1

Introduction

1.1 Motivation

In ageing modern societies, an increasing number of elderly citizens is living independently. At a higher age, falls are a huge risk for the seniors' health and continued wellbeing. The growing manifold of technological approaches towards this issue offers a variety of solutions for supervision, allowing to detect when a fall has occurred. While fall detection potentially saves lives and reduces the response time to the fall incident, preventing the fall in the first place avoids the injuries and prevents long-term harm. Thus, fall prevention is clearly preferable over fall detection, albeit significantly more challenging. This is due to the fact that an imminent fall risk has to be detected within a sufficiently short period of time to initiate suitable countermeasures. Consequently, real-time monitoring of the body posture is required to identify fall-related postures in time to take preventive action.

Monitoring a user's body posture can either be achieved with posture estimation or posture recognition. Posture estimation, i.e. reconstructing an arbitrary posture from measurements, is very flexible but very challenging. Posture recognition on the other hand, i.e. the recognition of postures based on calibrated patterns, is significantly easier to implement. It further benefits from the recent advancements in the domain of machine learning but relies on and thus requires reliable training data. We will pursue the recognition approach in this thesis, after an earlier thesis [1] in the Wireless Communications Group at ETH Zurich explored the estimation approach.

A variety of sensors for posture monitoring is available, reaching from fixed radar- [2, 3] and camera-based systems [4–6] to wearable inertial sensors like accelerometers and/or gyroscopes [7]. Wireless signals have proven to be a suitable means for posture recognition both in the radio frequency domain [8] as well as in magneto-inductive systems [9–11]. Wearable systems of inertial or wireless sensors have the advantage

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1

over camera-based solutions of preserving the user's privacy. Furthermore, they are independent of external infrastructure and thus operate in all environments. Another important advantage of wireless signaling for posture recognition is the possibility for secondary use such as data transmission from other body-mounted sensors or radar applications to detect obstacles or monitor the gait [12–14]. The inherent communication capabilities enable the system to exchange data with a smartphone which provides computing resources and the possibility of integration into an app for the respective smartphone ecosystem.

Despite their advantages and the recent progress in the e-health domain, such assistance systems are still not as common as one might expect. A recent study on fall prevention and detection [15] identified user comfort as a key parameter for acceptance. It has further been found that low-cost and low-complexity systems are better received by the target group of elderly people [16]. This highlights the requirement for simple, affordable, and comfortable (wearable) fall prevention systems.

1.2 Related Work

A vast variety of literature is available in the context of fall prevention and posture recognition. Various surveys [17–19] structure and categorize the literature base in different ways, often with an individual focus such as low power systems [20]. In the following, we will provide a brief overview over the relevant works in relation to this thesis, particularly approaches which rely on radio frequency for posture recognition.

As outlined above, a diverse category consists of systems for ambient sensing without wearable components. Among radio systems, this includes UWB radar for posture recognition (e.g. [2, 3]) and radio signals between nodes in the surroundings [21, 22]. Mixed systems combine external infrastructure with body-worn nodes, e.g. using RFID [23]. Off-body channels for UWB systems have been modeled and analyzed e.g. in [24]. Aiming for ubiquitous operation without external infrastructure, we require a fully wearable system relying solely on on-body channels. UWB WBAN channels for four links between the wrist and other body parts have been analyzed by Abbasi et al. [25]. They consider different arm postures and compare different environments, namely an anechoic chamber and an indoor scenario. Their focus lies on the channel model, propagation effects and different modulation schemes for communication. Similar analysis was done by others, e.g. in [26, 27]. In a more recent work, a system proposed by Huang et al. [28] recognizes postures from UWB-based distance measure-

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2

ments between 14 body-mounted receivers and a ceiling-mounted transmitter array. While the system is versatile regarding the postures, it requires the fixed transmitters and a large number of nodes to reconstruct the body posture accurately.

Einsmann et al. [29] have simulatively explored the feasibility of a posture capturing system based on on-body time-of-flight measurements. Their study identifies potential for such a system to reconstruct arbitrary body postures and examines suitable sensor locations. Their approach is limited to a purely simulative posture estimation study, however.

Farella et al. [30] developed a wireless posture recognition system based on accelerometers. In their practical implementation [31] they provide detailed information of the WBAN to merge sensor information, including hardware and a power consumption analysis. The combination of an accelerometer-based system with posture recognition based on the signaling itself is a very attractive option to increase reliability and robustness.

Quwaider and Biswas [32] combine accelerometers with on-body narrowband received signal strength indicator (RSSI) measurements to also recognize low-activity postures, which are difficult to identify solely using accelerometers. They coarsely classify postures into four groups (stand, sit, walk, run). For tests with three subjects, they report high accuracy and outperform a threshold-based approach.

