Rapid prototyping of smart garments for activity-aware applications

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Abstract. Continuous miniaturization of electronics and sensing elements stimulate the evolution of novel unobtrusively integrated smart garments that sense their environment and provide personalized assistance to its wearer. The development of smart garments requires robust integration techniques for electronics and textiles in one common system. Furthermore, recognition algorithms are needed to derive information on the wearer’s activity and context within the smart garment. In this work both challenges are addressed in a smart shirt system, called SMASH. SMASH was developed as a rapid prototyping system for smart garment developments. We introduced in this work our approach for prototyping smart garments and present design, implementation, and evaluation of SMASH. The SMASH system embeds a distributed hierarchical architecture of sensing and processing functions in an off-the-shelf long-sleeve shirt. The system design focused on scalability regarding sensors and processing resources, as well as rapid deployment in different applications. We demonstrated the versatility of SMASH in three application evaluations that represent different prototyping phases of smart garments. For these studies several systems of different sizes were implemented. The SMASH system helps to bypass time- and cost-intensive implementation iterations using multiple garment prototypes.

Keywords: SMASH, smart garments, rapid prototyping, smart environments

1. Introduction

Clothing is an essential accessory worn by large portions of the population. Besides its use for safety, climatic, and aesthetic reasons, clothing has a unique role for smart system solutions that provide information feedback and coaching assistance for their users. Originating from the visionary concept of ambient intelligence that supports individuals, as postulated by Mark Weiser [35], current developments have arrived at initial concepts and solutions for smart garments today. In these concepts garments can serve as base layer for smart functions, as they provide space and body contact. In particular body contact is an essential feature, since many assistant systems depend on personal information that is hard to acquire from ambient and infrastructure sensors only. While wearable sensing in garments can provide vital details of a wearer’s activities and context, smart garments also preserve individual privacy as sensing and processing can be performed on-body. Hence, smart garments may become the most universal and natural human-computer interface in the near future [14]. Towards the vision of ambient intelligence, smart garments with integrated activity and context-aware functions will complement intelligent infrastructure systems and extend their assistance functions to wherever the wearer is.

Recent advances in textile developments showed promising results for realizing smart functions directly in garments [6,8,19,22,27]. However, we cannot expect to integrate all electronics and sensing modalities in fabrics directly, hence, electronic units are often attached to textiles. Consequently, realizations of smart garments depend on continuous miniaturization and integration of electronic sensing and processing elements. Two crucial lines of research have evolved from these efforts: (1) to embed electronic components and functional units in garments used in daily life [5,28],
and (2) to derive user activity and context information from embedded sensors, using embedded sensing and processing resources [7,9,21].

This work addresses both research challenges by introducing design and evaluation of a highly versatile SMArt SHirt, called SMASH. We propose SMASH as a novel platform for rapid prototyping in crucial development phases of smart garments. While specific smart garments have been introduced in related works (please see our discussion in Section 1.1 below), a generic system that could be utilized and customized to different applications has not been attempted.

SMASH essentially consists of (1) a technology for quick and unobtrusive attachment of sensors onto clothing, (2) a failsafe interconnection system to seamlessly collect data from these sensors, and (3) an embedded hierarchical processing architecture optimized for distributed on-body signal processing and pattern recognition. With SMASH, the garment evaluation in applications is as simple as placing sensors and loading the processing algorithms onto the garment. The SMASH system is not restricted to particular types of sensors and thus can accommodate textile and silicon-based units.

We present in this work our approach to utilize SMASH in distinct prototype development phases of smart garments. Moreover, we evaluate SMASH systems in three applications, which all benefit from sensor pattern recognition: exercise support, control of home appliances, and rehabilitation of children. These evaluations demonstrate how our rapid prototyping approach is implemented in different prototyping phases and application challenges.

1.1. Background

Realizations of smart garments are tightly coupled to integration techniques for electronic systems in textiles. In this first line of smart garment research efforts, the garb is typically considered as a most natural substrate for sensing, computing, and interconnection. Nevertheless different material properties and manufacturing techniques of textiles and electronics create challenges for a seamless integration of these parts. The integration must be robust enough to sustain daily activities. However, during the development phase, the system architecture shall allow to customize sensor placement and exchange processing tasks in order to adapt for application needs. Consequently, the design of smart garments requires an iterative process of application-dependent sensor selection, system performance characterization, and architecture optimization. Currently this process requires time-consuming and costly implementation rounds, involving several prototypes and intermediate tests in the intended application environment. Novel tools are needed to rapidly prototype smart garments, before committing to production processes. We consider SMASH as a novel generic tool for this purpose, as it permits us to perform changes in sensor placement, system architecture, as well as to modify the garment’s processing tasks.

