Communicating Semantic Content to Persons with Deafblindness by Haptograms and Smart Textiles: Theoretical Approach and Methodology

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Abstract— **By means of a proof-of-concept prototype, which is work in progress, we adopted a multidisciplinary approach to develop a smart-textile-based communication system for use by people with deafblindness. In this system, sensor technologies and computer vision are used to detect environmental cues such as presence of obstacles, faces, objects, etc. Focusing on the communication module here, a new ontology connects visual analytics with the user to label detected semantic content about objects, persons and situations for navigation and situational awareness. Such labelled content is then translated to a haptogram vocabulary with static vs. dynamic patterns, which are mapped to the body. A haptogram denotes a tactile symbol composed over a touchscreen, its dynamic nature referring to the act of writing or drawing. A vest made of smart textile, in the current variant equipped with a 4 x 4 grid of vibrotactile actuators, is used to transmit haptograms on the user's back. Thereby system messages of different complexity -- both alerts and short sentences -- can be received by the user, who then has the option to respond by pre-coded questions and messages. By means of grids with more actuators, displays with higher resolution can be implemented and tested, paving the way for an extended haptogram vocabulary, covering more detailed ontology content.**

Keywords - deafblind communication; haptograms; word and sentence semantics; ontology; smart textiles.

I. INTRODUCTION

Communication with and between people with deafblindness is constrained by the nature of the condition and the lack of supportive tools and societal structures. This study explores novel communication modes for this group.

Deafblindness refers to a unique combination of vision and hearing loss, where the level of loss in either senses is such that it does not allow compensation of one impaired sense by the other. This condition in its various forms, ranging from congenital (i.e., present at birth or acquired prior to language development) to acquired (i.e., due to illness, accident or ageing), involves a broad diversity in abilities. Based on [1], we report work in progress that aims to address communication challenges that accompany deafblindness. Our approach combines a simple conceptual language, with navigation, situational awareness and communication components. The communication is conducted by means of haptic stimuli, projected on appropriate parts of the human body via a smart textile screen, and is intended to be useful across the complete spectrum of this condition.

Our research is carried out in the SUITCEYES (https://suitceyes.eu/) EU Research and Innovation Action project, with the mission to deploy a prototype which is wearable, combines situational awareness, visual analytics and communication by a joint ontology, and works in distance mode by wireless connection as a default. Instead of a combination of elements of touch, e.g., consecutive dots, dashes and strokes by hand to encode characters and their sequences, we propose to use haptograms, where the limited size and resolution of a body part as screen is counterbalanced by evolving patterns, i.e., the dynamics of signs. Our effort is in line with the approach by [2], building on their Tactile Brush findings. However, the focus here is on language design by means of an ontology-compliant vocabulary vs. grammar, where the latter implements relational contextualization and sign sequencing. Thus, our work belongs to the category of a priori defined spatial-temporal patterns in the semiotic vein. Here we will discuss the integration of ontology, haptograms and textile aspects only from a theoretical and methodological perspective.

The rest of the paper is structured as follows: Section II reviews research in haptics relevant to our design considerations, contrasted with its respective linguistic underpinnings. Section III introduces the SUITCEYES ontology that plays the role of the unified model for semantic integration of information from the environment, while Section IV presents our approach for designing the haptogram vocabulary. Section V discusses implementation in smart textile, whereas Section VI concludes the paper and refers to future work directions.

II. RELATED RESEARCH

A. *Research in haptics relevant to our design*

For haptogram development we were inspired by [3], and [4], where the authors' work expands over multiple decades. Their approach, Social Haptic Communication (SHC), basically reproduces ideograms on different regions of the body by a combination of hand strokes, gestures, pressure, etc. For this, they developed a rich set of tactile signs, compiled into a simple language with its own syntax built from *haptemes*, i.e., building blocks of touch, and vocabulary of so-called *haptices*, tailored to a range of situations and topics of great practical importance for the receiver. At the same time, due

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to its consensual nature, this approach is idiosyncratic, and in its social mode unable to be applied at a distance.

The above phonemic approach in [4] finds support from [5], where the authors found that decomposing language into phonemes that are transcribed into unique vibrotactile patterns enables people to receive lexical messages on the arm. A potential barrier to adopting this new communication system is the time and effort required to learn the association between phonemes and vibrotactile patterns. However, their study was limited to the learning of 100 patterns by different methodologies, displayed on the arm, and the concepts were not connected to an ontology.

On the other hand, in [6], the authors experimented with a new tactile speech device based on the presentation of phonemic-based tactile codes. The device consisted of 24 tactors, under independent control for stimulation at the elbow to wrist area. Using properties that included frequency and waveform of stimulation, amplitude, spatial location, and movement characteristics, unique tactile codes were designed for 39 consonant and vowel phonemes of the English language. The participants, 10 young adults, were then trained to identify sets of consonants and vowels, before being tested on the full set of 39 tactile codes.

In [7], the authors investigated several haptic interfaces designed to reduce mistakes in Morse code reception of 12 characters. Results concluded that a bimanual setup, discriminating dots/dashes by left/right location, reduced the amount of errors to only 56.6% of the errors compared to a unimanual setup that used temporal discrimination to distinguish dots and dashes.

Very much in line with what we would like to achieve, the authors in [2] proposed Tactile Brush, an algorithm that produces smooth, two-dimensional tactile moving strokes with varying frequency, intensity, velocity and direction of motion. The design of the algorithm was derived from the results of psychophysical investigations of two tactile illusions, *apparent tactile motion* and *phantom sensations*. Combined together they allowed for the design of high-density two-dimensional tactile displays using sparse vibrotactile arrays. In a series of experiments and evaluations, they demonstrated that Tactile Brush is robust and can reliably generate a wide variety of moving tactile sensations for a broad range of applications.

