Energy Efficient Heart Rate Sensing using a Painted Electrode ECG Wearable

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Objectives

Overview IoT in healthcare initiatives in the UK and how we align with these

Motivate the need for and benefit of wearable sensors for IoT in healthcare

Demonstrate a wearable ECG unit with more than one month of battery life
Ageing of the global population is unprecedented and the existing medical system will soon not be able to meet this increasing demand.

Therefore the use of emerging digital technologies for healthcare monitoring is essential.

Our aim is to impact a range of healthcare needs by employing data-fusion from a common platform of largely non-medical networked sensors in a home environment.
Our contribution: Smart sensors

- Biological world
  - Brainwaves
  - Heart rate
  - Gait

- Electronic world
  - Smartphones
  - PCs
  - Internet
  - mHealth
  - Big Data
  - Internet of Things

- Wearable sensor node
  - Interface / Electrode
  - Signal conditioning
  - Online signal processing
  - Wireless link
  - Power delivery (Battery or energy harvesting)
  - Feedback / treatment
Smart sensors in Manchester

CASSONlab

Biological world

Electronic world

Wearable sensor node

Brainwaves
Heart rate
Gait

Interface / Electrode

Signal conditioning

Online signal processing

Power delivery (Battery or energy harvesting)

Wireless link

Feedback / treatment

Smartphones
PCs
Internet

mHealth
Big Data
Internet of Things

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The SPHERE Platform:

- Activity monitoring via accelerometers (& others)
- Temperature, light levels, humidity, air-quality
- Video: Emotion, gait, activity, interaction
- Base-station, +social media, +encryption
- Water consumption, electrical consumption
- Data display
- Analysis, pattern extraction, feature extraction

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On-body sensors

- Our vision is to develop a robust, energy efficient and user acceptable wireless communication system, consisting of:
  - one (or multiple) on-body wearable sensor(s) (e.g. accelerometer), and
  - an in-house network of access points.

- The system will provide real-time information regarding physical activity and localisation.

- The on-body node will ideally be powered using energy harvesting techniques.

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Home Gateway
Intel NUC i5 running SPHERE software:
Data collection from sensor systems and real time classifier implementation.
Person-identification algorithm.
Raw data stored on encrypted SSD.

SPHERE Gateway
SPHERE hardware & firmware
BLE and 802.15.4 receivers.
ARM M3 processor.
Mains powered.

Wristbands:
SPHERE hardware:
TI CC2650 integrated circuit.
Dual accel. and gyro, ARM M3.
SPHERE firmware:
Implement BLE or TSCH MAC.
Battery power. Qi Wireless charging.

Environmental Sensors
SPHERE hardware:
TI CC2650 integrated circuit.
PIR, temperature, light, humidity
SPHERE firmware:
Implementing 802.15.4 TSCH & RPL mesh network.
Battery power (1 year life)

ASUS Xtion depth cameras
connected to Intel NUC i5
running SPHERE software
Implementing real time tracking, bounding box, silhouette, appearance and biometric feature calculation

Summaries and diagnostics sent via 3G/4G to SPHERE control centre.
For liability reasons in this context, raw data physically collected on SSD.

802.11ac network
extracted features
control signals

802.15.4 TSCH &
6LoWPAN/RPL mesh network. raw sensor data

SPHERE GUI
For homeowner
On/Off
Delete Data
Data visualisation

Off the Shelf CurrentCost
Appliance Monitoring

Off the Shelf water sensor
connected to SPHERE wireless solution
Example of SHERE IoT enabled house

• Items per system
  • 1 x Router 4G / 3G, WiFi
  • 4 x Gateway Raspberry Pi 3 (built in WiFi and BLE)
  • 1 x Wristband SPHERE (BLE, ADXL362, 4Gb FLASH)

• The Router and Gateways are fixed and the Wristband is worn by the participant
  • Charge when showering

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Motivation for this work

Want to integrate heart monitoring into this platform

PPG is common in smart watches, and great, but:

