ECG Feature Extraction based on Joint Application of Teager Energy Operator and Level-Crossing Sampling

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Agenda

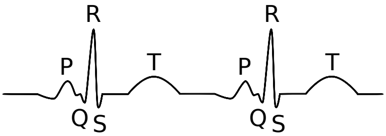
- Continuous health monitoring
- Study of arrhythmia detection algorithms within a CardiaCare project
- Arrhythmia detection algorithms are heavily rely on features extracted from electrocardiogram recordings
- Teager energy operator is an easy-to-compute tool for peak emphasizing
- Level-crossing resampling allows to detect peak areas
- Joint application of Teager energy operator and level crossing sampling resulted in high QRS detection performance

Motivation

- 31% of all global deaths in 2012[1]
- Contribution of CVDs to mortality in CIS (percents)

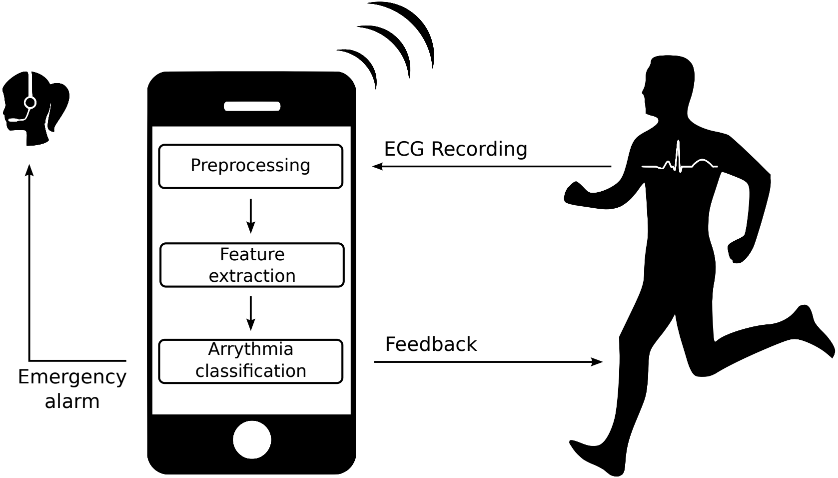
Georgia	67
Ukraine	64
Azerbaijan	60
Russia	57
Moldova	56
Belorussia	53
Kazakhstan	50
Armenia	50
Kyrgyzstan	49
Tajikistan	39

- Can be prevented by addressing behavioural risk factors (tobacco use, unhealthy diet, obesity, physical inactivity, etc.)
- Need early detection and management
- Can be done based on ECG analysis



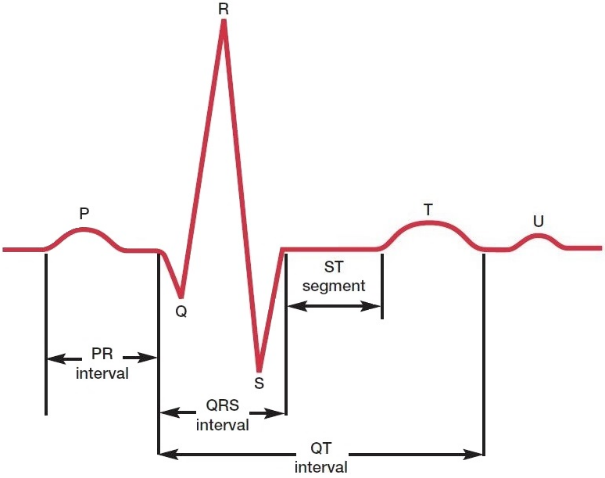
[1] Source: WHO

Arrhythmia detection based on continuous monitoring



ECG Morphology

We are interested in R peaks and QRS complexes.