Another related track of research [8] conducted four experiments to evaluate tactile localization and tactile pattern recognition on the torso by means of a one-dimensional eight-tactor display vs. a two-dimensional 16-tactor display to present tactile cues to the waist and back, respectively. They found that a display with eight tactors mounted circumferentially around the waist can provide tactile cues that are perceived very accurately in terms of the location of stimulation, whereas the 16-tactor array on the back was found to be inadequate to support precise spatial mapping, but an array with fewer elements could provide such spatial cues, so that simple navigational and instructional commands can be presented tactually on the torso. These findings were augmented in [9], where the authors evaluated the effectiveness of tactile displays either on the forearm or the back to communicate simple instructions and commands in a military context. Their results suggested that with the judicious selection of tactile patterns both the arm and back provide a functional substrate for tactile communication.

A next source of inspiration was [10], which described a different domain of study. As in a situation of sensory overload, touch is a promising candidate for messaging given that it is our largest sensory organ with impressive spatial and temporal acuity, there is need for a theory that addresses the design of touch-based building blocks for expandable, efficient, rich and robust touch languages that are easy to learn and use; moreover, beyond design, there is a lack of implementation and evaluation theories for such languages. To overcome these limitations, he proposed a unified, theoretical framework, inspired by natural, spoken language, called *Somatic ABC's* for Articulating (designing), Building (developing) and Confirming (evaluating) touch-based languages. To evaluate the usefulness of Somatic ABC's, its design, implementation and evaluation theories were applied to create communication languages for two very unique application areas: audio-described movies, and motor learning. It was found that Somatic ABC's aided the design, development and evaluation of rich somatic languages with distinct and natural communication units.

Implementation-wise, the approach to conveying any tactile code to the body is often rather simple. Glued-on solutions or non-compliant devices are common in many of the more research-oriented studies. For more technical descriptions with users in focus, textiles and garment have been employed and are described by many [11], [12]. The interest in the literature is typically in the hardware and its control system, which soon becomes problematic when the number of actuators and connections increases. Gaming has attracted a lot of interest. By far the most common haptic output device used is the vibrator, denoted vibrotactile element (VTE), with textile aspects being secondary. In [13], the authors provide a solution with pieces made out of neoprene, which is stretchy. Hook-and-loop fasteners were used to keep five large pieces (for left shoulder, right shoulder, left elbow, right elbow, wrist belt) together. Comfort was not discussed, neither was wiring. What was denoted heavy weight Lycra was used in a harness design in [14], in order to achieve tightness and close fit to the body. Assembly and design were not in focus. The authors in [15] used a tight-fitting T-shirt in a study of haptic elements for promoting motion training. Once again, the technical focus was on the hardware. In general, there are few studies where the role of textile and the construction thereof is central.

B. Semantic theories underlying haptograms

Semantic content in language is manifest by means of word vs. sentence meaning. To pin down word semantic vs. sentence semantic theories which can help one identify kinds of meaning implementable for deafblind communication, we took inspiration from Chinese *logograms* representing concepts, instead of characters that stand for speech sounds. They come as a blend from different directions and schools of semantic research [16]. More importantly, one can apply touch primitives to create haptic drawings for concepts, with connections to several semantic theories briefly listed below.

To conceive a set of actuator patterns, which correspond to units in a mental vocabulary, partly overlapping with ontology labels, *semantic primitives* [17] and *semantic universals* [18] were relevant points of departure. These include elementary, archetypical concepts such as substantives (*you, I; someone, people; something*), mental predicates (*think, know, want, feel, see, hear*), descriptors (*big, small*), temporality (*when, after, before, a long time, a short time, now*), etc., while their concatenations can be related to the *Language of Thought hypothesis* [19], a theory which describes the nature of thought as possessing "language-like" or compositional structure, with simple concepts combined in systematic ways (akin to the rules of grammar in language) so that in its most basic form, thought, like language, has syntax. Another aspect to connect semantic primitives as components of concepts with *haptemes* as components of touch [3] originates in structural linguistics [20]; here we chose the interpretation that *phonemes* constitute an abstract underlying representation for segments of words. *Distributional semantics* as in [21], [22], and [23] -- responsible for meaningfulness in dimensional reduction methods and feeding forward to the ontology -- adds another relevant semantic theory to the aforementioned, with statements derived from ontology labels by semantic reasoning going back to *logical semantics* [24]. Another umbrella term for the above in a deafblind context is the research field of *sign language semantics* [25]. A number of relevant PhD theses augmented our resources to relate semantics mapped to the body in a sensory deprivation context, e.g., [26], [27], and [28].

III. THE SUITCEYES ONTOLOGY

The key aim of the SUITCEYES ontology is to semantically integrate information coming from the environment (via sensors), and from the system's analytic components (e.g., visual analysis of camera feed). In this sense, the ontology is primarily focused on semantically representing aspects relevant to the users' context, in order to provide them with enhanced situational awareness, and augment their navigation and communication capabilities. More importantly, the proposed ontology also serves as the bridge between environmental cues and content communicated to the user via the haptograms described in the next section.