A broad spectrum of applications can benefit from smart garments. These include personal monitors that continuously determine patient health state [12,33], worker assistance and learning tools [2,30], as well as support systems for exercise, rehabilitation, and monitoring applications, as discussed in this work. Nevertheless, imminent challenges in the second line of smart garment research remains the robust extraction of user activity and context information from sensors. While sensor-based smart infrastructure monitoring [29] has evolved into industrial solutions already, human activities and context are by far more complex and variable. Viable solutions to derive robust activity information and assistance services are expected from flexible multi-channel sensing and distributed signal processing. SMASH was designed to accommodate these needs in a scalable system architecture that can be utilized in different applications. Finally, the garment should be worn in various situations and daily activities. For this purpose, we maintained for SMASH a garment design and perception that is similar to classic clothing. Figure 1 illustrates an example implementation of SMASH.

Fig. 1. The SMASH prototyping system for smart garment developments. Interfaces (encircled) at the upper arm, back, and lower waist provide links (SMASH Gateways) to attachable sensing units (SMASH Terminals).
In Section 2 of this paper, we present our approach to rapid prototyping using SMASH. Section 3 then introduces the SMASH system architecture in detail and discusses design choices regarding the requirements for smart garment developments. Subsequently, Section 4 presents our evaluation of SMASH in three application scenarios. Section 5 concludes on the results of this work.

2. Rapid prototyping approach

Prototyping of smart garments typically affect many design aspects, including sensor selection and placement, modifications in garment processing task, and even changes in the system architecture towards the final design stage. Besides addressing particular prototyping phases with SMASH, it is essential to maintain a broad interoperability with commonly used data recording systems and analysis tools. In the following sections, we detail our approach regarding both aspects.

2.1. Garment prototyping phases

Our attempt to consider separate prototyping phases originates from the challenges to iteratively refine application-specific garment solutions. We have categorized the smart garment development into three phases that can be supported with specific implementations of the SMASH system. Starting from a generic SMASH design template, each of the phases has particular development goals towards a final, application-specific smart garment system.

1. Smart garment feasibility evaluation using a generic SMASH system.
2. Pilot study evaluation using a customized SMASH prototype.
3. Application-specific smart garment prototype.

In the first evaluation step a generic smart garment system implementation is used to evaluate the general application feasibility of using a smart garment. In this garment configuration multiple sensor channels and sufficient garment-based data processing resources are used in order to analyze system design and develop signal processing algorithms. From the acquired data, sensor modalities and locations can be selected. Moreover, potential system restrictions could be identified. For example, the effect of body movements on the garment alignment could be evaluated. Main concern in this prototyping phase is a basic realization of the application, hence evaluations involve a small group of specifically selected users in a controlled study design. The SMASH design specifically addresses this first phase by providing a scalable system architecture. Sensors are fixated using removable tape or Velcro. As a generic system is used in this phase, the smart garment may not achieve sufficient wearer comfort in a specific application. Adaptations of the design and component integration may be performed in the second phase.

The second phase is intended to support pilot studies using the smart garment. The phase aims to confirm the design choices made in the previous phase by including larger user samples. Regarding garment development, this requires, e.g., to manufacture garment prototypes in different sizes in order to fit body proportions. Sensors, component positioning, and processing resources are now optimized for the intended application. Sensors are fixated on the garment or directly integrated to match the final system function as close as possible. While in the first phase most algorithms could have been evaluated online as well as off-line on recorded sensor data, algorithms are now primarily deployed onto the garment. The SMASH system can be scaled to this task by implementing subsets of sensors and processing elements based on the generic architecture.

In a third prototyping phase a final application-specific smart garment is developed. It contains the experience gathered in all preceding evaluations and may match a final production garment already. Sensor modalities, positioning of sensors, and data processing are realized specifically for the application. While such a highly optimized design can not be configured directly using the generic SMASH system, the SMASH architecture can provide building blocks for this implementation, including sensors, processing elements, and algorithms.

2.2. Interoperability

In particular for the first prototyping phase sensor data may be recorded and transferred over wireless links for off-line analysis and algorithm development. Our design choices for SMASH include a standard feature-vector based data format that can be interfaced to analysis tools for data inspection, signal processing, and pattern recognition.

For data recording SMASH can be synchronized with other on-body or ambient sensing modalities us-
ing e.g. the Context Recognition Network Toolbox [3]. Subsequently, algorithm developments for sensor data preprocessing, feature selection, pattern classification, and information fusion can utilize the sensor data in Matlab or, when converted to an ARFF format, by Rapidminer [26] or WEKA [37] toolboxes. For an analysis of movements, data can be imported into GT²k [36] as well.

3. SMASH prototyping system

As the upper body can provide information on many human activities, a smart shirt could become an optimal monitoring garment. The base layer of SMASH is a commercial off-the-shelf long-sleeve shirt. The shirt design was chosen as it allows to attach sensors at various locations, even at wrists, while being conveniently worn as casual cloth during daily life. Specifications of a shirt used for SMASH are summarized in Table 1.

