Pulse Oximeter Signal Fusion for Robust Hypoxia Detection

Sayandeep Acharya; Arjun Rajasekar; Barry S. Shender; Leonid Hrebien; Moshe Kam

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Hypoxia is diminished availability of oxygen to the cells of the body. It can occur due to inadequate oxygenation of the lungs for extrinsic reasons, deficiency of oxygen in atmosphere, venous-to-arterial shunts (intrapulmonary or intracardiac), inadequate transport and delivery of oxygen, or inadequate tissue oxygenation or oxygen use. Exposure to severe hypoxia can lead to death of cells and depressed mental activity. Sometimes it culminates in coma and reduced work capacity of the muscles. Hypoxia occurs most commonly in people traveling to high altitude, or performing strenuous exercise or work for prolonged periods of time at high altitudes. Another population at risk is combatants such as fighter pilots who undertake high G maneuvers.

Measuring the blood oxygen saturation (S_pO_2) is the most common and easiest way to instrumentally determine the presence of hypoxia. A healthy human has on average a S_pO_2 value of 95–100%. S_pO_2 values below 90% are considered low and are taken as a possible indication of onset of hypoxia. The most common noninvasive device used to measure blood oxygen saturation levels is the pulse oximeter. The device uses a photo detector to measure the difference in the extinction curves of hemoglobin and oxygenated hemoglobin using light of different wavelengths. The common types of oximeters are applied either on the finger or on the forehead of the subject being monitored.

Hypoxia monitoring has been reported in several previous studies. A hypoxia detection and warning system was patented as an Aviation Hypoxia Monitor,[2] which has a single pulse oximeter attached to the ear and provides a visual and audio signal if the blood level of a subject decreases significantly. The Hypoxia Detection and Warning System described by Kelly and Pettit[4] is composed of an electrochemical oxygen sensor located within the breathing mask of a pilot. It provides a vibratory warning within the mask when partial pressure of oxygen in the system falls below a set point. A personal hypoxia monitoring system has been proposed which uses the cross-correlation between heart rate, respiratory rate, blood flow velocity, and blood oxygen saturation levels to identify the onset of hypoxia.[3]

Even though pulse oximeters are very popular in operating rooms, emergency medical aids, and for ambulatory use by heart and respiratory system patients, oximeters are prone to inaccuracies due to several sources, most notably light scattering inside blood tissues. They are also affected by noise artifacts due to motion, ambient light interference, respiratory maneuvers, and pooling of blood at the point of measurement due to body orientation. In situations where fast and reliable hypoxia detection is required, a single pulse oximeter may not be sufficient, and it may be advantageous to use a combination of several such devices.

In a study[5] conducted at the Naval Air Warfare Center Aircraft Division (NAWCAD), 45 datasets from 26 volunteers (4 women and 22 men) were collected. The subjects were exposed to a varying altitude profile ranging from 0 to 18,000 ft, simulated using a Reduced Oxygen Breathing Device (ROBD). The experimental profile was: ascent at 1000 ft $\cdot$ s^{-1} (304.8 m $\cdot$ s^{-1}) to 10,000 ft (3048 m), hold for 10 min, ascent to 18,000 ft (5486.4 m) at the same rate and hold for 20 min, and then descent at the same rate to ground level. The volunteers spent up to 20 min at the equivalent of a maximum altitude of 18,000 ft (5486.4 m), during which time the data from a finger pulse oximeter (Respironics Novametrix 515B, Murrysville, PA) and two forehead pulse oximeters (Nonin 9847, Plymouth, MN, and Masimo RAD-87, Irvine, CA) were recorded. Subjects were exposed to one to three repetitions of the profiles.

From Drexel University, Philadelphia, PA; the Human Systems Department, Naval Air Warfare Center Aircraft Division, Patuxent River, MD; and the New Jersey Institute of Technology, Newark, NJ.

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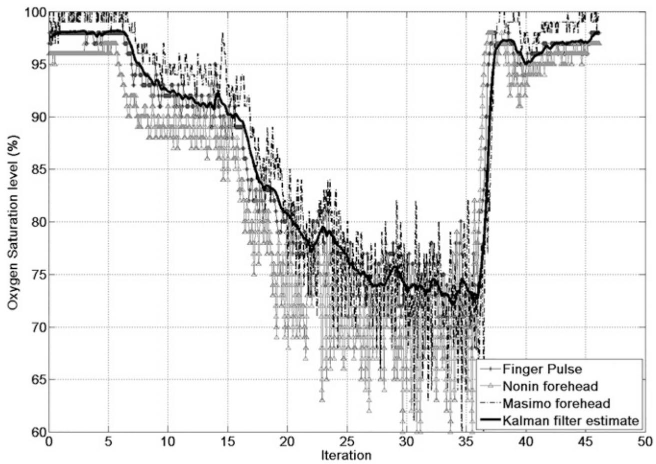

Fig. 1. Kalman filter estimate and raw oximeter readings for blood oxygen saturation level.

Kalman Filtering of Pulse Oximeter Signals

The study attempted to fuse the observations of three oximeters using Kalman filtering so as to obtain a smoother and more reliable estimate of the blood oxygen saturation level than what one can get from a stand-alone single oximeter. The fusion algorithm can be executed in real time and has moderate computational requirements (computations can be carried out using wearable processors). The idea is that the filtered estimate of the blood oxygen saturation level being less noisy would be a much more robust candidate signal to be used as a reliable trigger for subsequent hypoxia detection or mitigation systems.

The pulse oximeter readings had data dependent noise characteristics (noise variation increased as readings went below approximately 90%) and also temporal correlation. A second order auto regressive process was used to model the correlated noise samples. State augmented Kalman filtering resulted in a smooth blood oxygen saturation level estimate (**Fig. 1**). A more detailed description of the study can be found in Acharya et al.[1]

The study assumed that the state dynamics are autonomous (zero input). However, an attempt can be made to derive a relationship between altitude and blood oxygen saturation level which could then possibly be incorporated in the Kalman filter formulation with the altitude variation being the input. This effort may also pave the way to incorporating information from multiple heterogeneous sensors like altimeters, accelerometers, and anti-G suit pressure monitors (for fighter pilots) into a combined framework which can potentially detect the onset of hypoxia more reliably in real time. The combined result can be further used as an activation trigger signal to control hypoxia mitigation technologies as well.

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