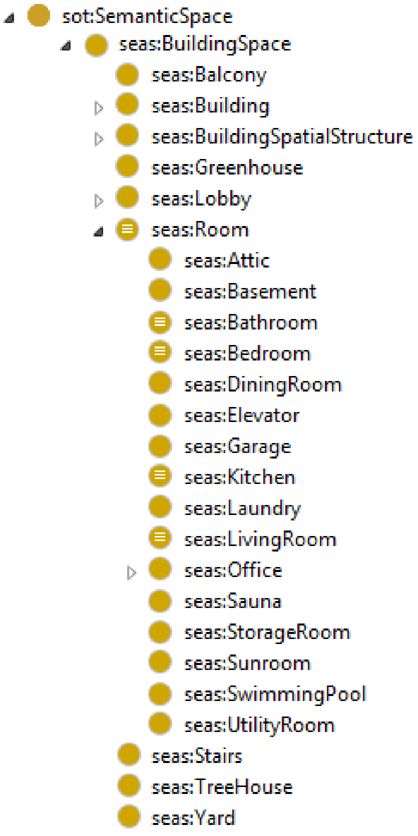
In ontology engineering, it is common practice to reuse existing third-party models and vocabularies during the development of a custom ontology, in order to rely on previously used and validated ontologies. We thus adopted the semantic representation of objects and activities from the Dem@Care ontology [29], [30], which contains a set of descriptions of everyday activities and common objects used in an everyday context that are highly relevant to our goals (e.g., mug, plate, toothbrush, furniture, window, door, etc.), all inspired by real case scenarios. Moreover, we relied on SOSA/SSN [31] for representing sensors and the respective observations, and on the Friend-Of-A-Friend (FOAF) specification [32] for representing persons and social associations. Finally, we integrated the SEAS (Smart Energy Aware Systems) Building Ontology [33], which is a schema for describing the core topological concepts of a building, such as buildings, building spaces and rooms. A summary of all imported ontologies is presented in Table 1. The hierarchy of concepts related to rooms and space, adopted from both Dem@Care and the SEAS Building Ontology, is visualized in Fig. 1. The latter set of concepts is grouped under the notion of *sot:SemanticSpace*, where *sot* is the namespace prefix for the SUITCEYES ontology. Moreover, we extended our ontology with additional concepts that emerged during the requirements analysis (see deliverables D2.1 and D2.2 posted on the project website) of our *Haptic, Intelligent, Personalised, Interface* (HIPI), which is a key SUITCEYES outcome.

The ontology, populated with the incoming information (i.e., detected persons, objects etc.), constitutes the system's Knowledge Base (KB). An additional component, the Knowledge Base Service (KBS) that sits "on top" of the KB, ensures that the incoming data are semantically annotated and fused properly into the KB, providing the groundwork for producing a higher-level interpretation of the combined information. The end goal is to enable the HIPI to deliver semantic content to the user with respect to his/her physical surroundings.

TABLE 1. A LIST OF THIRD-PARTY ONTOLOGIES UTILIZED AND EXTENDED WITHIN THE SUITCEYES ONTOLOGY

prefix	**Ontology**	**URL**	**Concepts**	**Imported in SUITCEYES version**
foaf	Friend-Of-A-Friend	http://xmlns.com/foaf/spec/	Person and its asserted properties	v1
sosa	Semantic Sensor Network	https://www.w3.org/TR/vocab-ssn/	Sensor and its asserted properties	v1
dem	Dem@Care	http://www.demcare.eu/results/ontologies	Activity Object Room and their asserted properties	v1 v1 v2
seas	Smart Energy Aware Systems Building Ontology	https://ci.mines-stetienne.fr/seas/BuildingOntology-1.0	BuildingSpace Room and their asserted properties	v2 v2

Finally, a rule-based semantic reasoning mechanism serves specific queries for inferring the context-related information, either in the form of structured content in JSON format, or as natural language phrases.



- sot:SemanticSpace
  - seas:BuildingSpace
    - seas:Balcony
    - seas:Building
    - seas:BuildingSpatialStructure
    - seas:Greenhouse
    - seas:Lobby
    - seas:Room
      - seas:Attic
      - seas:Basement
      - seas:Bathroom
      - seas:Bedroom
      - seas:DiningRoom
      - seas:Elevator
      - seas:Garage
      - seas:Kitchen
      - seas:Laundry
      - seas:LivingRoom
      - seas:Office
      - seas:Sauna
      - seas:StorageRoom
      - seas:Sunroom
      - seas:SwimmingPool
      - seas:UtilityRoom
    - seas:Stairs
    - seas:TreeHouse
    - seas:Yard

Figure 1. Concept hierarchy related to semantic space, which were adopted in the SUITCEYES ontology from Dem@Care and SEAS Building.

A. *Ontology conceptualization*

Fig. 2 displays an overview of the core ontology classes based on the Graffoo ontology visualization notation [34]: the yellow rectangles represent classes, while the green ones represent data properties (i.e., properties that take a raw data value, like, e.g., integers and strings). The prefixes in front of some of the class names indicate the namespace of the respective third-party ontologies, as mentioned above. Classes and properties that have no prefix belong to the core SUITCEYES ontology.

As indicated in Fig. 2, class *Detection* is fundamental within the context of the SUITCEYES ontology and refers to environmental cues detected by the sensors that have been instantiated in the KB. An instance of type *Detection* may be associated with the relevant sensor(s) that provide data to the ontology, via property *providedBy*. Currently, there are two specific categorizations of class *Sensor* (i.e., *Camera* and *iBeacon*), which are related to the relevant operational sensors attached to the HIPI and provide data to the KB. On the basis of the sensors' data, an instance of class *Detection* can be associated with one or more instances of type *Person* (known or unknown persons), *Object*, *Activity*, and/or *SemanticSpace* (i.e., rooms, building spaces, as previously described); the relevant assertion is achieved via property *detects*. On the basis of the semantic reasoning mechanism mentioned previously, higher-level results that combine incoming data from all sensors, are produced and represented in the ontology via class Output and its specializations: *Alert*, *Message*, and *Warning*.

