D5.8
WEKIT Wearable Design Solutions

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WEKIT Wearable Design Solutions

WP 5 | D5.8

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Table of Contents

Revision History 2
Table of Contents 4
List of Figures 6
List of Tables 6
Executive Summary 7
1. Introduction 8
2. Methodology 9
   3. Key Design Considerations from Design Methodology for Wearability (WP5.1) 9
   4. WEKIT Wearable Design Solutions Methodology 11
5. Development Process of New Prototypes 11
   6. Determining Design Objectives 12
   7. Design Integration 12
   8. Design Characteristics 12
9. Initial Design 13
   10. Garment 1 14
   11. Garment 2 14
   12. Refinement pre-fabrication 16
13. Fabrication 18
   14. Garment 1 18
   15. Iteration 2: 18
   16. Iteration 3: 19
   17. Iteration 4: 19
   18. Garment 2 19
   19. Iteration 2: 19
   20. Iteration 3: 19
   21. Iteration 4: 19
22. Testing 22
23. Other Design Solutions 23
List of Figures

FIGURE 1: SENSOR ARRANGEMENT CONSENSUS FROM THE SET OF PARTICIPATORY DESIGN WORKSHOPS, CONSOLIDATED FROM EXERCISES WITHIN EACH CASE-SPECIFIC WORKSHOP ................................................................. 13
FIGURE 2: INITIAL DESIGN FOR GARMENT 1 ........................................................................ 14
FIGURE 3: INITIAL DESIGN FOR GARMENT 2 ........................................................................ 15
FIGURE 4: (LEFT) SCHEMATIC OF EMBEDDED WIRE CHANNELS (RIGHT) INITIAL TEMPLATE FOR PATTERN-CUTTING ................................................................. 16
FIGURE 5: DECIDING THE EXACT PLACEMENT OF ELECTRONICS ON THE INITIAL DRAFTS OF EACH GARMENT ........................................................................ 18
FIGURE 6: VARIOUS IMAGES FROM THE CONSTRUCTION PROCESS i) USING MASKING TAPE TO INDICATE WHERE WIRE CHANNELS SHOULD BE LOCATED ii) THREADING WIRES THROUGH THE CHANNELS iii) IMU SENSOR WITH CUSTOM PCB AND CONNECTOR iv) 3D PRINTED ENCLOSURE FOR PCB/ESP32, WITH SENSORS ATTACHED VIA SOFT SILICONE-INSULATED WIRES. ........................................................................ 20
FIGURE 7: AN EXAMPLE OF REVISION NOTES DURING DESIGN ITERATIONS ......................... 20
FIGURE 8: FINAL VERSION OF GARMENT 1 ........................................................................ 21
FIGURE 9: FINAL VERSION OF GARMENT 2 ........................................................................ 21
FIGURE 10: GARMENT 1 BEING WORN IN A WEKIT TRIAL AT ALTÉC’S FACILITY ................. 22
FIGURE 11: THREE TYPES OF HARNESS INITIALLY CONSIDERED ........................................ 23
FIGURE 12: INITIAL SCHEMATIC FOR GARMENT 3 .................................................................. 24
    FIGURE 13: INITIAL PROTOTYPE OF GARMENT 3 ................................................................. 25
    FIGURE 14: ELECTRONICS FOR GARMENT 3 ...................................................................... 25

List of Tables

TABLE 1: WEARABILITY FACTORS FOR SKIN INTERFACES, XIN LIU ET AL [1] ...................... 9
TABLE 2: MATERIAL SELECTION PROCESS ........................................................................... 17
Executive Summary

Relation to WEKIT Objectives

As per the previous deliverable on this theme, D5.2, the goal here is to refine the wearables design methodology via iterative user test cycles, to develop and evaluate design solutions for WP3 and WP4, and then to assess ways to begin to disseminate and exploit the findings and the design solutions. The Wearable Design Solution (WP5.8) is derived from the outputs and results of the Design Methodology for Wearability (WP5.1), Wearable Design Solutions I (WP5.2), Design Methodology for Wearability and Ergonomics (WP5.11). The solution has implemented the result of the Sensor Technology Specification (WP3.1), Wearable capturing platform (WP3.2). The Introduction lists the types of sensors now supported.