With an application of firefighter operations in mind, Geng et al. [33] aim to identify particular activities such as crawling or climbing a ladder from narrowband on-body signals. Various statistical characteristics of the on-body channels in the time and frequency domain serve as features for the classifying support vector machines (SVMs). Experiments in different indoor locations provide the basis for a detailed analysis of the importance of the features and the on-body links. In addition, the authors compare their approach to different accelerometer-based methods. Identifying static postures is challenging for both the proposed approach as well as accelerometer-based systems with few features, but less important for the intended field of application, i.e. firefighter operations. For posture monitoring in the context of healthcare applications, however, static postures are equally important. Furthermore, identifying critical fall-related postures requires a posture recognition from a snapshot measurement and does not leave sufficient time for observing statistical channel characteristics during a longer period.

Paschalidis et al. [34] have developed a posture recognition approach based on Generalized Likelihood Tests, which is compared to an SVM for classification based on

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3

narrowband on-body signals. Due to the fluctuations of the measured RSSI of the three links considered, a larger number of measurements is required for reliable classification. Although the authors provide little information on the measurements, it becomes clear that the focus lies on distinguishing similar standing postures. An analysis of the topology or possibilities of wideband measurements are not performed, and the measurement campaign appears limited despite the emphasis on a measurement-based approach.

In the Wireless Communications Group at ETH Zurich, recent publications have successfully demonstrated posture recognition for a limited set of postures using purely passive magneto-inductive coils [9–11]. With individual advantages (e.g. material penetration) and disadvantages (e.g. strong sensitivity towards metallic surroundings), a combination with conventional radio (as presented in this work) has potential to increase robustness of the posture recognition.

The most closely related work is by Yang et al. [35], who demonstrate human posture recognition based on on-body signaling in an anechoic chamber as well as an office environment with accuracies of about 80 % and 75 %, respectively. Their selection of postures, however, is substantially smaller than in this work, and their system only uses narrowband measurements in the 2.4 GHz-band, leaving the possibilities and the analysis of wideband solutions out of scope. Furthermore, their WBAN is limited to six links between the hip and various body parts. A systematic analysis of suitable node placement is not performed. Overall, their work has a variety of insightful initial approaches to various aspects of the topic, such as different environments or hyper-parameter tuning. However, their analysis remains superficial. We thus acknowledge it as a starting point and provide a more comprehensive, generalized, and detailed analysis of the topic of wearable wireless posture recognition in this thesis, enriched by additional aspects on e.g. the implementation and the robustness of such a wearable system.

Identification of shortcomings:

To summarize the state of the art, the existing literature provides a variety of approaches towards recognizing body postures from wireless signals. Wireless channels around the human body have been studied for different environments and postures. However, we have identified several gaps in the existing work: Posture recognition essentially relies on comprehensive calibration data to identify postures of various daily

CHAPTER 1. INTRODUCTION

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4

activities. The existing studies mostly lack a comprehensive and diverse set of training data, and/or are limited to few groups of postures. This does not allow for a feasibility evaluation of concrete problem setups like fall prevention for elderly citizens. Furthermore, very few approaches explore the benefits of wideband signaling. Especially with ultra-wideband capabilities of modern smartphones, it is worthwhile to explore possibilities beyond the 2.4 GHz-band. A systematic topology analysis or reduction is lacking, despite the importance of a low number of on-body sensors for comfort and cost of the system. Furthermore, most presented systems are not analyzed regarding their robustness and limitations, reporting high accuracies for a single test person and/or environment without examining a core challenge of posture recognition, i.e. the extension towards unknown postures.

1.3 Contributions

In this work, we propose a design for a wearable posture recognition system based on WBAN signals between on-body nodes. In the course of our measurement-based approach, we conduct an extensive measurement campaign to obtain the necessary data for this task. For a variety of 43 postures from various daily activities including fall-related postures, we measure the complete wideband channel matrices between 18 body-mounted nodes. We obtain a diverse dataset by recording data for all postures performed by three subjects of different physique in varying indoor environments.

We conduct a preliminary feasibility analysis based on the acquired data, for which we develop a simplified system model. For different levels of measured raw data, we provide the corresponding maximum likelihood classifiers for the system model. In addition to a demonstration of the feasibility of posture recognition based on WBAN signaling, we use the simplified system model for an evaluation of a suitable parameter space regarding signal-to-noise ratio (SNR) and frequency range.

From a variety of established machine learning approaches, we identify suitable classifiers for the posture classification task based on a quantitative comparison. For our favored selection (Random Forest classifiers based on UWB energy measurements), we conduct a deeper analysis of the parameter space for operation. This includes a systematic minimization of the WBAN topology, i.e. the number and placement of on-body nodes. Furthermore, we evaluate the robustness of the proposed configuration towards test data from different subjects, environments, and previously unknown postures which are not present in the training data. Finally, we propose a feasible concept

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5