With regard to spatial relations, we focus on orientation (left/right), existence (in a room) and distance (far/close/immediate). Thus, an entity that occupies space (e.g., persons, objects) is considered a *SpatialEntity*, and the occupied space (e.g., a room or a location) belongs to the *SemanticSpace*. These two aspects formulate the

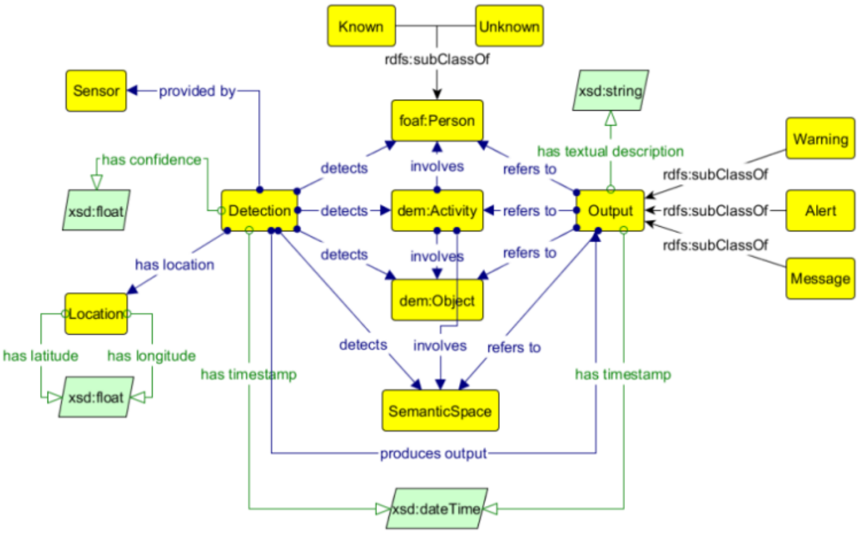


Figure 2. Overview of the core classes of the SUITCEYES ontology.

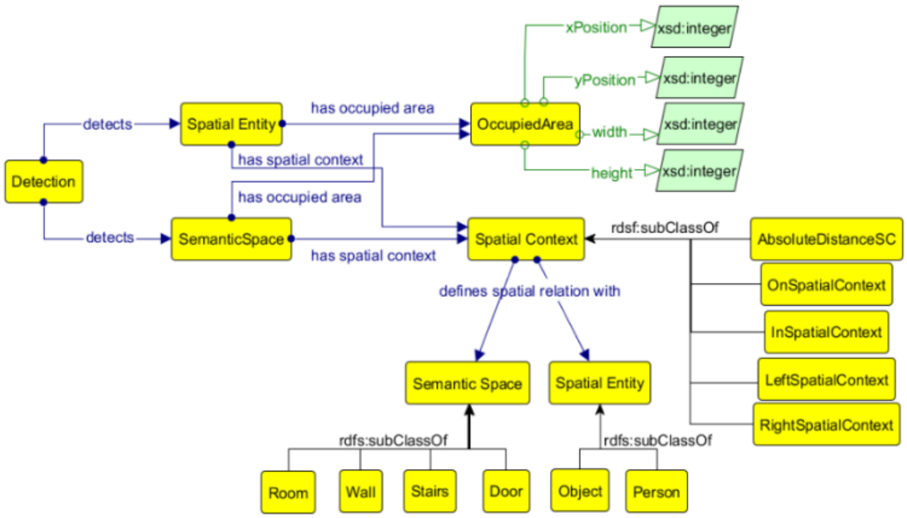


Figure 3. Semantic spaces and spatial contexts in the SUITCEYES ontology.

respective entity's *SpatialContext*, which provides information regarding the entity's relationship to the semantic space it is located in. Examples include *in*, *on*, *left*, *right*, *far*, *close*, etc. The aforementioned concepts are depicted in Fig. 3. These definitions play a key role in the semantic reasoning mechanism, as they form the basis for inferring spatially related information to the user, e.g., which objects are close to or far from the user, what sort of entities are located in the room where the user is, etc.

B. *Sample instantiation*

Based on the ontological concepts presented above, Fig. 4 illustrates a sample instantiation, resembling an activity detected by the system's camera. The activity involves two people speaking to each other: one of them is known to the user (i.e., John) whereas the other is unknown. Moreover, these two people are currently located in the kitchen (i.e., in_room_spatial_context), and the respective message is communicated to the user via a textual description, which is then converted to haptograms as described next.

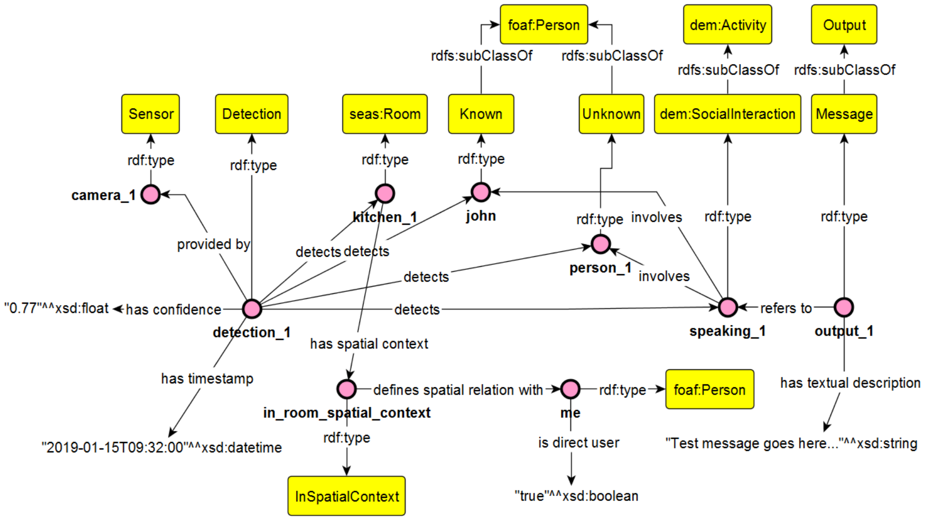


Figure 4. Sample instantiation of an activity involving two people discussing in the kitchen.