T5.2 is the key bridging task for all of this. In that task, we integrated the experience capturing WP3-prototype and created a wearable design solution responding to the recommendations. We considered wearability factors and design options (eg use of new materials and advanced manufacturing techniques and design applications). User test cycles will continue and will be executed as defined in the Design Methodology. Results have been fed back in cycles to WP3 for final technological improvement, culminating in the final design solutions soon to be released for potential Open Access.

Methods

Following the initial garment designs of WP5.2 and the proposed Sensor Specifications of WP3.1, we conducted participatory design workshops (WP5.11) to determine the final design specifications of the Wearable Design Solutions in accordance with their intended industrial use-cases. This document details the design, prototyping and evaluation of (initially) two sensor-containing garments developed in parallel, based on the above specifications.

Results

Both garments were tested in numerous design iterations and then during WEKIT industrial trials. We found the use of complete garments presented numerous challenges, specifically providing an inadequate means of securing sensors to a wide range of body shapes over wide-ranging environmental conditions, and additionally found each design iteration to be costly and time-consuming. Thus, a third and final garment design was produced, based on an adjustable harness which was found to be far cheaper, more easily manufactured and more robust to variations in body shape and environmental temperature. Garment-based technology is still a nascent field and as such our experiments here have identified a set of guiding principles, which we present in our Conclusions.
1. Introduction

Wearable technology has seen great progress in recent years, with smart-watch sales peaking at 8.1m in Q4 2015 (statista) and reality augmenting glasses from Intel, Microsoft and Snapchat greenlighting the next phase in human-computer interaction. Technology embedded directly into clothing has been somewhat more limited, though 2018 has seen big-brand offerings such as Under Armour’s Hovr line of GPS-tracking running shoes and Levi’s Commuter Jacket featuring Google’s Project Jaquard technology. The latter example is notable for incorporating capacitive fibres into the yarn, rendering the garment itself a touch interface.

This work package details the design, fabrication and testing of WEKIT’s experience-capturing garment in two iterations. Preliminary iterations are described in WP5.2 however further developments were necessary as the industrial use-cases and sensor components (WP3) evolved. The final set of electronics comprised:

- Photoplethysmography (PPG) pulse sensor
- Galvanic skin response (GSR)
- Temperature and humidity sensing of both the user’s skin and the environment
- 9-axis inertia (IMU) at two points on the body (accelerometer, gyroscope and magnetometer)
- Myo electromyography (EMG) armbands for tracking hand movements
- Microsoft Hololens heads-up display with Simultaneous Localisation and Mapping
- Custom ESP32 based PCB and battery for powering and communicating with sensors
- Two vibration motors for haptic feedback
- An external computer for capturing and logging the sensor data, incorporating datastream processing for real-time visualisation on the Hololens (WP4.4)

The garments are to be used in conjunction with the AR display in the WEKIT trials, initially being worn by an expert to record the steps of each task, and then by the cohort of volunteer experimental subjects acting as trainees. Questionnaires given after the task will evaluate the trainees’ knowledge retention, and whether this was improved by the AR interface as compared to a control group. Additionally, a support vector machine (SVM) classifier will investigate whether data captured from the garment can predict the degree of knowledge retention (WP4.4), and further work will consider how this can inform live feedback to improve performance during the task itself.

The garment will be utilised in two trial scenarios - performing maintenance work on an air ambulance helicopter at Lufttransport’s hangar in Tromso, Norway, and performing maintenance and repairs on a Mars Rover vehicle at Altec’s space-mission training facility in Turin, Italy. The medical use-case scenario used only the Hololens, so garments were only required for the space and aerospace cases.
2. Methodology

3. Key Design Considerations from Design Methodology for Wearability (WP5.1)

Much of the methodology given in Design Methodology for Wearability (WP5.1), was referenced as a basis for initial methodology and design guidelines. This section references some key extracts here for convenience. In the Executive Summary for 5.1, the key consideration was that the material devices, sensors or technologies will go through a sequential process of:

- Selection
- Placement and
- Integration

Of particular importance was the role body and device factors in relation to Wearability of Skin Interfaces. These are important as the WEKIT sensor system uses skin linked sensors for Heart Rate Variability, Temperature and Galvanic Skin Response (GSR) data gathering. Key factors were given in Xin Liu et al [1] listed in Table 1.

| Table 1. Wearability Factors for Skin Interfaces, Xin Liu et al [1] |
|---|---|---|
| **Factors** | **Wearables** | **Skin Interfaces** |
| Location | Clothing and accessories | Skin and its appendages (i.e., hair and nails) |
| Body movements | Micro and macro movements | Extra skin movements (stretch, shear, bounce) |
| Body characteristics | Size, shape, muscle strength, constantly evolving | Skin characteristics, skin types, wrinkles, purples, skin hair, color, moisturization, abrasion, contusions, eczema, rash, irritation, etc. |
| Weight | Heavy devices may be uncomfortable to wear | Heavy devices may cause encumbrance, annoyance, fatigue, injury or falls |
| Attachment methods | Garments, accessories, clips | Skin glue, hair accessories, piercing, bands Underneath the clothing and accessories |
| Accessibility | Visual, tactile, auditory or kinesthetic access on the body | Underneath the clothing and accessories, surgical |
| Interaction | Sensors and actuators | Sensors and actuators, direct and sympathetic |
| Aesthetics | Electronics could be invisible or visible, shapes, materials, textures and colors | Electronics could be invisible or visible, tattoo, cosmetics, prosthetics, artificial nails and hair |
| Conductors | Commercialized rigid and flexible PCB; cables; Conductive fabric, yarns for clothing applications | Conductive ink, Conductive Cosmetics Epidural Electronics Systems Fluid Metal |
| Insulation | Soft materials and rigid materials | Skin-friendly materials are highly preferred; Avoid electronics directly in contact with skin; Body shielding or grounding the body |
| Device care | Washability | Removing and reattaching methods; Encapsulation; Protection from showering, water, salt, oil |
| Connection | As part of clothing (conductive yarns & threads); Rigid components can be adapted to common PCB fabrication process. | Low-temperature solder, Conductive adhesives; Direct contact with pressure |
| Communication | Wiring; Wireless Communication: Bluetooth, Wi-Fi, radio, etc. | Customized antenna (RFID, NFC/inductive, nanotechnology), capacitive PAN, optical, Miniature electronics with BLE-Wi-Fi chip, Wired connection to a wearable |
| Battery life | Rechargeable commercial batteries | Ultra-thin battery requirement; Energy harvesting, wireless charging |

Of the factors discussed, Environment and Fabric considerations were key. The following extracts refer to those factors:
Environment:
Whether monitoring the internal or external spaces of aircraft, operating theatres or space stations is being considered, environmental factors must be ascertained in order to ensure systems are kept operational. Such factors include microbial transmission, cosmic radiation and micrometeorites as well as pressure, humidity and turbulence. Environmental signals and factors that move effect from one location to another or simply intensify or alter them within a localised space or time are essential for designing wearables. Typically, this includes factors such as waterproofing, protection against radiation as well as buffering from mechanical forces or noise that is either visual, auditory, chemical or electrical.

Fabric:
A wearable technology is often incorporated into clothing and as such may have to work in concert with the fabric of that clothing in order to work. The fabric may be waterproof to protect the device or heat resistant to ensure it can survive high-temperature operating environments.

In designing the garments, their physical and cognitive burdens needed to be minimised as emphasised by DeVaul et al. [2] indicating that “user interfaces shall maximize provided information value while minimizing physical and cognitive burdens imposed by accessing it.”

Of the Soft Design features the following were considered to be relevant in the prototype design:

- **Visibility**: When should a technology be visible if at all? Must it be visible in different ways under different conditions?
- **Portability**: How will the tech be attached or carried and what size will it be?
- **Accessibility/Availability**: Will the tech be in use constantly and how easily will it be able to be controlled?

Ergonomic Affordance How will the technology fit in with the current user’s personal space as well as extended environment? Will it interfere with other activities or operations, physical functions or psychological states?