We used the shirt as substrate to embed electronic units and wiring, as shown in Fig. 2. The embedding allows a broad spectrum of electronic functions to be added to the shirt. In our design, functional flexibility was a key consideration, as SMASH is intended for rapid prototyping of activity-aware applications.

The SMASH system architecture is detailed in the following section. The system integration, in particular the embedding of electronics units and wires, is presented. Finally, we discuss critical design choices and present our considerations and evaluations of the system.

3.1. SMASH system units and architecture

The SMASH system architecture was developed to scale the number of sensors and processing resources to the application needs of a final smart garment. A typical design choice for sensing and processing networks in wearable systems are star-topologies with central data processing, e.g. [31,34]. However, we selected a hierarchical architectures as this reflects body anatomy and typical data processing requirements in the topology choice [16]. A hierarchical architecture allows to optimize overall system weight by minimizing weight at the limbs. Moreover, it enables dynamic changes in functional units, such as attaching or removing further sensors.

Figure 3 illustrates our concept to align the SMASH hierarchy to a three-layer stack of standard tasks performed for activity recognition: signal sampling and sensor data preprocessing, feature processing, and pattern recognition. The corresponding functions are implemented in the SMASH units Terminals, Gateways, and a Konnex.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garment</td>
<td>Calida 15019-989</td>
</tr>
<tr>
<td>Size</td>
<td>large (GER: 6, US: 42/44)</td>
</tr>
<tr>
<td>Material</td>
<td>cotton</td>
</tr>
<tr>
<td>Weight</td>
<td>280 g</td>
</tr>
<tr>
<td>Chest size</td>
<td>104 cm</td>
</tr>
<tr>
<td>Arm length</td>
<td>54 cm</td>
</tr>
<tr>
<td>Wrist circumference</td>
<td>22 cm</td>
</tr>
</tbody>
</table>

**Table 1** Specification of the SMASH substrate garment

SMASH Terminals Terminals are peripheral sensing units that represent the lowest processing layer of the SMASH system architecture and the activity recognition stack illustrated in Fig. 3. Terminals are used to carry sensors and preprocess sensor data, e.g. by filtering and preparing further processing at higher layers. Each Terminal implements an 8-bit ATmega48 microprocessor for signal processing.

The SMASH Terminal design aimed at an unobtrusive solution, by minimizing weight and size of the unit. A particularly important design aspect of SMASH Terminals is their free positioning at the shirt, which can be adapted according to application requirements. Figure 5 shows two Terminals that integrate an analogue-digital converter and a 3D-acceleration sensor. Table 2 summarizes the properties of all currently implemented and validated Terminals.

Terminal nodes are connected to SMASH Gateways by a 2-wire I²C bus. Each Terminal is equipped with
Fig. 3. SMASH system architecture designed in three processing layers of standard activity recognition tasks. Sensor data is acquired and preprocessed by Terminals (first layer), features are computed by Gateways that fuse sensor data (second layer), and recognition tasks are performed by a Konnex (third layer). The network implementation in SMASH is illustrated in Fig. 6.

a unique address. We partitioned the Terminal address space in parts for type and serial number. The SMASH system can detect newly attached Terminals by polling the address space during idle time. If a Terminal responds to a previously unallocated address, the SMASH system automatically registers the type of sensed data in a list of available services. The Terminal interface provides a maximum data-rate of 343 Kbps with a maximum sample rate of 21 kHz. The bandwidth is sufficient to transfer raw sensor data from various modalities and sampling rates to the Gateways. For the 3D-accelerometer Terminal used in evaluations of this work, the sampling rate was set to 100 Hz.

SMASH Gateways SMASH is designed to host up to four Gateways that acquire sensor data from all attached Terminals, fuse data, and process features from the sensor data. Gateways represent the second layer in the activity recognition stack. Each Gateway is equipped with an MSP430 processor and four sock-

Table 2
SMASH Terminals that are currently implemented and tested

<table>
<thead>
<tr>
<th>Terminal Function</th>
<th>Size [mm]</th>
<th>Weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration Sensing shirt and body orientation.</td>
<td>10 \times 8 \times 5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Analog-Digital Converter (ADC)</td>
<td>Provides four ADC channels for specific sensing applications, including temperature or textile strain.</td>
<td>8 \times 8 \times 5</td>
</tr>
<tr>
<td>Input/Output Provides four input buttons and four feedback LEDs.</td>
<td>45 \times 30 \times 5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3
SMASH system units