TABLE 2. EXAMPLE QUERIES FOR WHICH THE ONTOLOGY CAN PRODUCE RESULTS IN NATURAL LANGUAGE TEXT

#	Query	Answer
Q1	Where is my <phone> now?	Your <phone> is located on your <left>, <close to> you.
Q2	In which room am I now located?	You are located in the <kitchen>.
Q3	When and where was my <mug> detected for the last time?	Your <mug> was found in the <living room>, <10 seconds> ago.
Q4	Which <entity> is observed on my <left> side?	A <table> is on your <left> side.
Q5	Which are the objects I am <close to>?	A <laptop> and a <chair> have been found <very close> to you.
Q6	How many persons have been detected <close to> me?	There are <3> persons <close to> you.
Q7	Are there any <known> persons detected?	<John> is detected <far from> you.

This flexible ontology-based representation allows the system to convey various types of information to the user. In order to deliver semantic content through haptic media, messages generated by the KB should be structured as a *natural language phrase* rather than a simple alert or indication. This information is then communicated to the user by aligning each word or sentence with its haptogram representation, allowing for a semantically richer messaging mechanism.

In the final HIPI prototype, the user will also be able to submit queries through a special panel. For this reason, we have implemented a set of SPIN rules [35] that allow the KBS to respond to queries submitted by the person wearing the HIPI as natural language phrases. Table 2 includes a representative subset of such queries.

IV. INTRODUCING HAPTOGRAMS

A. *From user needs to haptogram design considerations*

Based on an extensive user survey to advance the match between human needs and system support in the specific case of deafblindness, we opted for the transmission of perceptible messages to a grid of actuators mounted onto a smart textile surface on the body. The set of haptic signals had to: (i) be easy to distinguish and perceive; (ii) represent a simple language whose vocabulary is either similar to established vocabularies familiar to the user, or intuitive and simple enough to be learned; (iii) enable sentence building; and (iv) comply with ontology constraints for message generation. Compared with SHC (e.g., in [3] and [4]), where simple and typically environment-related messages are conveyed to the back of the user and other appropriate parts of the body by a human signer, our idea was to similarly convey simple messages, but digitally, by means of actuators. Towards this, a number of complex issues needed to be considered.

A human communicator can simply adapt communication to the actual situational circumstances. For example, in a confined physical space a signer may switch to using the upper arm instead of the back. Similarly, any distortion in reception (as indicated by the body language of the receiver) may be addressed by repetition of the message or further clarification. In an automated system these decisions and interventions need to be preconceived and replaced by other means. Also, in SHC, the signs can easily be adapted and renegotiated between sender and receiver to facilitate perception based on the situational experiences of the receiver. Therefore, next to being idiosyncratic, SHC signs can vary from person to person, and even established tactile sign languages are culturally bound, existing in variants from country to country.

The level of complexity goes beyond this, as by its nature deafblindness involves a very broad spectrum of abilities and impairments, e.g., from those who may have just a handful of concepts in their vocabulary to those who possess a full and rich language ability and can communicate in a sophisticated manner using tactile sign language or even spoken language. This means that the set of concepts and haptogram patterns has to be customizable in due course. Furthermore, SHC involves fine-tuned, compound three-dimensional hand-on-body movements, while the actuator-based haptic patterns need to be rather simple and conveyable in a two-dimensional format, at least for the time being. To handle these research constraints, we fell back on user-centric co-design where potential users' preferences and feedback have been captured. This involved an extensive user study (i.e., 80 detailed interviews conducted in 5 different countries), and ideation workshops (involving participants with deafblindness and communication experts), leading to psychophysics experiments.

The current co-design was constrained by different technological and disciplinary bottlenecks. One of the goals was to build a communication module which could manage at least 100 concepts by haptograms, in the range of the smallest SHC vocabulary known to us [38]. The matrix arrangement of vibrotactile actuators to generate 100 different patterns was considered a viable solution to this end. However, a 3 x 3 actuator grid was too small to allow for this variety, so we opted for a 4 x 4 one as our starting point. On the other hand, static patterns on one's back, not a screen with the best resolution, are more difficult to distinguish than dynamic ones, whereas the latter also extend the number of possible haptograms. Because our ontology at the time of writing this article already included hundreds of concepts to match the capacity of visual detection, 4 x 4 dynamic patterns were a compromise between detection capacity vs. the need to keep things simple for psychophysical experimentation: opting for a larger grid, apart from its wiring problems from a hardware and smart textiles perspective, would have unnecessarily overcomplicated testing. Also, we had to keep in mind that haptogram evaluation by default is an iterative process, to result in designs to be scrapped and replaced time and again.

B. *Technical aspects.*

Haptograms as a term were proposed by [36]. In their approach, "Haptogram" is a system designed to provide a point-cloud tactile display via acoustic radiation pressure: a tiled 2-D array of ultrasound transducers is used to produce a focal point that is animated to produce arbitrary 2-D and 3-D tactile shapes. The switching speed is very high, so that humans feel the distributed points simultaneously. The Haptogram system comprises a software and a hardware component; the software component enables users to author and/or select a tactile object, create a point-cloud representation, and generate a sequence of focal points to drive the hardware.

Our idea of a haptogram is different and corresponds to logograms. That is, *concepts* are communicated by touch-based drawings, and not character sequences to invoke them. Haptograms are, in short, synthetically generated haptic patterns with a meaning, to be communicated as stimuli to the human body. They could be discretized, i.e., represented by a number of matrix cells, but could also be continuous, illustrated for example as Bezier curves [37]. The meaning of such patterns could be both at word and sentence level. Further, we distinguish between *stable* vs. *changing* patterns and call them *static* vs. *dynamic* haptograms in a communication context, where both can be pulsating for easier recognition. The purpose of haptograms in our framework is to implement an ontology-constrained messaging language for situation awareness assessments, and as raw material for everyday conversation. Both visual and audial information can be translated to haptic patterns.