Dunne and Smyth [3] state that clothing comfort is generally believed to be influenced by the following factors:

- Pressure/Constriction
- Texture
- Thermal balance
- Moisture transport
- Freedom of movement

Gemperle et al. [4], suggest design guidelines based on Positioning and Convenience that are intended to communicate the considerations and principles necessary for the design of wearable products.


Factors affecting users’ discomfort in a wearable garment can include those referenced by Kazuya Murao et al. [7]. A list of these factors includes:
● Low Wearability
● Strange appearance
● Modes of operation
● Learning/Application Task.
● Maintenance Repair
● Economic Sustainability
● Interoperability
● Style Design
● Fashion
● Branding/Commerce

An overview of design challenges of real wearables was given by Reiss and Amft [8]. This included reference to Harms et al. [9] who built a torso-worn system into a loose fitting long sleeve shirt. Harms et al. created a balanced distribution of terminals over the entire body and limiting wiring stretches below 85 cm. Reiss and Amft also refer to Curone et al. [10]. They used three garment components: a T-shirt as inner garment, a jacket as outer garment, and a pair of boots. Each component was sensor-equipped for real-time monitoring of physiological, activity, and environmental parameters.

It was thought that some components of the WEKIT prototype could be integrated into belt-based design. Amft et al. [11] presented a belt-integrated wearable computer called QBIC, where main system electronics running Linux had been integrated into the belt buckle, including microcontroller, memory, and wireless interfaces. The belt itself was used as extension bus and mechanical support for interfaces, consisting of two layers of leather with a flex-print wiring system in between. Belt interfaces included a head-mounted display connector, as well as RS232 and USB ports.

4. WEKIT Wearable Design Solutions Methodology

We have used user-centred method combined with practice-based design approach; we integrated the participatory design outcomes into the design development cycles. The participatory design process included:

1. Initial discovery process
2. Exploration
3. Participatory prototyping process
4. Design development cycles (put the findings in design practice based on Wearability of Workplace Integration including major factors of user-centred methods including usability, comfortability and practicality)
5. Working closely with fashion designers and sample machinists as part of the practice-based design approach we created sample pieces as proof of concept prototypes.

5. Development Process of New Prototypes

WP5.11 defined the participatory design outcomes. Based on these outcomes with consideration to WP5.2 outcomes (review of initial prototypes) design objective have been established as part of the practice-based design research process.
After the review of the three initial prototypes, the design objectives were the following:

6. **Determining Design Objectives**
   - Analysis of the current situation and co-construction of problem formulation
   - Conceptualisation of design, designing and evaluating possible design solutions
   - Implementing changes including training people for new practices
   - Evaluation, maintenance and ongoing improvements
   - Iterative design.
   - Temperature/Humidity Sensor, Inertial Measurement Unit (IMU) Accelerometer/Gyroscope for Motion/Position, Vibration Motors

7. **Design Integration**
   - Integration of all sensors (including on skin sensors) based on Wearability specifications (WP5.11)
   - Integration of battery pack based on Wearability specifications (WP5.11)
   - Integration of wires based on Wearability specifications (WP5.11)
   - Integration with HoloLens based on Wearability specifications (WP5.11)

8. **Design Characteristics**
   Following the literature review of Section 8 the following key characteristics were proposed for WEKIT garments:
   - Comfort
   - Freedom of movement around the arms and hands
   - Breathable
   - Insulating
   - Weight of garment
   - Compensation in the outfit for temperature / humidity to allow for accurate measurement of body and workplace temperature.

Participatory design workshops were conducted at Ravensbourne for each of the use-case scenarios, with experts from the respective industries offering guidance and criticism on design considerations including sensor placement, materials selection, ergonomics and any other application-specific features or requirements.
Figure 1. Sensor arrangement consensus from the set of participatory design workshops, consolidated from exercises within each case-specific workshop. Marker numbers indicate component type (e.g. 1 = ESP32, 2 = battery, etc) and colours indicate use-case.