- High power due to light source.
- Difficult to extract heart rate variability.
- Less clinically relevant information than the ECG.
- Not integrated with IoT infrastructure.
Our aim

We aim to make a wrist worn ECG device

- Lower power as no light source.
- Very light weight.
- ECG waveform allowing heart rate, heart variability, and other measures to be extracted.
- More healthcare relevant information than just PPG.
- Integrate with SPHERE IoT infrastructure.
Design requirements

**Power:**
- 1 month battery life
- 10 μW power consumption, 1.8 V supply

**Data:**
- Ability to extract HR and HRV
- Accuracy of a few BPM

**Safety:**
- 18 μA max fault current into user
Challenge of wearable ECG

Single wrist (5x zoom)

Upper arm (5x zoom)

Chest

Both wrists

500 μV

0.5 s
Final system

Electrodes on both sides of body to get large signal size

Painted electrode

PPG reference

SPHERE board

ECG board

SPHERE ECG
Electrodes

Medical grade Silver/Silver Chloride electrodes painted on

Allows size and shape personalisation

3D print for more complicated shapes and personalisation

Painted electrode

Bumps for penetrating hair
Front-end circuit design

User connection and safety

Bias

Electrode 1
- R1: 10 MΩ
- 100 kΩ
- 120 kΩ
- C1: 100 nF
- 120 kΩ

Electrode 2
- 100 kΩ
- 120 kΩ
- C2: 100 nF
- 120 kΩ

High input impedance buffers

LPV542

Difference amplifier, gain 33

LPV542

Second order low pass filter,
30 Hz cut-off

To ADC on SPHERE board

Biasing network

1.8 V

R2: 1 MΩ

R3: 1 MΩ
SPHERE wearable

- Based on TI CC2640
- Bluetooth low energy wireless transmission
- Local SD card memory
- 100 mAh rechargeable Li-ion battery
- Qi wireless charging
- ADXL 3-axis accelerometer

- We use the TI sensor controller for low power ADC and data storage without waking main MCU.
Software

Two options for communication

‘Connected’ state

✓ All data transmitted over BLE.
✓ Allows online and offline signal analysis in basestation.

‘Not-connected’ state

✓ Heart rate calculated on the wearable.
✓ Just heart rate information transmitted.
✓ Low data rate means data can be included in the BLE advertising packets.
✓ Reduces power significantly if full ECG trace is not required.
System performance

Raw data shows clear heart beats

This is before standard ECG processing for noise removal

Deliberately high noise floor to keep power low
Comparison to a reference PPG

Methods for offline comparison of data

1. Raw ECG data filtered: Butterworth first order low pass, highpass and notch
2. Baseline wander removed with Discrete Wavelet Transform
3. Noise removed from ECG using extended Kalman filter
4. Heart beats detected using standard Pan-Tompkins algorithm
5. Heart rate calculated from beat timings
6. Kalman tracking filter applies with zero-order-hold model to smooth heart rate when incorrect (missing and/or additional) beats detected

Compare heart rate to that from a commercial PPG device
## System performance

Accurate to within a few beats to minute

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<th>Record</th>
<th>Mean difference (BPM)</th>
<th>Standard deviation (BPM)</th>
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<td>4.02</td>
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<tr>
<td>Mean</td>
<td>4.56</td>
<td>3.23</td>
</tr>
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</table>

Note: We estimate the reference PPG device is accurate to 2 bpm
System power consumption

Connected mode:

Quiescent: 11.3 μA
System power consumption

If measure heart rate for 30 s every hour this gives an average current draw of 86 µW

Gives 48 days battery life from a miniature 100 mAh battery

Step change for a wrist worn ECG IoT device weighing only 29 g
Future steps

✓ Improve signal quality further
✓ Use electrodes to provide touch input to the wearable
✓ Add 3 electrode design
✓ Use capacitive driven right leg
Summary

30 g ultra low power ECG unit

Integrates with UK IoT smart home demonstrator

Battery life >1 month

Personalisable electrodes

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