Such haptograms can be mapped to one or more parts of the body, in single or multiple modes. Unlike studies that focus on using hands (e.g., by developing communicative gloves), our system does not use the hands in order to keep them free for other purposes, such as holding a cane, giving a handshake, examining surfaces or objects, etc. The semantic content is transferred to the body to trigger actuators of vibration, pressure, tapping etc., as well as combinations thereof.

Actuators to display haptograms are advantageously arranged in a matrix form of rows and columns. It is not necessary that they are of equal number; rather the general approach is an *m* x *n* arrangement with *m* rows and *n* columns. A two-dimensional (2D) arrangement of haptic actuators has several benefits over, say, a one-dimensional (1D) linear array arrangement. A single point vibrator - what could be called a zero-dimensional (0D) arrangement - can only convey alarm-like semantic content, such as "Something is happening". (For example, this is the case for cellphones which, while vibrating, can indicate that there is an incoming call or time is out). This way is not best suited to conveying richer content like *what* is happening, or if several things are happening in parallel, including their direction, etc. Compared to 1D, a 2D arrangement enables richer *directional* information: it is possible to identify from where a haptic stimulus is coming. In a 2D arrangement one can use the columns, say, for a certain general class of ontological entities (e.g., related to eating, moving, friends, relationships, etc.) and letting each row to correspond to different concepts therein these realms. This could not be done in 0D and 1D.

The world is inherently three-dimensional but humans have a developed understanding and capability for extracting information out of two-dimensional projections. This holds for exploration both by sight and touch. In the latter case, a 2D vibrator arrangement is much closer to a 2D topological tactile description of a surface than a 1D array. In fact, most often interpreters using SHC describe a room or scene in front of the user by sketching it as a 2D projection, indicating borders, exits and windows, significant objects and persons. A 2D arrangement of actuators lends itself very well to this case. Synonymous is to say that 2D enables *localization* better. 2D arrangements also open up for *dynamic* patterns as actuators corresponding to dots in a haptogram could be made to vibrate in a certain order. This is not only beneficial for perception, compared to the static case, but also yields more possible combinations of patterns over *m* x *n* vibrators. In the limit of increasing *m* and *n* within a given area and even letting *m* and *n* approaching infinity, the resolution increases and continuous patterns are made possible. Of course, human capability to resolve two spatially or temporally separated haptic stimuli is limited, and has to be taken into account. Finally, a 2D arrangement is also a step towards *haptic pictures*, i.e., leaving the paradigm of using symbols. Haptic pictures are such that they mimic a tactile object by levels of contrast of its parts.

Our vocabulary was designed for in-principle receiver testing over a 4 x 4 actuator grid for a proof of concept. We were interested in finding out if the ontology and such a haptic conceptual vocabulary can be aligned, and how pattern sequences reminiscent of sentences can implement the transmission of more complex semantic content. To enable hypothesis testing, we departed from the following:

- Screen on the back, vibrational actuators only:
    - 104 dynamic signs, matching the magnitude of [38];
    - Homonymy disambiguation by different dynamics for the same patterns vs. synonymy representation by two different approaches.
- Vocabulary signs for:
    - Start, stop, alert, sentence type markers, question words, agree/disagree;
    - Known/unknown person, personal pronouns (4);
    - Place adverbs (15), time adverbs (4);
    - Nouns (48), verbs (13), adjectives (3).

Concrete examples below go back to the ontology-compliant sentence sample in Table 2.

C. *Examples*

As haptograms in principle can be static or dynamic, and can represent both word meaning and sentence meaning, Fig. 5 illustrates the basic idea of the former which was derived from the ASCII code table, where in its matrix cells, instead of characters, concepts are encoded by bit strings in the rows vs. columns.

In Fig. 6, we illustrate two sample dynamic haptograms. In the upper part, numbers indicate the firing sequence of the actuators for concepts (a) and (b), meaning "*stand*" and "*door*". In the lower part the completed shapes of the dynamic haptograms are indicated.

Moving over to sentence meaning, in Fig. 7 we show how three simple statements, "*You are in the kitchen*" (Example 1), "*The bottle is close to the left on the table*" (Example 2), and "*There is an unknown person in the hallway*" (Example 3), can be constructed by concatenating dynamic haptograms. The statement begins with a single-blink sign, indicating the start of a new message, and finishes with a double-blink, pulsating one, indicating end of transmission. Any statement can be accompanied by a separate alert sign to add weight to the communicated content.

Apart from this example, our test included declarative sentences, questions and exclamations to enable a future dialogue between two users with deafblindness, or a user with deafblindness and her/his assistant, family member, educator, etc. Further, the vocabulary is both aligned with the ontology, and is including concepts and parts of speech not covered by the current version, i.e., hints at expansion opportunities. Likewise, e.g., logical operators, numbers, signs for operations etc. can be added following the same line of thought.

Experiment constraints included that over a 4 x 4 grid, no digital numbers could be specified, and screen resolution, i.e., actuator grid granularity was too low for simulating genuine SHC signs.

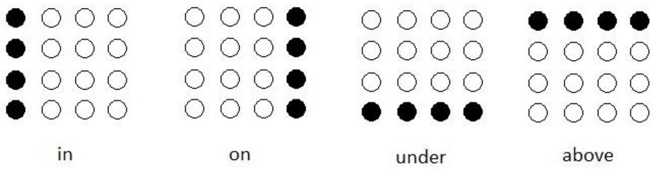


Figure 5. The idea of static haptograms over a 4 x 4 actuator grid.