<table>
<thead>
<tr>
<th>Unit</th>
<th>Function</th>
<th>Size [mm]</th>
<th>Weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal</td>
<td>Sensing and data preprocessing, see Table 2.</td>
<td>see Table 2</td>
<td></td>
</tr>
<tr>
<td>Gateway</td>
<td>Interface to Terminals, data fusion and feature processing.</td>
<td>30 \times 30 \times 7</td>
<td>7</td>
</tr>
<tr>
<td>Konnex</td>
<td>System master, interface to Gateways, data and feature fusion, pattern recognition.</td>
<td>55 \times 45 \times 7</td>
<td>15</td>
</tr>
<tr>
<td>Battery</td>
<td>Powering</td>
<td>45 \times 35 \times 5</td>
<td>28</td>
</tr>
<tr>
<td>Complete SMASH System</td>
<td></td>
<td></td>
<td>440</td>
</tr>
</tbody>
</table>

SMASH Konnex Depending on the SMASH configuration, Gateways send raw signal data, preprocessed data, or features extracted from sensor data to the Konnex. The interconnection is realized through a wired system bus. The Konnex represents the highest layer in the activity recognition stack and consequently serves pattern recognition algorithms. Moreover, the Konnex is a central system master for communication within the SMASH system, system maintenance, and power supply. The unit integrates a MSP430 microprocessor to perform all tasks. The choice of wired interconnections was made, since in this architecture power can be provided from a central source, compared to individual power sources attached to each sensor node. Moreover, wireless links may fail or require retransmission if links are blocked, e.g. by body parts.
The firmware running on the Konnex and all dependent units (Gateways, Terminals) permit reconfiguration, e.g. to perform raw data acquisition and forwarding or online recognition. For online recognition, we implemented a Nearest Centroid Classifier (NCC) to perform a sample-wise pattern classification using sensor data provided by Terminals and Gateways. This implementation was used to confirm the SMASH operation in different applications. However, further more complex algorithms could be deployed to address activity recognition tasks.

Sensor data and classification results can be either stored into 512 Kb non-volatile memory or sent to ambient services via an integrated Bluetooth module. In both operation modes, stored and transmitted data is encoded with a custom protocol that contains additional information, including the data source (Gateway and Terminal).

Battery and powering The complete SMASH system is powered by a central buck-boost converter that is implemented in the Konnex unit. It is sourced by a 5 mm flat, detachable lithium polymer battery with a capacity of 1100 mAh (see Fig. 2). This battery capacity is sufficient to guarantee a continuous operation of 12 hours for a configuration with seven acceleration Terminals sampling at 16 Hz and permanent Bluetooth transmission of all raw sensor data. The system can be supplied by any battery providing between 2.5 V and 16 V. The battery itself can be detached from its interface plug to allow replacement.

3.2. Textile integration

The integration of electronic units in textile substrates, as well as interconnection between units in textiles proposes mechanical and electrical challenges that are related to the different material properties [19]. Moreover, the embedding requires specific considerations to preserve the textile properties, e.g. avoid stiffness of large garment areas, as well as to obtain a mechanically robust and lightweight system. Electronics needs to be protected from mechanical stress, electrical shocks, humidity, and moreover, from body sweat and skin particles. Current embedding solutions for electronic units include detachable electronics [1,32], e.g. for washing or exchange of faulty units. Methods for direct integration of electronics include stitching and sewing [5,18] as well as gluing [24] of units on textiles. Smart garments require specific precautions to maintain functionality even in situation of material failure of wires or electronic units [14,15,23].

For the SMASH system we chose to encase electronic units (Gateways and Konnex), as well as their interconnection wires at the inner side of the shirt using silicone gel (acetoxyisilane, see Fig. 5). Silicone gel fixes the electronic units at the textile and acts as an insulating and protective housing. While silicone is protective, it is also flexible and lightweight to cover even long wired busses across the upper body shirt without critically stiffening the textile. Due to its low toxicity, electronics can be hidden in the inner side of the textile, where the gel might get into contact with the skin. From a manufacturing perspective, silicone gel is cheap, easy to process, and develops only small exothermic heat during curing.

We performed the packaging procedure in several steps. First, the targeted textile area where silicon would be applied was delimited with adhesive tape. We than primed the textile with a viscous type of silicone gel to seal textile pores. Onto this base layer of silicone we aligned the electronics and created a sheathing frame of polystyrene for a second layer of silicone. As shown in Fig. 4, we subsequently filled the frame
with a more liquid type of silicone to enclose the electronic unit. During the filling process, a plug was attached to a vertical programming connector in order to protect it from silicone contamination. All auxiliary constructions and the plug were removed in a last step and spare silicone was removed using a scalpel. The final result for a SMASH Gateway is shown in Fig. 5. We expect that this procedure can be adapted to an efficient industrial production process.

3.3. System design considerations

A number of garment design requirements must be considered to obtain a sufficiently robust and usable smart garment system. In this section we discuss the SMASH design approach and present system evaluations with regard to several requirements considered essential for a generic prototyping system.