Key considerations identified by all trial partners were that the garment must be comfortable, flexible and not interfere with the wearers’ ability to carry out their tasks within the environment. Within WEKIT and Ravensbourne technical meetings we identified additional constraints that the garment must:

1. Keep the PPG, GSR, EMG and temperature/humidity sensors in direct, fixed contact with the skin
2. Accommodate the full range of adult human body shapes
3. Be comfortable to wear across the varied temperatures of both the aerospace (Norwegian Arctic Circle, -20 -> 20°C) and space (Turin, -3 -> 30°C) use cases.
4. Securely embed the electronics and wires such that they do not protrude into the environment nor irritate the wearer
5. Accommodate rapid donning and doffing plus relatively easy access to individual sensors for diagnostics and replacement if necessary

The requirements that the garment be optimised for comfort in hot and cold environments were seemingly at odds with one another, as were the requirements it be simultaneously tight-fitting, comfortable/flexible and suitable for all body shapes and sizes. Coupling this with the research-driven nature of the project it was decided to proceed with the development of two garments in parallel.

9. Initial Design

We set up a practice-based research and development cycle where garment designs were produced based on the design objectives and reviewed based on the requirements. The designs were produced by fashion design professionals in collaboration with fashion design students. After four design review processes there was the practical prototype development cycles. The first prototype
was trailed on users based on Design Characteristics and improved for the second design development cycles. These processes were careful considerations by the design team in collaboration with the production team and mechanist. The second review process have been within the actual work environment gaining feedback from the actual users (see Testing section). The final garments (Garment 1/ Garment 2) were then produced based on the Testing at workplace.

10. Garment 1

The following two-piece design consists of a tight-fitting interior layer of thin Lycra to house the skin-contact sensors and a vest on the outside to house the bulkier components. Adjustable for better fit via straps with buckle fastenings. The idea behind the design was to create a flexible and adjustable garment solution where the tighter fitted shirt would carry the on skin sensors and the vest would facilitate battery and items that do not need to take near-body measurements. Buckles allowed adjustment on the body for comfort.

![Figure 2. Initial design for Garment 1](image)

11. Garment 2

This design solution was inspired by sportswear design processes and combined lycra and neoprene materials for better comfort. The valco stripes allowed full adjustment on the body.
Figure 3. Initial design for Garment 2
12. Refinement pre-fabrication

Figure 4. (left) schematic of embedded wire channels (right) initial template for pattern-cutting

Following the initial rough-designs of Section 2 a network of embedded channels for wires connecting each of the sensors to the PCB was added. It was decided to use flexible insulating wires (as opposed to more experimental approaches such as conductive fabrics) since they are readily available and capable of multi-channel transmission of power and data. As a means of simplification Garment 2 was redesigned as a purely upper-body piece. Discussions with the pattern-cutter and machinist yielded additional simplifications to Garment 2 in particular, following which patterns were drawn up for cutting.

Some of the material selection process is summarised in Table 2.
Table 2. Material Selection Process

<table>
<thead>
<tr>
<th>Fabric function</th>
<th>Possibility 1</th>
<th>Possibility 2</th>
<th>Possibility 3</th>
<th>Quantity more or less</th>
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<tr>
<td>Outside layer thermo control</td>
<td>Outlast Xelerate¹</td>
<td>Dryarn²</td>
<td>2dry. Siti Spa.³</td>
<td>1,50 m</td>
</tr>
<tr>
<td>Outside layer breathing areas</td>
<td>HeatGear Armstrong⁴</td>
<td>Coolmax⁵</td>
<td>Nanotex moisture management⁶</td>
<td>1m as max</td>
</tr>
<tr>
<td>2-layer skin contact</td>
<td>Superouboux, or lycra⁷</td>
<td>Gemme merino e tencel</td>
<td>Microsense Sitip Spa⁹</td>
<td>1,70 m</td>
</tr>
<tr>
<td>Compression areas</td>
<td>2xu compression¹¹</td>
<td>Skins A400¹²</td>
<td>Lycra¹³ Eurojersey:sensitive sculpt¹⁴</td>
<td>0,80m more or less</td>
</tr>
<tr>
<td>Padding reinforce area</td>
<td>D3o</td>
<td></td>
<td>Memory foam (easy to find I’ve a storage of it yet) or thermolite</td>
<td></td>
</tr>
<tr>
<td>Velcro</td>
<td>Morito¹⁵ (some examples¹⁶)</td>
<td>LYNx¹⁷</td>
<td>Powerhook: YKK¹⁸</td>
<td></td>
</tr>
</tbody>
</table>

