ICU Monitoring: An Engineering Perspective

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Industrial Automation: A Paradigm
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Process Plant/Actuators → Sensors → Decision-Making and Control
Key Advantages of Industrial Automation Systems

- Fully scaleable designs integrating data collection, informatics, real-time control and decision-making by providing:
  - secure access to control and information systems
  - tracking of user and automated control actions
  - tools to manage assets, configure process instruments, ...
  - seamless mgmt of data archiving, system backup and recovery, ...

- Based on Open Standards
  - HART (Highway Addressable Remote Transmitter), an open protocol designed to connect analog devices through field device communications
  - FOUNDATION Fieldbus (digital, serial, two-way communications system for the base-level network) Connectivity
    - Fieldbus is a family of industrial computer network protocols used for real-time distributed control (IEC 61158)
  - Profibus-PA (Process Field Bus) Connectivity
    - Profibus-PA is a digital replacement for analog (4-20 mA) signaling for process field devices
Typical Automation System Architecture
An Integrated Healthcare Framework
Current ICU Monitoring

Monitors/Sensors

Patient

Trend Visualization and Display
Proposed ICU Monitoring

Monitors/Sensors

Plug/Play Std Interface

Process

Data Aggregation and Feature Extraction

Data Warehouse

Visualization
Feature Extraction

Variability: Quantify how patterns are changing over time

Applications:

- Engineering
- Physical and social sciences
- Biology
- Medicine
  - Physiological time series data
    - EEG, respiration, heart rate, sleep/awake cycles
Variability Analysis Techniques

Time domain analysis
- Mean, variance, etc

Frequency domain analysis
- Windowed spectral analysis, PSD, Periodogram, etc

Entropy measures:
- Shannon entropy, approximate entropy, sample entropy, interval entropy, and spectral entropy

Linear stochastic signal models
- Regression, correlation analysis, coefficient of variation, time domain modeling (AR, ARMA, etc)

Scale independent or power-law techniques:
- Correlation dimension, Detrended Fluctuation Analysis, …
Automatic Tracking of Scale-Dependent Signal Characteristics using Change Point Detection

\[ \dot{x} = \frac{dx(t)}{dt} \]

is approximated using three-point Lagrangian approximation of the derivative:

\[ \dot{x}(t_k) = \frac{x(t_{k+1}) - x(t_{k-1})}{2h} \]

Change point detection [Brodsky et al. 1999] identifies the most statistically invariant segments

**DFA**

- Pointwise Gradient
- Detected Gradient

**Intracranial EEG During Ictal**

- Log(Fn)
- Log(n)
- Time(Seconds)
1) Ti-Hr=Interval from onset of Inspiration to the next EKG R-wave.

2) Te-Hr= Interval from onset of Expiration to the next R-wave.

3) Hr-Ti= Interval from the R-wave to the onset of Inspiration.

4) HR-Te= Interval from the R-wave in Inspiration to Expiration
The concept of Shannon Entropy, a central concept in information theory, is a measure of uncertainty that has also been used as a measure of information content. The entropy of a discrete random variable with probability $p_i$ is given by:

$$- \sum_{i=1}^{N} p_i \log_2 p_i$$

where $N$ is total number of events. For a continuous random variable $x$, we have:

$$H(x) = \int_{S} f(x) \log_2 f(x) \, dx$$

The entropy of an interval is defined to be the continuous Shannon entropy of the interval of interest.
Detection of R-waves and the onset of inspiration and expiration.

Calculate the desired time intervals between heart activation and inspiration or expiration.

Generate 19 surrogate heart rate signals to meet the statistical significance as follows:

- Detection of R-R intervals.
- Generation of surrogate R-R. The surrogate R-R time series have the same mean, standard deviation and histogram of the original R-R time series. Also, the autocorrelation of the surrogate R-R is almost the same as original R-R.
- Surrogate heart rate generation by cumulative sum of surrogate R-R intervals.
- Entropy analysis of the intervals computed from both the original and surrogate data of heart activation, inspiration and expiration.