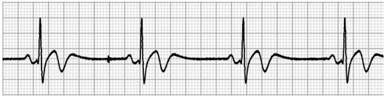


Significance of confident R peak detection

- Normal sinus rhythm

- Sinus tachycardia

- Sinus bradycardia



- Sinoatrial block

- Atrial flutter

- Wolff-Parkinson-White syndrome

Source: Medical Training and Simulation LLC
http://www.practicalclinicalskills.com

Teager-Kaiser energy operator based approach

From Hooke's law the second order differential equation can be deduced by means of Newton's second law to describe the simple harmonic motion as

$$F = \frac{d^2x}{dt^2} + \frac{k}{m}x = 0 \tag{1}$$

The solution to equation is given by

$$x(t) = A\cos(\omega t + \phi) \tag{2}$$

where $x(t)$ is the position of the object at time t, A is the amplitude, ω is the frequency, and ϕ is the initial phase. The total energy of the object is given as the sum of kinetic energy of the object and the potential energy of the spring, given by

$$E = \frac{1}{2}kx^2 + \frac{1}{2}m\dot{x}^2 \tag{3}$$

By substituting $x(t) = A\cos(\omega t + \phi)$, we get the following expression for the energy:

$$E = \frac{1}{2}mA^2\omega^2 \tag{4}$$

Teager-Kaiser energy operator based approach (cont.)

Now we consider the continuous-time form of Teager energy operator defined to be

$$\Psi_c[x(t)] = (\dot{x}(t))^2 - x(t)\ddot{x}(t) \tag{5}$$

Substituting $x(t) = A\cos(\omega t + \phi)$, we obtain

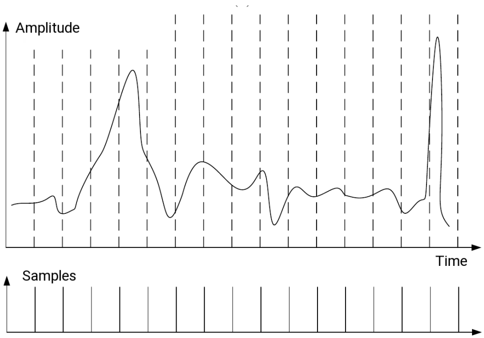
$$\Psi_c[x(t)] = A^2\omega^2 \tag{6}$$

Thus, the operator defined by 5 is the amplitude and frequency product squared. But from 4 the total energy is proportional to the amplitude and frequency product squared. The discrete-time form of the Teager energy operator is defined by

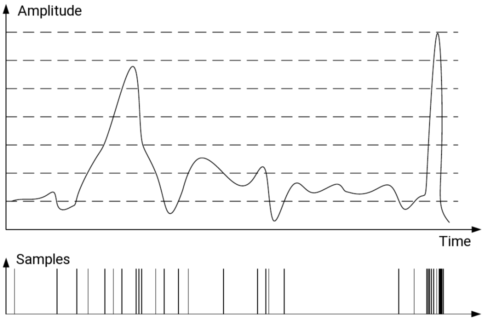
$$\Psi_d[x_n] = x_n^2 - x_{n-1}x_{n+1} \tag{7}$$