¹ http://www.outlast.com/en/technology/
³ http://www.sitip.it/i-marchi-sitip/
⁵ https://coolmax.com/en/About-the-COOLMAX-Brand/The-COOLMAX-brand
⁶ https://www.nanotex.com/coolest-comfort/
⁷ https://www.marcellobergamo.it
⁸ http://www.giemme-tessuti.it/ita/tessuti/finescence/#3
⁹ http://www.sitip.it/i-marchi-sitip/tessuto-comfort-in-microfibra/
¹⁰ http://www.sensitivefabrics.it/it/tessuti-indemagliabili/ricerca-tessuti.html#EASY-CARE
¹² https://www.skins.net/eu/product-comparison/
¹⁴ http://www.sensitivefabrics.it/it/tessuti-indemagliabili/ricerca-tessuti.html
¹⁵ http://www.morito.co.jp/english/jigyo/apparel.htm
¹⁷ http://www.lynxfast.com/index.php
13. Fabrication

Initially Garments 1 & 2 were fabricated without the wire channels or pockets for individual sensors, to allow for early criticism and feedback and to accommodate continuing refinements at the electronics end.

Figure 5. Deciding the exact placement of electronics on the initial drafts of each garment

Subsequent design/production iterations are detailed below:

14. Garment 1

15. Iteration 2:
   - Sensor pockets and wire channels added
   - Length of outer layer increased to waistline
   - Battery pocket rotated 90 degrees to increase comfort
   - Waist band of outer layer found to be too loose even when maximally tightened

18 https://www.ykkfastening.com/products/hook_loop/powerhook/
16. **Iteration 3:**
   - Sleeves extended to wrist on each side, with elasticated section above the elbow to accommodate Myo armbands
   - Wire channels attached with Velcro (they were previously stitched at both edges), since threading wires across the length of the garment proved to be difficult
   - Sensor pockets expanded to accommodate 3D printed enclosures for the sensors
   - Waist band of outer layer still found to be too loose even when maximally tightened

17. **Iteration 4:**
   - Pockets for battery and electronics extruded out from the garment to improve body-conformance
   - Decision to keep the two components of the garment fully separate, with a 16 pin DIN connector to join wires at the interface. A Velcro flap added between the shoulders to accommodate this.
   - Waist band of outer layer still found to be too loose even when maximally tightened.

18. **Garment 2**

19. **Iteration 2:**
   - Pockets and channels added
   - Garment was found to be too tight to don and doff so zips were added along the sides of the chest

20. **Iteration 3:**
   - Velcro fastenings around the waist were found to be weak and replaced with a buckle
   - Pockets for battery and electronics extruded out from the garment to improve body-conformance

21. **Iteration 4:**
   - Pockets and channels revised to accommodate 3D printed enclosures for the sensors
   - Channels revised to accommodate zips
   - Breathable fabric on the chest was found to be too transparent and replaced
Figure 6. Various images from the construction process i) Using masking tape to indicate where wire channels should be located ii) Threading wires through the channels iii) IMU sensor with custom PCB and connector iv) 3D printed enclosure for PCB/ESP32, with sensors attached via soft silicone-insulated wires.

Figure 7. An example of revision notes during design iterations

Each garment was produced in small, medium and large sizes resulting in a total of six garments. The three sizes were produced at different stages of the iterative process, so for some garments revisions were merely added in whereas for others they were integrated from scratch.
Figure 8. Final version of Garment 1

Figure 9. Final version of Garment 2
22. Testing

The garments were taken to Lufttransport for use in a WEKIT trial, however due to time constraints the iterations were only at around Step 2, so Garment 1 was only available in medium and Garment 2 only in small. Numerous issues with the electronics and HoloLens components prevented the trials from taking place so they have been rescheduled. However, the testing in-situ revealed issues that informed further iterations, notably the need for Velcro wire channels and 16 pin DIN connector in Garment 1. Garment 2 was found to be too small for anybody present while the process of putting on and removing Garment 1 was found to be cumbersome.