Comfort: textile placement and routing

Comfort of garments is perceived through a number of textile properties such as texture sensation, durability, lightweight, as well as breathable materials. These properties have been developed to a high standard in classic clothing. Moreover, the obtrusiveness, placement, and form language of wearable objects influences the interaction between the objects and the wearer [13]. One central design challenge for SMASH was to unobtrusively place system units on the shirt and provide an interconnection bus system.

Our final placement and interconnection routing solution is illustrated in Fig. 6. We proceeded by initially placing the Konnex and battery units. These locations were chosen according to garment comfort criteria. Both units were placed near to the body’s center of mass, at the lower back, where the extra weight is hardly noticeable for wearers.

The number and location of Gateways were chosen according to the premise that every part of the body should be accessible by Terminals. We constrained wiring distances to 80 cm, in order to ensure reliable I²C communication. However, to align the topology to body anatomy and garment cut, each upper arm was equipped with a Gateway. In addition, this design allows the fusion of body segment-specific sensor data and features. A third Gateway was placed at mid-line of the back to reach shoulder and head locations. A fourth Gateway was placed at a front side, lower waist region to reach the legs. The position of all Gateways are shown in Figs 2 and 6. The disadvantage of placing the system units on the wearer’s back is a lowered sitting comfort when a back rest was used. While the silicone material helped to distribute upper body pressure on the units, the units remained noticeable during back rest sitting.

All system bus connections between Konnex and Gateways were implemented using standard wires and attached using silicone gel. Without specific consideration of garment properties, a straight routing would have stiffen the shirt. Wearers would notice the garment as inflexible and unusual behavior during movements. Consequently, we routed the buses in winding paths to permit garment stretching and to sustain textile strain in horizontal and vertical directions. From previous movement evaluations with tight-fitting long-

![Fig. 6. Placement and routing of the SMASH system with two Terminal units. The system bus (blue lines) was embedded on the shirt using silicone gel. Red dotted lines indicate sewing lines where the system bus was routed for unloading of mass and garment strain. Orange lines, perpendicular to shirt stretching zones, indicate the textile strain that was considered by routing in winding paths.](image)
sleeve shirts, we concluded that most elongations occur at the lower back region in vertical direction as a consequence of back bending [25]. Therefore, our routing at the lower back region addressed vertical strain specifically. At the upper back, strain occurs in horizontal direction, due to arm and shoulder movements. This strain was considered similarly, by winding path routing. Whenever possible, the system bus was routed along the shirt seams to absorb mass loading. In situations where the system bus needed to cross a seam it was not covered with silicon gel in order to bridge the patches. This solution was acceptable since the seams are much less stretchable, hence the system bus is not exposed to mechanical stress as in continuous patches. In regions of arm patch sealing, both silicone and system bus wiring was noticeable to wearers, however movement freedom was not compromised. Both techniques, winding path routing and routing along seams, are illustrated in Fig. 6.

We focused in this work on technical considerations of comfort aspects. An evaluation of comfort with SMASH wearers could provide additional insight, however, this is beyond the scope of this work. Moreover, as SMASH is a prototyping system, it cannot be compared to a application-specific smart garment implementation that had been optimized for its particular use.

**Reliability:** system fault recovery and stress testing

While detachable electronics need robust interconnection solutions [1,4], permanent textile packaging approaches using glob top or silicone gel prohibit quick unit exchange or repair. Consequently, we decided to embed fail-over functions and link redundancy [8,10] to compensate potential link faults.

Gateways and Konnex are connected by a 4-wire Serial Peripheral Interface (SPI). In order to obtain a fault-tolerant network architecture, the SMASH Gateways are redundantly interconnected to the Konnex. The SMASH system interconnection scheme is shown in Fig. 6.

In case a Gateway becomes inaccessible due to one or more broken wires, the Konnex detects access time-outs. To use an alternate link, the Konnex resends the request to the second Gateway that is linked to the target and triggers a message forwarding using a dedicated hop-signal wire. If the previously inaccessible Gateway responds, the Konnex signals a system bus error and continues to communicate via the intermediate Gateway. If the Gateway is still inaccessible, the Konnex signals a broken Gateway. In both situations the SMASH system remains functional.

In practical applications of SMASH we did not observe a Gateway or system bus failure. Besides the material wear-out that may contribute to such errors, washing is a challenging procedure for SMASH. During machine washing the garment and attached system units are exposed to humidity, high mechanical forces, aggressive chemicals, and high temperatures. In initial tests, we attached one Gateway unit onto a piece of textile with the same process as utilized for SMASH systems. We washed the patch five times using machine washing (in total 250 minutes of washing duration) at 40°C with standard washing agent. After all washing iterations the silicone showed no signs of damage and the Gateway stood functional. We observed no water leak through or under the programming connector. Although these are initial results, they are promising for a long-term stability of the SMASH system.

