

# Adaptive Wake and Sleep Detection for Wearable Systems

THÈSE N° 4391 (2009)

PRÉSENTÉE LE 27 AVRIL 2009

À LA FACULTÉ DES SCIENCES ET TECHNIQUES DE L'INGÉNIEUR

LABORATOIRE DE SYSTÈMES INTELLIGENTS

PROGRAMME DOCTORAL EN INFORMATIQUE, COMMUNICATIONS ET INFORMATION

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

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ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

Suisse  
2009

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# Abstract

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Sleep problems and disorders have a serious impact on human health and well-being. The rising costs for treating sleep-related chronic diseases in industrialized countries demands efficient prevention. Low-cost, wearable sleep / wake detection systems which give feedback on the wearer's "sleep performance" are a promising approach to reduce the risk of developing serious sleep disorders and fatigue.

Not all bio-medical signals that are useful for sleep / wake discrimination can be easily recorded with wearable systems. Sensors often need to be placed in an obtrusive location on the body or cannot be efficiently embedded into a wearable frame. Furthermore, wearable systems have limited computational and energetic resources, which restrict the choice of sensors and algorithms for on-line processing and classification. Since wearable systems are used outside the laboratory, the recorded signals tend to be corrupted with additional noise that influences the precision of classification algorithms.

In this thesis we present the research on a wearable sleep / wake classifier system that relies on cardiorespiratory (ECG and respiratory effort) and activity recordings and that works autonomously with minimal user interaction. This research included the selection of optimal signals and sensors, the development of a custom-tailored hardware demonstrator with embedded classification algorithms, and the realization of experiments in real-world environments for the customization and validation of the system. The processing and classification of the signals were based on Fourier transformations and artificial neural networks that are efficiently implementable into digital signal controllers.

Literature analysis and empiric measurements revealed that cardiorespiratory signals are more promising for a wearable sleep / wake classification than clinically used signals such as brain potentials. The experiments conducted during

this thesis showed that inter-subject differences within the recorded physiological signals make it difficult to design a sleep / wake classification model that can generalize to a group of subjects.

This problem was addressed in two ways:

First by adding features from another signal to the classifier, that is, measuring the behavioral quiescence during sleep using accelerometers. Conducted research on different feature extraction methods from accelerometer data showed that this data generalizes well for distinct subjects in the study group.

In addition, research on user-adaptation methods was conducted. Behavioral sleep and wake measures, notably the measurement of reactivity and activity, were developed to build up a priori knowledge that was used to adapt the classification algorithm automatically to new situations.

This thesis demonstrates the design and development of a low-cost, wearable hardware and embedded software for on-line sleep / wake discrimination. The proposed automatic user-adaptive classifier is advantageous compared to previously suggested classification methods that generalize over multiple subjects, because it can take changes in the wearer's physiology and sleep / wake behavior into account without adjustment from a human expert.

The results of this thesis contribute to the development of smart, wearable, bio-physiological monitoring systems which require a high degree of autonomy and have only low computational resources available. We believe that the proposed sleep / wake classification system is a first promising step toward a context-aware system for sleep management, sleep disorder prevention, and reduction of fatigue.

**Keywords:** Sleep / wake classification; wearable devices; cardiorespiratory signals; neural networks; adaptive systems; human centered systems; context awareness; sleep management.

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# Zusammenfassung

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Schlafstörungen beeinträchtigen das menschliche Wohlbefinden und die Gesundheit. Die steigenden Kosten zur Behandlung schlafabhängiger chronischer Erkrankungen in den Industrieländern erfordern eine effiziente Prävention. Günstige, tragbare Systeme zur Schlafüberwachung, welche den Benutzer über sein Schlafverhalten aufklären, könnten dem Auftreten von gesundheitsschädigenden Schlafstörungen vorbeugen.

Leider ist es noch nicht möglich, alle wertvollen bio-medizinischen Parameter mit tragbaren Systemen aufzuzeichnen und zu klassifizieren. Vielfach sind die Sensoren dem Träger hinderlich und die Prozessorleistung zu eingeschränkt. Ausserhalb des Labors sind die Signale oft sehr verrauscht, was die Qualität von Klassifikationsalgorithmen stark beeinträchtigen kann.

Diese Dissertation beschäftigt sich mit der Entwicklung eines tragbaren, autonomen Schlaf / Wach Detektors basierend auf der Messung von kardiorespiratorischen Signalen und Aktivität. Es werden die Auswahl und Integration von Sensoren und Elektronik, die Entwicklung eines angepassten Algorithmus zur Klassifikation und die nötigen Experimente zur Validierung des neuartigen Systems beschrieben. Zur Klassifikation der EKG-, Atmungs- und Bewegungssignale wurden spektrale Merkmale mittels Fourier Transformation ermittelt und anschliessend mit Neuronalen Netzwerken klassifiziert.

Individuelle physiologische Differenzen zwischen verschiedenen Personen erschweren die Entwicklung eines generell anwendbaren Klassifizierungsalgorithmus. Deshalb wurde zusätzlich zu den physiologischen Daten auch das Bewegungsmuster der Probanden verarbeitet.

Um den Algorithmus anpassungsfähiger zu gestalten, wurden zwei zusätzliche Messungen eingeführt, welche zwei typische Schlaf / Wach Verhalten (Reaktion und Aktivität) erfassen. Diese Messungen erlaubten in regelmässigen Ab-

ständen, den Klassifikationsalgorithmus automatisch auf neue Benutzer oder andere Veränderungen anzupassen.

Die Resultate dieser Dissertation tragen zu neuen Entwicklungen im Bereich von intelligenten, tragbaren bio-medizinischen Geräten bei, welche auf einen geringen Stromverbrauch und Rechenleistung angewiesen sind.

**Schlüsselwörter:** Schlaf / Wach Klassifikation; anpassungsfähige Systeme; Menschzentrierte Systeme; Künstliche Intelligenz; Neuronale Netzwerke; Schlafmanagement

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