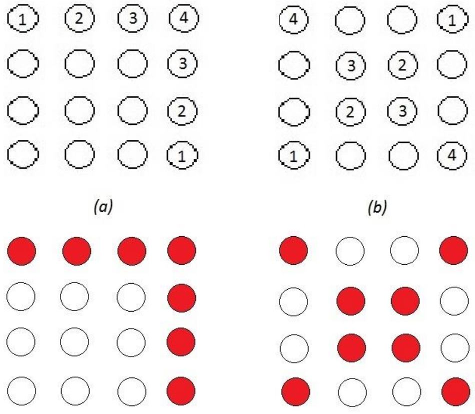


Figure 6. Unfolding sequences of two patterns over a 4 x 4 actuator grid, yielding different dynamic haptograms: (a) "*stand*"; (b) "*door*".

V. HAPTOGRAM REALIZATION IN SMART TEXTILES

Haptograms are to be transmitted to different locations on the body and need ample space as they are inherently extended. Very naturally this leads to the use of textiles. Textiles have been there in all human activities throughout the ages, regardless of sex, social status, culture, and occupation. In the form of garments, they cover large parts of the body, such as one's back or upper arms, those areas where haptograms are to be transferred. Important is also that textiles are pliable and adapted to the complicated geometry of the human body. They could be made to tightly fit one's shape, which is very important for any haptic communication as typically, good mechanical contact is central.

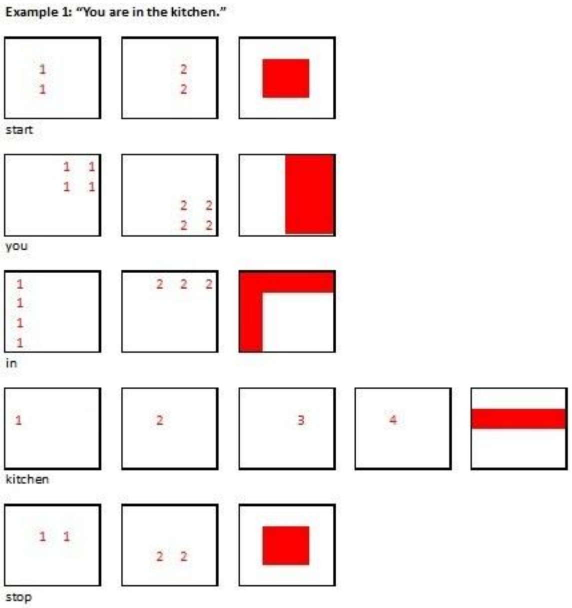
Textile is then a platform. Its enrichment with sensors and actuators, including haptic devices, is often referred to as smart textiles. A basic thought behind the application of haptograms has been to allow the transmission of perceptible messages to the users via actuators mounted into and onto textiles. We opted for discrete haptic signs inherent in the matrix approach above.

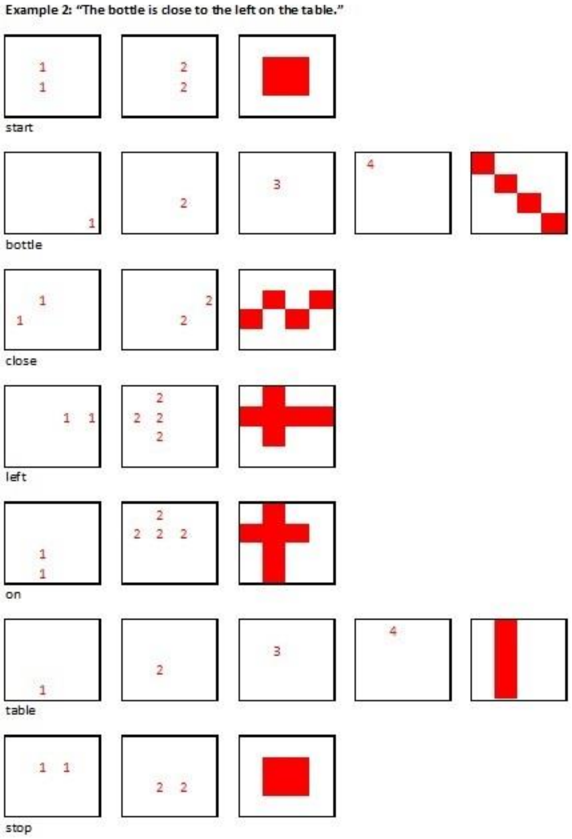
We define *location* as the geometrical position on the body, i.e., an anatomical measure, whereas *placement* is the positioning of some actuator (or sensor) on the textile. A given actuator with a given placement is positioned as close as possible to a target location when taking on the garment, and while wearing it. Further on, we define *cell* as a physical construction on, or in the textile, such as a pocket having a certain placement from which actuation could take place. Typically, we will have many more cells than vibrators in a garment. Cells that have an actuator that is actuating are *active* or firing. Such an active cell corresponds to a *dot* in a *pattern*, a set of active dots. Thus, a pattern of actuators could either simultaneously become active, which is the static version of haptograms, or becoming active in a sequence, i.e., the dynamic alternative.

Last but not least, from a smart textile perspective, a set of cells close to each other constitute a *panel* to host actuators in any particular arrangement. There could be a panel for the back, another for the upper arms, for the waist, and so on.

We constructed a textile testing device for the back (Fig. 8). The human back has a complicated geometry with both convex and concave regions. Added to this is that users are of different sizes. In order to fulfil the simultaneous need of fixed location of actuators, as well as good mechanical attachment for maximal haptic signal transmittance, we opted for a construction with both vertical and horizontal stripes that could be tightened individually at the front by buckles, giving a good fit to the body for all sizes. This structure takes inspiration from a weave with interlaced parts. On the inside, towards the body, detachable pockets are placed, each of them able to host an actuator. These pockets have openings as well so that cables for powering could be taken out and contacted. In total, a very versatile system was created for the realization of haptograms.

