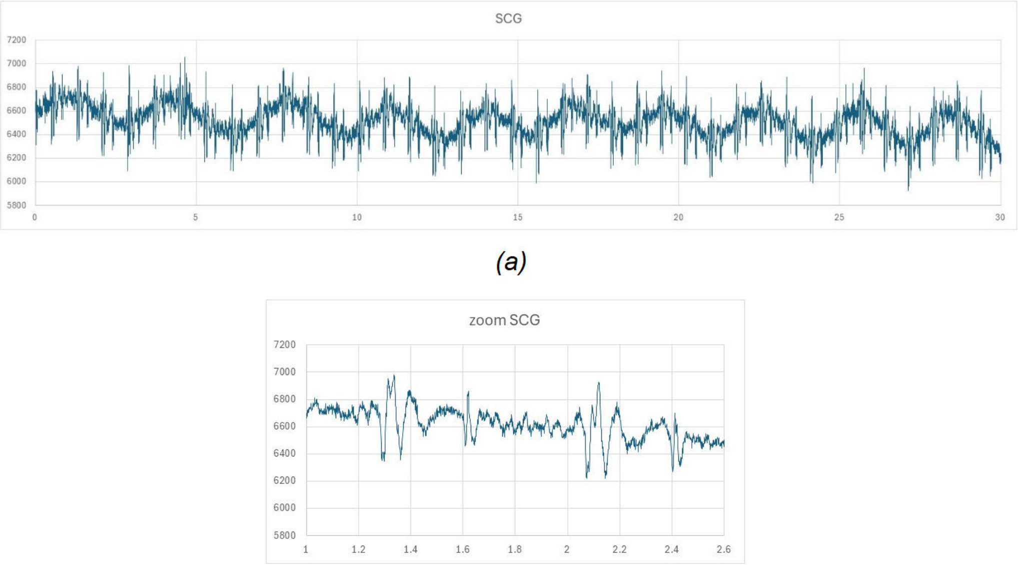
(a)

(b)

All waves P, W, R, S, T, and U are visible by using a sampling rate of 240 Hz. This resolution is optimal for getting an ECG signal with a good resolution for computing with precision heart rate and heart rate variability features.

The following figure illustrates an SCG signal acquisition at 960 Hz sampling rate using the electronic skin patch with ST1VAFE6AX enabled.

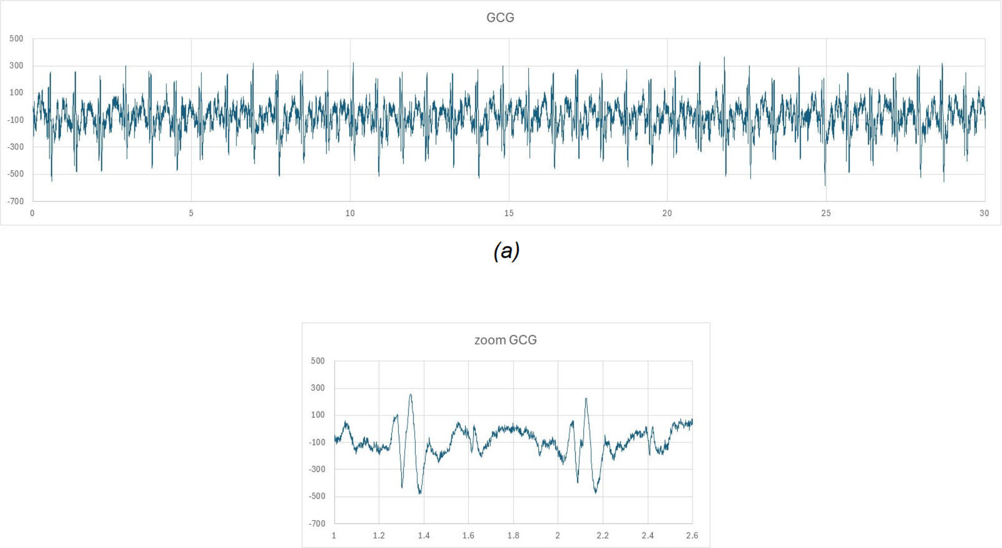
Figure 9. **(a) SCG signal acquired by ST1VAFE6AX; (b) zoom of SCG signal**



(a)

(b)

Figure 10. **(a) GCG signal acquired by ST1VAFE6AX; (b) zoom of GCG signal**

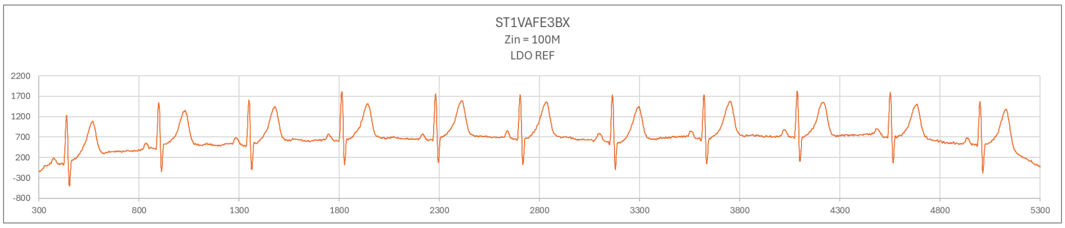


(a)

(b)

ECG signal acquisition using the electronic skin patch with ST1VAFE3BX enabled is illustrated below.