## 4. Application evaluations

In this section we present three different application scenarios, where smart garments could be deployed to support their wearer. The application scenarios are considered in the first and second prototyping phases (as introduced in Section 2) to confirm the applicability of the prototyping approach and of SMASH.
Moreover we consider user-dependent and user-independent evaluations to analyze the recognition performance that can be achieved by using a smart garment. The user-dependent mode corresponds to a dedicated training of the recognition algorithm for a wearer. In contrast, the user-independent mode allows to estimate the recognition performance for a new user of the system. Moreover, we did not standardize the garment fitting. Hence our evaluations include a measurement variability for individual participants due to varying garment orientations at the body.

While we believe that SMASH can provide activity-aware services in a broad spectrum of applications, we focused in this work on posture-related applications. These allowed us to study different prototyping phases and application situations. In particular, we analyzed recognition performance constraints, the garment impact on sensor orientation, and limitations of the used sensor modality.

4.1. Recognition of postures for exercise support in supervised environments

In movement rehabilitation a therapist guides patients in performing exercise sequences to recover function of an affected limb. Such exercises include shoulder- or elbow-related posture sequences. We studied in this scenario whether the exercise postures can be discriminated from acceleration Terminals attached to the SMASH system. This posture recognition could be deployed in a smart garment to support the patient during individual training without the therapist.

In an initial step an appropriate-sized garment has to be chosen and the exercises need to be practiced under therapist supervision. Moreover, this step serves to train the shirt classification system. During independent training, the shirt can provide feedback on the training progress, repetitions, timing, and coaches the individual on the prescribed training plan. This information is vital feedback on training performance for the therapist too, enabling training diaries and precise tracking of progress.

During the first prototyping phase we used the SMASH system to evaluate the posture discrimination performance that can be achieved with a smart garment. The garment has an appropriate size and is trained on the user under supervision.

Evaluation procedure

SMASH was equipped with acceleration Terminals at the wrist and upper arm using conventional tape to study the discrimination of 21 shoulder- and elbow-related exercise postures. Figure 7 depicts the position of acceleration sensors.

We controlled the evaluation for influences related to body proportions by including three healthy participants (body height: 180 cm, 182 cm and 183 cm), that fitted perfectly into the SMASH according to the manufacturer’s size guide.

Figure 8 depicts all postures, as they were performed in exercise sequences. All exercises were explained and shown on pictures to the participants. Hence, there is natural variation between the individual posture executions. The exercises were performed in sequence, the whole set was repeated three times. An experiment observer annotated the conducted postures. Each exer-

![Fig. 7. SMASH system indicating the placement of acceleration Terminals on right lower and upper arm. This setup was used for the application evaluation in Section 4.1.](image)

![Fig. 8. Shoulder and elbow rehabilitation exercise postures performed with the SMASH system. Posture classification was evaluated to support independent exercise performance.](image)
exercise began and ended with a neutral position: standing upright, arms relaxed (see Fig. 8, posture 1). Besides its function to prepare for the next exercise, the neutral position was intended to restore the garment’s natural alignment on the body. The garment alignment was not otherwise purposefully manipulated.

The ability to discriminate postures was studied by classification, using the acceleration patterns recorded by the SMASH Terminals. In order to analyze the results, the classification was performed off-line, on an external host computer using an NCC algorithm as it was implemented on SMASH. We performed a threefold cross-validation scheme, training the algorithm on two repetitions of the exercises and testing the classification performance on the left out exercise repetition. Each repetition was used once for testing only.

Results and discussion

The classification reached a mean normalized accuracy of 81%. This result indicates a good recognition performance of the system for the 21 posture classes. Figure 9 shows the classifier confusion matrix indicating the correctly classified instances in the main diagonal. Confusions are indicated by colored cells besides the main diagonal. The confusions can be explained by the following three causes:

Similar postures can be confused as a consequence of their similarity in the sensor data pattern. Examples are postures 1 and 6, where the confusion is caused by a variable execution of postures during the exercise repetitions.

Limitations of acceleration sensing lead to confusions of posture-pairs (3, 8), (13, 15), and (16, 17). These errors are related to the gravity-based acceleration sensing that cannot differentiate these particular postures. In order to compensate acceleration sensors and minimize such confusions, additional orientation-sensing modalities, such as magnetic field sensors, can be used.

Textile influences on sensor deviations lead to confusions of postures 11, 14, and 15. In particular at the wristband, the textile does not follow lower arm rotations when the elbow is bent at the same time. Hence, exercise postures should be individually considered and a smart garment deployed for independent training should indicate a confidence in the recognition result for affected posture types.