Level-crossing sampling

Non-uniform sampling



a) uniform sampling

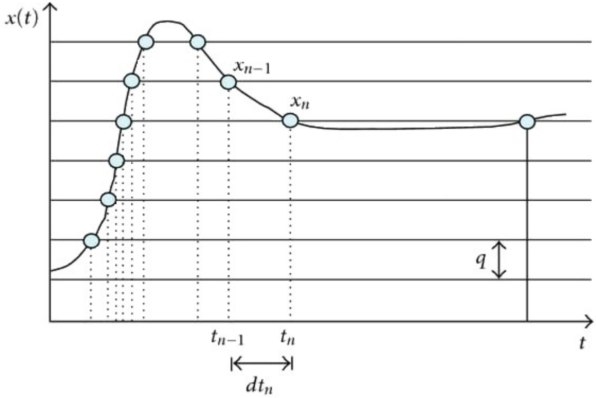


b) level-crossing sampling

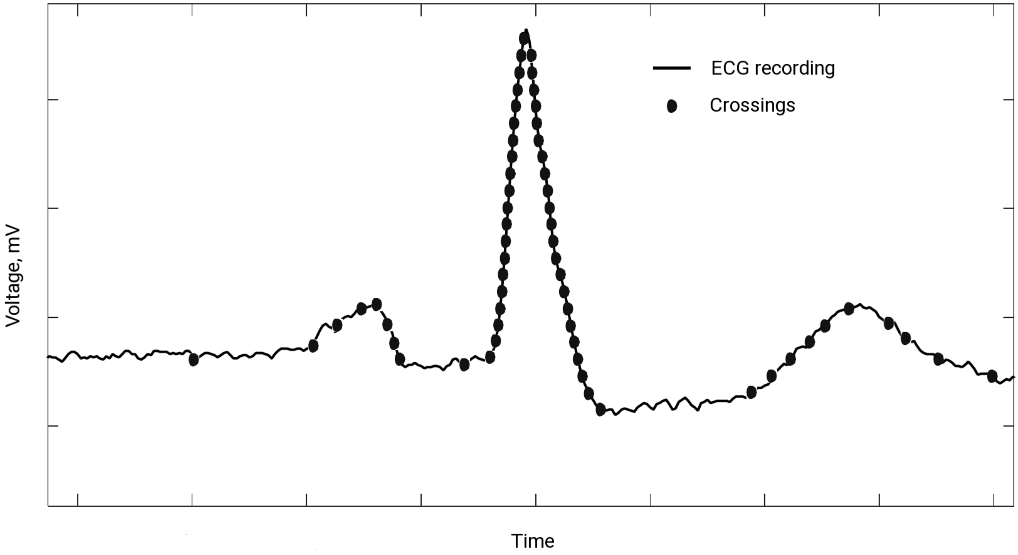
Can be applied to digital signals as well!

Notation

Let $x(t) be the signal$. Select the levels $\{L_1, \ldots, L_m\}$ ($\Delta L = q$).
Applying the method, we obtain the sequence $\{x_1, \ldots, x_n\}$ and time moments $\{t_1, \ldots, t_n\}$. Denote the intervals $[t_{i-1}, t_i]$ as dt_i.

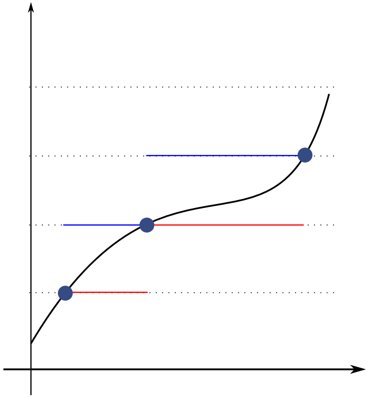


Level-crossing for peak areas detection

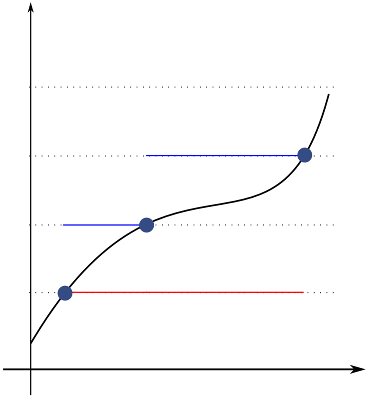


Level-crossing with denoising

- Assume, we have M bits for a sample, then there are $2^M - 1$ levels.
- The input signal is between N less significant bit value q.
  $q = 2A/2^M$.