Rank ordering and counting the number of entropy values for the intervals of the surrogate data that exceed those of the original data, to quantify, in a statistical sense, the existence of non-linear coupling in the data.
Detrended Fluctuation Analysis

The time series is integrated

\[ y(k) = \sum_{i=1}^{k} \left[ B(i) - B_{\text{ave}} \right] \]

The integrated data is divided into equal segments of size ‘\( n \)’. The trend in each segment is removed using a linear least squares fit. The Root Mean Square (RMS) fluctuation \((F)\) is calculated. This process is repeated to obtain \( F \) as a function of \( n \).

\[ F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left[ y(k) - y_n(k) \right]^2} \]

The gradient of the bi-logarithmic plot of \( F \) vs. \( n \) is estimated.
Phase 1: Data Integration

Development of proof of concept data collection system, built from “Commercial Off The Shelf” components, that will connect with current patient monitoring devices.

The goal will be to collect and integrate not only the parametric data but also acquire the underlying waveforms at high sampling rates.
Experimental Setup

Bedside Monitor

Ventilator

Video-EEG Monitor

Data Acquisition Module
Real-Time Feature Extraction Results

<table>
<thead>
<tr>
<th></th>
<th>Total Recording Time (Sec)</th>
<th>Detected R-Wave</th>
<th>Average Heart Rate (B/Min)</th>
<th>Average Breaths Per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>1425</td>
<td>2129</td>
<td>89.64</td>
<td>9.17</td>
</tr>
<tr>
<td>Subject 2</td>
<td>1208</td>
<td>1659</td>
<td>82.40</td>
<td>5.31</td>
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<tr>
<td>Subject 3</td>
<td>2949</td>
<td>2657</td>
<td>54.06</td>
<td>6.43</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DFA</th>
<th>SD1C</th>
<th>SD2C</th>
<th>SD1C to SD2C Ratio</th>
<th>Conditional Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>0.74</td>
<td>0.0346</td>
<td>0.1485</td>
<td>0.23</td>
<td>1.21</td>
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<tr>
<td>Subject 2</td>
<td>0.78</td>
<td>0.0091</td>
<td>0.0645</td>
<td>0.14</td>
<td>1.17</td>
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<tr>
<td>Subject 3</td>
<td>0.61</td>
<td>0.0586</td>
<td>0.1430</td>
<td>0.40</td>
<td>1.30</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Inspiration</th>
<th>Expiration</th>
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<tbody>
<tr>
<td>R</td>
<td>Ti</td>
<td>Te</td>
</tr>
<tr>
<td>HR3</td>
<td>HrTi</td>
<td>HrTe</td>
</tr>
<tr>
<td>HR4</td>
<td>TiHr</td>
<td>TeHr</td>
</tr>
</tbody>
</table>

- **TotTi**: Time intervals from start of inspiration until beginning of next expiration
- **TotTe**: Time intervals from start of expiration until beginning of next inspiration
- **Ti**: Time intervals from start of inspiration until the start of the next inspiration
- **Te**: Time intervals from start of expiration until the start of the next expiration
- **HrTi**: Time intervals of heartbeat initiation until the next inspiration
- **HrTe**: Time intervals of heartbeat initiation until the next expiration
- **TiHr**: Time intervals of start of inspiration until the next heartbeat initiation
- **TeHr**: Time intervals of start of expiration until the next heartbeat initiation

<table>
<thead>
<tr>
<th></th>
<th>Interval Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-R</td>
</tr>
<tr>
<td>Subject 1</td>
<td>-1.31</td>
</tr>
<tr>
<td>Subject 2</td>
<td>-2.45</td>
</tr>
<tr>
<td>Subject 3</td>
<td>-1.18</td>
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Phase 2 will be divided into two phases:

Phase 2a: Develop trend detection, feature extraction and data processing software.

Phase 2b: Develop a user-friendly and intuitive interface for signal quantification, interpretation and display.