The results confirm that appropriately sized garments can be used in combination with the selected sensor setup for a recognition of rehabilitation postures. At least 15 of the 21 considered postures were classified without major confusions (see Fig. 9). Confusions in the remaining 6 postures can be resolved by removing too similar postures that suffer by incorrect execution and by adding complementary sensing modalities.

4.2. Recognition of control postures in unsupervised environments

Smart garments that recognize postures can be used to control appliances and services available in the current environment, such as in the wearer’s home. In this application smart garments may serve as a very natural control interface to manage a home entertainment system [11,17] or call for help in an assisted living home. The intriguing advantage of smart garments over buttons and remote controls is their pervasive anytime availability as a part of the normal outfit.

An optimal smart garment for these applications must be comfortable to even permit elderly- or disabled individuals to put the garment on and off autonomously. However, posture recognition requires stable sensor operation and positioning to achieve a reliable operation, in particular under imperfect fitting of the garment. As such a smart garment shall operate as off-the-shelf system, particular tight fitting and exact garment orientation cannot be warranted. Moreover, control postures must be ergonomic and intuitive to permit quick execution, while providing discriminative sensor patterns.

In this scenario, we utilize the SMASH system to identify robust posture patterns that can be discrimi-
nated from the SMASH Terminals even with varying wearer body heights and proportions. Moreover, in this evaluation we considered an user-independent operation of the garment, since algorithm personalization may not be feasible for pre-programmed off-the-shelf smart garments. The principle recognition challenge in this application is harder than in the application detailed in Section 4.1, due to the user-independent operation, imperfect garment fitting and, hence, the garment-induced drift in sensor orientation. However, a smaller set of postures is sufficient for typical appliance operations.

**Evaluation procedure**

Every posture generates a specific deviation of textile-attached sensors relatively to the skin. Hence, in a first step we analyzed the discrimination of postures using the set considered in Section 4.1 regarding the garment influence. For this purpose we attached an additional acceleration Terminal to the skin at the wristband location. We subsequently studied the sensor alignment error by calculating the absolute angular deviation between gravity vectors of skin- and garment-attached Terminals at the wrist. Figure 10 shows the SMASH system setup with the two acceleration Terminals.

Figure 11 shows the angular deviation for all three exercise repetitions of postures 2–21 for an individual who fitted the shirt according to the manufacturer’s sizing guide. The box indicates lower quartile, median, and upper quartile of angular deviation. The whiskers lines extending from the boxed area indicate the extent of remaining values. The first neutral posture (posture 1) is not shown, since the angular deviation was removed before each exercise.

The postures showed a spread between $3^\circ$ to $70^\circ$ in angular deviation. Postures that incurred a large angular deviation were not considered as potential control postures. We used a subjective limit of $15^\circ$ to identify 14 postures ($5–14, 16, 17, 19, 21$) that maintain a relatively low angular deviation. For these postures the garment orientation remains stable and hence, they are may serve for control operations.

Based on initial ergonomic considerations, we selected a set of the three postures $6, 12$ and $16$ for our further evaluation. We considered that the abduction of the right forearm could lead through a menu, where the left forearm is used for complementary forward-backward navigation.

Our evaluation focused on analyzing the discrimination of these postures for individuals of different body height and proportions.

We selected seven healthy participants (3 female, 4 male), aged between 20 and 35 years with body heights, between 163 cm and 190 cm. Body proportions of the participants are listed in Table 4.

![Fig. 10. Positioning of skin- and garment-attached acceleration Terminals (encircled). This setup was used for the application evaluation in Section 4.2.](image)

![Fig. 11. Absolute angular deviation between skin- and garment-attached acceleration Terminals for postures 2–21. Postures that incurred an angular deviation above $15^\circ$ were excluded as potential control postures for the evaluation in Section 4.2.](image)

### Table 4

<table>
<thead>
<tr>
<th>Participant #</th>
<th>Gender</th>
<th>Body length [cm]</th>
<th>Arm length [cm]</th>
<th>Chest size [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>m</td>
<td>180</td>
<td>55</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>m</td>
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<td>f</td>
<td>173</td>
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<tr>
<td>7</td>
<td>m</td>
<td>190</td>
<td>58</td>
<td>103</td>
</tr>
</tbody>
</table>
All participants repeated the postures three times. Two acceleration Terminals were placed at the right wrist, attached to the skin and the SMASH shirt (see Fig. 7). A further Terminal was attached to SMASH at the upper arm. For all classification evaluations a NCC algorithm was used.

Results and discussion

The posture classification accuracy reached 98% in user-dependent mode, where SMASH was trained to the individual wearer using the garment-attached Terminals. A three-fold cross-validation scheme was used to derive this result. Confusions occurred only for participants that were too small for SMASH, according to the sizing guide of the shirt manufacturer. If only the garment-attached Terminal at the wristband was used accuracy dropped to 96%.