a) N = 1

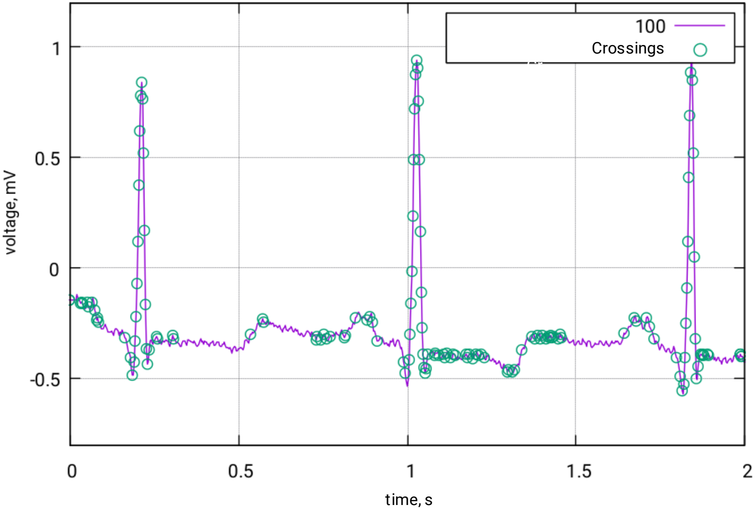


б) N = 2

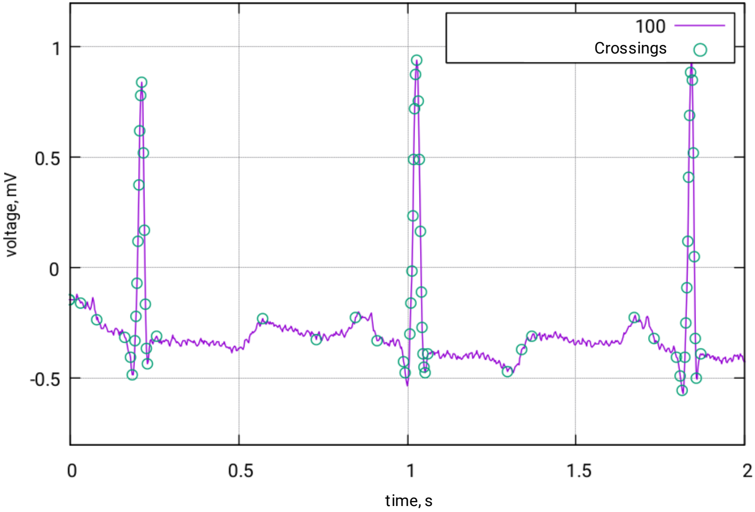
Crossings detection

Input: ecg – digital ecg recording as the collection of pairs:
t – sample time
v – voltage
procedure GETCROSSINGS(ecg)
    $voltage \leftarrow ecg[0].v$
    $level \leftarrow \lfloor (A + voltage)/(2 \times A) \times (2^M)) \rfloor$
    $lower = q \times level - A$
    $upper = q \times (level + 1) - A$
    for $i \in 1 \ldots ecg.size() - 1$ **do**
        $voltage \leftarrow ecg[i].v$
        $level \leftarrow \lfloor (A + voltage)/(2 \times A) \times (2^M)) \rfloor$
        if $voltage > upper$ **then**
            $lower \leftarrow q \times (level - N + 1) - A$
            $upper = q \times (level + 1) - A$
            yield $ecg[i].t$
        else if $voltage < lower$ **then**
            $lower = LSB \times level - A$
            $upper = LSB \times (level + N) - A$
            yield $ecg[i].t$

Level crossings detection with no noise suppression



Level crossings detection with noise suppression



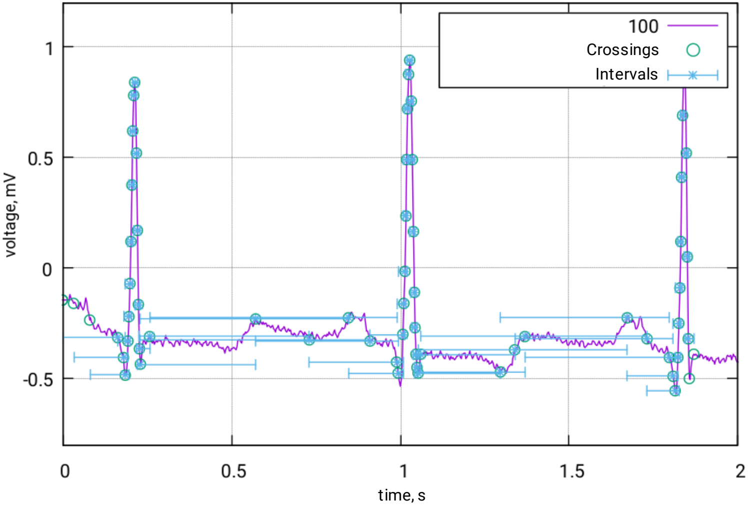
Interval lengths calculation

We search R-peaks among crossings t_k. Define the sliding window of W consecutive crossings