The finalized garments were put to use in trials at Altec’s facility, however numerous issues were revealed:

- All sizes of garment 2 were found to be a poor fit for any of the available participants
- Garment 1, supposedly optimized for hotter environments, was found to be unpleasantly hot to wear in the 28°C hangar
- Quality of the sensor readings was found to be unreliable, due in part to the garments being too loose on some participants

![Garment 1 being worn in a WEKIT trial at Altec’s facility](image)

For both trials it was agreed that a second attempt would be necessary, which has now been scheduled for September. Whilst considering the next stages of revisions to the garments, it was decided to instead abandon this approach completely in favour of a harness-based design. Reasons for this include:

- Adjustable straps allow a single device to accommodate all body shapes and sizes
- Greater simplicity would allow for much faster iterations
- Two orders of magnitude less costly to produce

Adaptable for a greater range of environments, since existing environmental apparel can be worn over the top:

- Easier to keep clean
- Considerably smaller footprint for transportation

After the testing we have produced the final garment solutions.
23. Other Design Solutions

Initially three types of harness were considered (Figure 11), from which the third harness was selected for its simplicity and versatility. An initial schematic of the new design was produced (Figure 12), however it was then decided to relocate the pulse and both temperature/humidity sensors to the wristband alongside GSR, with an additional accelerometer to compensate for motion artefacts (WP4.4).

Figure 11. Three types of harness initially considered
The selected harness featured elasticated straps, which formed a network suitable for wires connecting to each of the sensors. However, acquiring wires capable of accommodating the stretching proved difficult as stretchable electronics is a research field very much in its infancy. As such it was decided to embed the wires into a generic polypropylene webbing strap running in parallel to the elastic elements. The straps, which do not stretch, were sized to accommodate the largest anticipated body shape, resulting in a protrusion when worn by smaller subjects (Figure 13), however this could be remedied through adjustable fastenings to absorb the slack, as seen in items such as rucksacks that use the same webbing strap. Additional fixings for the upper-arm and wrist components were produced from generic Velcro watch straps. We found this to be a superior means for securing sensors to the body when compared with the previous garments.

Being made largely from off-the-shelf components, Garment 3 was considerably quicker to prototype. Straps were initially pinned into place on the mannequin, and once configurations and sizing's were finalised they were secured through combinations of glue, stitching and 3D printed nodes.

Figure 12. Initial schematic for Garment 3
Figure 13. Initial prototype of Garment 3. Note the protrusion of the webbing strap in regions where the webbing strap has been sized to accommodate larger body types.

Figure 14. Electronics for Garment 3 i) & ii) the wrist strap containing pulse, GSR, skin and environmental temperature/humidity sensors and an IMU for motion compensation, iii) Enclosure for motherboard (custom WEKIT PCB+ESP32) and battery located on the back.
24. Conclusions

The harness design, whilst still undergoing refinements, appears to be a superior approach for gathering the full set of biometric data across the variety of participants and is on track for deployment to the upcoming WEKIT trials in September. Garment based wearable technology is still an emerging field, so this component of WEKIT has been largely experimental and has revealed a number of guiding principles for the design and prototyping of such devices:

- Wearables pose a greater complexity than conventional garments and thus it is preferable to consider a single adjustable design rather than producing multiple sizes.
- When providing technology to be deployed across a range of environments it is wise to think as minimally as possible, favouring ease of integration with existing environmental wear over producing bespoke case-specific wearables.
- Where timing permits, it is advisable to prototype a single item and then test as thoroughly as possible rather than producing duplicates/variations in parallel.
- Wearables for industrial applications are likely to have multiple users in succession. Complete garments require regular washing which in turn requires removal and replacement of certain electronic components. Thus, wearable designs should be as modular as possible and keep areas of contact with the body to a minimum to reduce and simplify maintenance.
25. References

[1] Xin Liu, Katia Vega, Pattie Maes, Joe A. Paradiso, Wearability Factors for Skin Interfaces, Proceeding, AH ’16, 7th Augmented Human International Conference 2016, Article No. 21