In Fig. 9 the placements of 16 vibrotactile elements in a 4 × 4 matrix arrangement is illustrated. The stripes are arranged so that the actuators can be changed from the outside, making it simple to study pattern arrangements without taking off and on the garment.





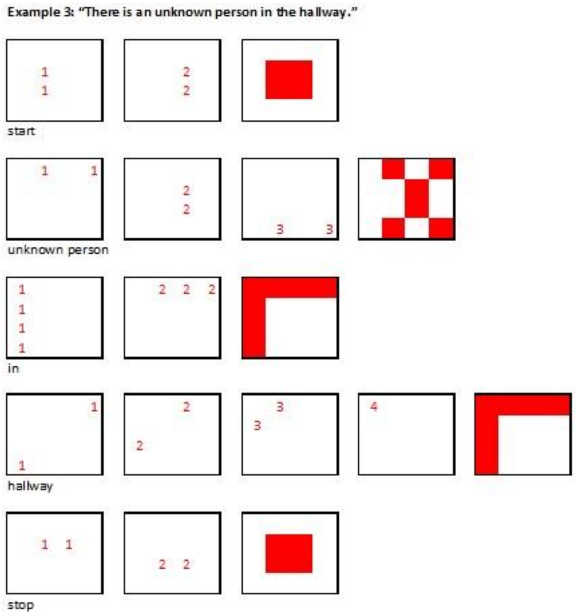


Figure 7. Examples 1-3 are system responses to predefined user queries over a 4 x 4 actuator grid, with patterns plus their unfolding sequences in red.

Figure 8. Back side of the textile testing device. Black squares belong to stripes in the vertical direction, white in the horizontal direction. Together a chessboard like appearance is formed. This results in an inherent matrix for specifying sign component positions.

VI. CONCLUSION AND FUTURE WORK

A constraint on this report has been the COVID-19 pandemic which, because of the extreme vulnerability of our user group, prevented the evaluation phase of communication by haptograms and smart textiles. This will be remedied in a next article in due course. Thereby our design considerations had to remain on a theoretical and methodological level.

By means of a proof-of-concept prototype which is work in progress, we adopted a multidisciplinary approach to develop a smart-textile-based communication system for use by people with deafblindness. Focusing on the communication module here, a new ontology connects computer vision with the user to label detected semantic content about objects, persons and situations for navigation and situational awareness. Such labelled content is then translated to a haptogram vocabulary with static vs. dynamic patterns, which are mapped to the body. A haptogram denotes a tactile symbol composed over a touchscreen, its dynamic nature referring to the act of writing or drawing. A vest made of smart textile, in the current variant equipped with a 4 x 4 grid of vibrotactile actuators, was used to transmit haptograms on the user's back. Thereby system messages of different complexity -- both alerts and short sentences -- can be received by the user, who then has the option to respond by pre-coded questions and messages.

The core target groups are users with deafblindness with a diverse range of communication skills, capabilities and needs. The design of our solution is therefore intended to cater for this diversity through personalization, both in terms of the complexity and number of haptograms, and in terms of fit and comfort. The current actuator arrangement made the transmission of 104 dynamic signs possible, including homonyms. This is in the range of the simplest available SHC resource. At the same time, over a 4 x 4 grid, no digital numbers or an alphabet could be specified, and screen resolution was too low to emulate genuine SHC signs.

By means of grids with more actuators, displays with higher resolution can be implemented and tested, paving the way for an extended haptogram vocabulary which can cover more detailed ontology content and, possibly, bridge language barriers among this demographic. Further, we plan to add a mobile sender unit to the prototype to enable de facto two-way communication, and aim to test multi-display message transfer by replacing the smart vest by a smart garment. Psychophysical experiments to evaluate the prototype are in place and in progress.

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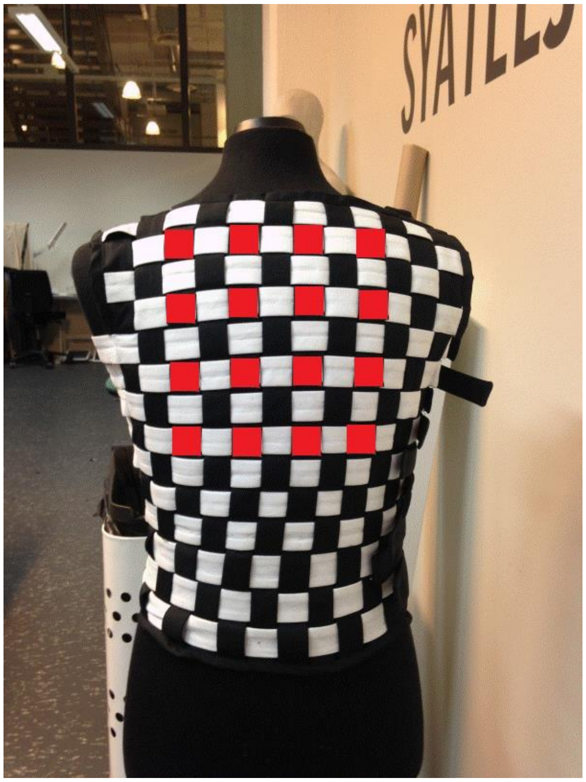

Figure 9. In-principle arrangement of 4 × 4 actuators on the back of the smart vest. Actuators are to be placed beneath the red markers, towards the skin. The non-flat geometry of the human body that any haptic device has to handle is clearly visible.

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