$$D(t_k) = \sum_{i=t_k-\lfloor\frac{W}{2}\rfloor}^{t_k+\lceil\frac{W}{2}\rceil-N} dt_i.$$

If $D(t_k)$ is lesser than T, then consider t_k as a peak.
We adopt the heuristics: the QRS width-to-height ratio should be less than one tenth.

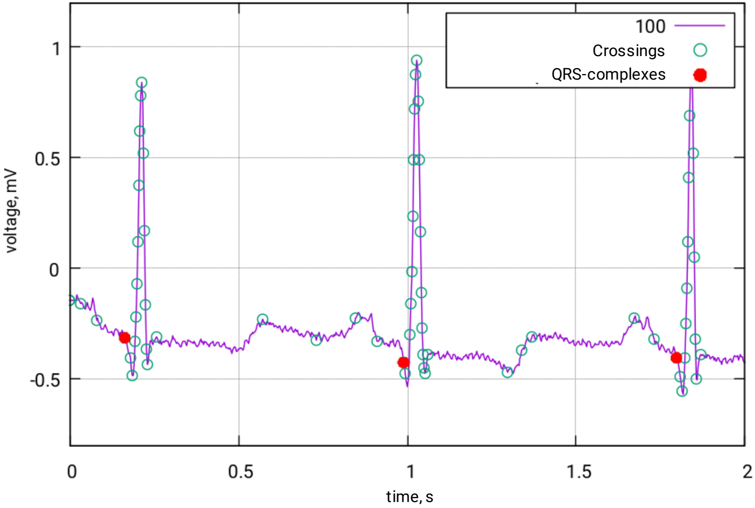
Interval lengths example



QRS detection algorithm

Input: $seqs$ – sequences as the collection of triples:
d – sequence duration
t – time moment of base crossing
v – voltage at the base crossing
Thresholding values:
T_{QRS} – maximum QRS
T_V – the most allowed distance between crossings
T_R – the threshold of width-to-height ratio
procedure $\text{GETQRS}(seqs)$
    for $i \in 1 \ldots seqs.size() - 2$ **do**
        if $seqs[i].d < T_{QRS}$ **and** $seqs[i-1].d \geq T_{QRS}$ **then**
            $l = i - 1$
            while $l \geq 0$ **and** $seqs[l+1].t - seqs[l+1].t < T_V$ **do**
                $l \leftarrow l - 1$
            $r = i + 1$
            while $r < seqs.size() - 1$ **and** $seqs[r].t - seqs[r-1].t < T_V$ **do**
                $r \leftarrow r + 1$
            $mx = \max(seqs[i].v \quad \forall i \in [l \ldots r])$
            $mn = \max(seqs[i].v \quad \forall i \in [l \ldots r])$
            if $(mx - mn)/(seqs[r].t - seqs[l].t) > T_R$ **then**
                yield (l, r)

QRS detection example



QRS detection performance

With the heuristics:

$$Precision = 94,6\ \%$$
$$Recall = 90,6\ \%$$
$$F - measure = 92,3\ \%$$

With the Teager energy operator support:

$$Precision = 97,4\ \%$$
$$Recall = 94,8\ \%$$
$$F - measure = 96,1\ \%$$

Conclusion

The proposed method has the following advantages:

- extremely low computational complexity;
- high performance have been proven on MIT-BIH database.

Disadvantages:

- considerable performance decrease on very noisy signals.