In user-independent classification mode, the NCC algorithm was trained on six and tested on the left out participant using all three posture repetitions. This cross-validation procedure was repeated for all participants. Due to the additional data that was available for classifier training in this procedure, a perfect performance was reached for all participants, even using the wrist-attached Terminal only.

These results confirm that pre-programmed off-the-shelf smart garments can be used with different body proportions to discriminate a small set of control postures. While three control postures is a small set, it is even sufficient for menu navigation that typically require up-down and select actions. Furthermore the user-independent performance accomplished with only one acceleration sensor at the wristband indicates the robustness of the approach.

4.3. Posture rehabilitation system for children

Postural control is essential for children with neurological impairment. Several therapeutic interventions aim to improve postural control [20,38]. However, up to date, there exist no satisfactory measurements which allows to evaluate therapeutic approaches in real-life environments. In this application, the SMASH system was adapted to monitor and recognize back angle in children during daily activities. The spine bending and other context-relevant information could be transmitted continuously to ambient systems for analysis or to provide a feedback.

This scenario was considered in the second prototyping phase, where application-customized SMASH prototypes serve as an objective measurement tool for the bendings of the spine in children. In a previous study, we evaluated sensor modalities and their positioning using the SMASH system. We used results to produce customized shirts in child sizes with silicone attached sensors for an extended pilot study and a larger number of subjects compared to the phase one evaluations.

Evaluation procedure

Two long-sleeve garments in child sizes (140 cm and 152 cm) were equipped with acceleration Terminals to estimate spine bending. Three sensors were directly placed on prominent spine positions (vertebrae C7, T10 and L5), additional sensors were placed on the rigid area of the scapula and the upper shoulder, see Fig. 12. Both shirts utilized the SMASH system architecture.

The shirt was examined using six upper body postures (0°, 10°, 20°, 30°, 40°, 50°, see Fig. 13). A wooden frame was used to align the children and control the back bending. In total 21 healthy children, aged between 8 and 15 years were included. In order to validate the SMASH system in this application, a video based analysis system (Dartfish) was used.

Results and discussion

The SMASH system was able to estimate all six upper body postures. We analyzed the error between SMASH and the optical system. Independent of the head position, about 70% of all measured sensor angles diverged less than 5° between the systems.
Results show that SMASH can reliably estimate back postures and is a feasible option to detect postures in healthy children. The results gained in this study encourage the use of comfortable garments for monitoring of spinal bending to improve postures in children. However, the shirt size must be appropriately selected.

5. Conclusion and future work

Smart garments can provide vital information on a wearer’s activity and context. Available space and close body contact make garments an ideal substrate for sensing and signal processing that complements intelligent ambient systems and maintains privacy. These prospect features allow to implement smart garments with information feedback and coaching functions that either perform on their own or rely on additional smart ambient services.

Currently, the iterative process of smart garment design and application validation requires time- and cost-intensive prototype implementations that often cannot be reused. The SMASH system presented in this paper, addresses the challenges of early development and validation by providing a garment platform for rapid prototyping. We introduced in this work a novel prototyping approach with three phases. When combined with the SMASH system, this approach simplifies and expedites prototyping, as standard tasks and building blocks are readily available. Moreover, the SMASH system architecture is scalable in the number of sensors and processing resources to accommodate advanced prototyping phases that extend beyond first feasibility tests. To this end, SMASH addresses solutions for two essential challenges in smart garment development: the embedding of electronic units in textile fabrics and the extraction of user activity and context information by using embedded resources.

The SMASH design addresses garment requirements regarding comfort, scalability, and reliability by integrating novel concepts for distributed on-body processing, flexible interfaces, as well as failsafe interconnections. These properties allowed us to deploy SMASH in several applications. While we demonstrated that our design and prototyping approach can be successfully applied, we identified specific limitations of current smart garment implementations. To this end, a crucial area for further work is the identification and compensation of garment-related sensor deviations, in particular for motion and posture sensing.

The SMASH system architecture focused on flexible sensor use and scalable resources. These properties were essential to deploy the SMASH system in different prototyping phases that have diverse requirements on sensor integration and processing resources. However, as SMASH is a prototyping system, it lacks comfort optimizations for a particular application. The garment is vital though, to identify specific requirements and optimizations targets from user and application evaluations – which is the main objective of SMASH.

For advanced prototyping phases SMASH can perform standard processing tasks for activity and context recognition, including signal preprocessing, feature processing, as well as pattern recognition and data fusion. We demonstrated in this work that SMASH supports posture recognition tasks for exercise support, control of home appliances, and rehabilitation of children. While these investigations showed the garment’s prototyping potential, our ongoing work aims to integrate other sensing modalities, such as magnetic field sensors and gyroscopes, for further dynamic movement based application studies.
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References