Figure 11. **ECG signal acquired by ST1VAFE3BX**



All waves P, W, R, S, T, and U are visible by using a sampling rate of 800 Hz. This resolution is optimal for getting an ECG signal with a good resolution for computing with precision the heart rate and heart rate variability features, and also for performing ECG morphology analysis for detection and classification of anomaly patterns.

8 Configuration of ST1VAF6AX registers

Common

Write 0x00 in reg 0x08	// Set uncompressed FIFO mode
Write 0x44 in reg 0x12	// Enable BDU and auto register increment, in multiple reads
Write 0x06 in reg 0x0A	// Set FIFO continuous mode
Write 0xBC in reg 0x16	// Enable AFE channel, set input impedance = 220 MOhm
Write 0xE0 in reg 0x17	// Configure accelerometer high-pass filter (f = 1.2 Hz), set FS = ±2 *g*
Write 0x10 in reg 0x18	// Enable accelerometer high-pass filter
Write 0x04 in reg 0x0B	// Put AFE data in FIFO to enable ECG

ECG mode

Write 0x00 in reg 0x10	// Set accelerometer in power-down
Write 0x00 in reg 0x11	// Set gyroscope in power-down
Write 0x00 in reg 0x09	// No accelerometer and gyroscope in FIFO

ECG + SCG mode

Write 0x09 in reg 0x09	// Put accelerometer in FIFO
Write 0x09 in reg 0x10	// Set accelerometer ODR = 960 Hz
Write 0x00 in reg 0x11	// Set gyroscope in power-down

ECG + SCG + GCG mode

Write 0x99 in reg 0x09	// Put accelerometer and gyroscope in FIFO
Write 0x09 in reg 0x10	// Set accelerometer ODR = 960 Hz
Write 0x09 in reg 0x11	// Set gyroscope ODR = 960 Hz

9 ST1VAF6AX data readout

Get N = number of unread samples in FIFO

Read 2 bytes starting from reg 0x1B and copy them in *data_L* and *data_H*

N = *data_L* + (*data_H* & 0x01) * 256

Get FIFO data

Read 7 bytes starting from reg 0x78 and copy them in the array *DATA*

Extract data TAG which identifies the sensor channel:

TAG = *DATA*[0]// TAG = [0x01: gyroscope; 0x02: accelerometer; 0x1F: vAFE]

Extract and rebuild the sensor data based on *TAG*:

X = two's complement of (*DATA*[1]) | (*DATA*[2] << 8) // vAFE or X-axis of gyroscope or accelerometer
Y = two's complement of (*DATA*[3]) | (*DATA*[4] << 8) // Y-axis of gyroscope or accelerometer
Z = two's complement of (*DATA*[5]) | (*DATA*[6] << 8) // Z-axis of gyroscope or accelerometer

10 Configuration of ST1VAFE3BX registers

```
Write 0x08 in reg 0x13          // Enable data batching in FIFO
Write 0x06 in reg 0x15          // Set FIFO continuous mode
Write 0x06 in reg 0x31          // Set 100 MΩ impedance, input gain = 16
Write 0x04 in reg 0x12          // High-performance mode
Write 0x10 in reg 0x10          // Automatic register address increment in multiple R/W operations
Write 0xBC in reg 0x14          // ODR = 800 Hz, BW = 45 Hz
Write 0x01 in reg 0x47          // Enable decimation /2 in FIFO (vAFE data stored is at 400 Hz)
```

11 ST1VAFE3BX data readout

Get N = number of unread samples in FIFO

N = content of reg 0x27

Get FIFO data

Read 7 bytes starting from reg 0x40 and copy them in the unsigned 16-bit integer array *DATA*

Rebuild the vAFE data as follows:

vAFE_data = two's complement of (*DATA*[6] << 4) | (*DATA*[7] << 8)

12 Bill of materials

Table 4. **Bill of materials**

Designator	Description	Footprint	Quantity	Manufacturer	Manufacturer code
U1	IC REG LINEAR 3.3 V 250 MA	SOT-23-5L	1	STMicroelectronics	LDLN025M33R
U2	Quad OpAmp	TSSOP-14	1	STMicroelectronics	TSU114IPT
U3	vAFE with 6-axis IMU	14-WFLGA	1	STMicroelectronics	ST1VAFE6AX
U4	Battery charger	30-UFBGA, FCBGA	1	STMicroelectronics	STBC02AJR
U5	IC REG LINEAR 1.2 V 250 MA	SOT-23-5L	1	STMicroelectronics	LDLN025M12R
U6	STM32 BLE module based on STM32WB55	86-LFLGA	1	STMicroelectronics	STM32WB5MMGH6TR
U7	Magnetic wireless charger	40-UFBGA, WLCSP	1	STMicroelectronics	STWLC38
U8, U9, U10, U11	IC EEPROM 4 MBIT SPI 10 MHZ 8WLCSP	8-UFBGA, WLCSP	4	STMicroelectronics	M95M04-DRCS6TPVF
U12	vAFE with 3-axis accelerometer	LGA-12L	1	STMicroelectronics	ST1VAFE3BX
U13	3-axis magnetometer	12-VFLGA	1	STMicroelectronics	LIS2MDLTR
U14	Water-resistant pressure sensor	6-CLGA	1	STMicroelectronics	LPS28DFWTR

Revision history

Table 5. **Document revision history**

Date	Version	Changes
07-Feb-2025	1	Initial release

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