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STATE-OF-THE ART REPORT

context

Smart textiles for personal protective equipment (WG3)

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ABSTRACT

The aim of this document is to provide information on the state-of-the-art related to the topics covered by each working group within the CONTEXT project. It provides information on materials and technologies used to develop smart textiles with targeted performance, general applications of smart textiles in the field, case-studies on the use of smart textiles, opportunities for smart textiles considering the needs of each field, trends on the development of smart textiles in terms of market and technical expectations.

This paper gives an overview of the potential of smart textiles for personal protective equipment, ongoing developments, state-of-the-art products and future developments.

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1. INTRODUCTION

According to the U.S. Occupational Health and Safety Administration (OSHA, 2006), personal protective equipment (PPE) "is designed to protect workers from serious workplace injuries or illnesses resulting from contact with chemical, radiological, physical, electrical, mechanical, or other workplace hazards". First responders, emergency service personnel, military personnel, and workers in specific occupations who work in environments with chemical, biological, radiological, and nuclear (CBRN) materials, fire, and heat are required to wear specialized PPE.[1]

The field of PPE has influenced the development of new materials and new manufacturing technologies. Smart PPE must possess additional functions which always enhance safety. PPE includes a wide range of items created for protection to the human body: eye and face, head, foot and leg, hand and arm, body, and hearing.[2] Protective clothing serves against several types of hazards such as thermal, biological, electrical, mechanical risks and chemical aggressors which can act simultaneously.[3]

The PPE market is an important sector for the technical textile industry. It has been an important field of research and innovation as well as business and technological development for many years, and it will continue to be so in the future.

One part of state-of-the-art focusses on the smart textiles (with integrated electronics), another part introduces some of the novel innovations in nanofibrous layers.

2. SMART TEXTILES FOR PERSONAL PROTECTIVE EQUIPMENT

As safety at work has become a number one priority in every industry, it is no wonder that new technologies and ideas are being tested to improve safety in a variety of workplaces, including surface and underground mining, construction sites, power plants, factories, etc[4]. Sensor technologies embedded in PPE can be employed to monitor workers' health, exposure to harmful elements, their proximity to danger zones, etc.

In materials and structures, "smart" is defined as sensing and reacting to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources.[1] Smart textile products use textiles as the platform for micro-processors, electronic devices, sensors and communication devices, so it can sense and react to environmental conditions or stimuli, and provide an enhanced environmental and personal awareness. Advances in miniaturization, new sensors, computing science and related technologies have resulted in the emergence of smart textiles. Electronic devices can be integrated in any type of PPE, such as suits, gloves, head and foot protection, and respirators.

Depending on the technology used, smart PPE can be divided into four different categories. Whether electronics are integrated or not gives the first level of division. Smart PPE with electronics can be further divided based on the data collection (see Figure 1).[5]

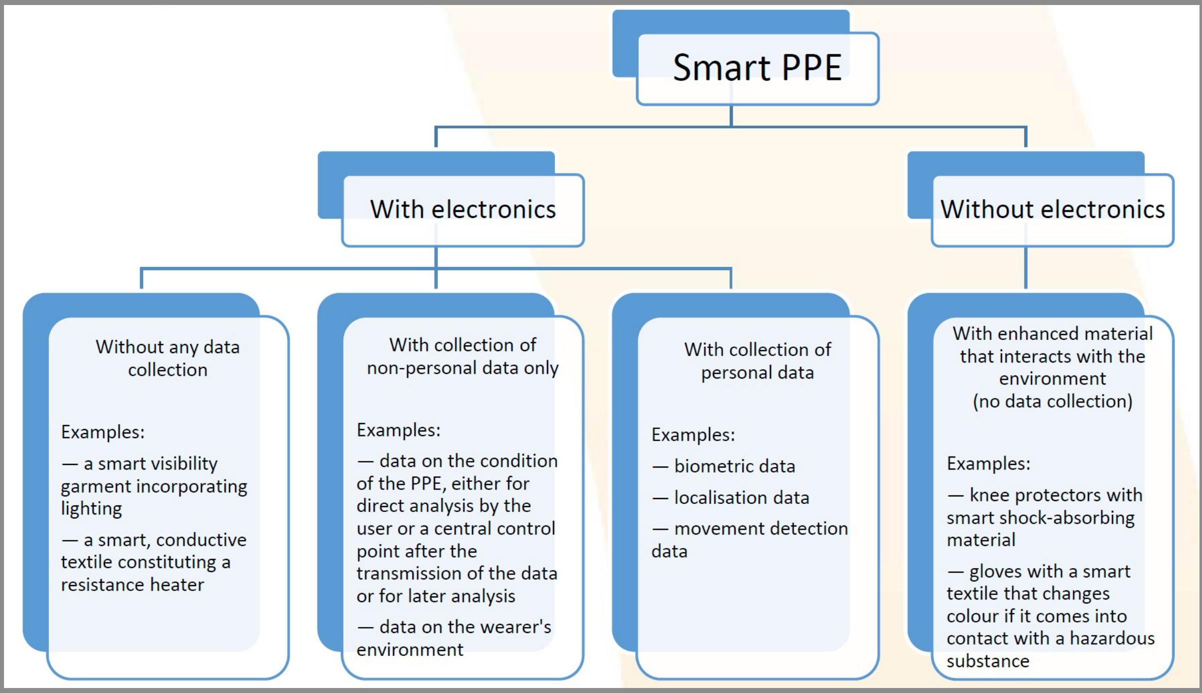

Figure 1 - Proposal for a classification scheme for types of smart PPE, according to composition and data collection capabilities

Some examples of PPE with integrated electronics or smart materials are listed below[6]:

Smart knee protectors

Smart shock-absorbing material can be soft and flexible, allowing normal movement such as walking (unlike traditional knee protectors, which are inflexible and hinder normal movement). However, in the event of a shock, the smart material's properties change and the shock-absorbing effect is revealed.

Smart, conductive textiles that constitute a resistance heater

Smart textiles can be conductive and thus have many applications, for example a smart resistance heater in a garment. The conductive material is connected to an electrical power supply with a constant output voltage and equipped with a temperature sensor to maintain a constant temperature around the heater.

Smart lighting garments

Optical fibres integrated into textiles and connected to a controllable light source can be used as part of smart garments. Equipped with a sensor, these garments will be able to adjust illumination to the amount of light provided by other light sources in the vicinity of the smart garment.

Smart gloves capable of identifying hazardous substances

Chromogenic materials take on a different colour depending on an external stimulus (e.g. heat, light, enzymes). This behavior can be used in smart gloves that change colour when they come into contact with hazardous substances.

Smart PPE that communicates with other (potentially hazardous) products

PPE can be equipped with detectors that communicate with corresponding detectors in other products in the vicinity of the wearer. Thus, situations that are to be prevented because they present a risk can be avoided. Such smart PPE can be used to avoid collisions with mobile machinery such as forklift trucks. Another example is smart PPE worn by operators of machinery that ensures that the machine starts working only when the operator is in the designated operator station.

Smart PPE that collects data about its own use

PPE can be equipped with sensors that collect data on use duration or quantity and communicate with a central database. Maintenance cycles can be monitored automatically. For example, the user could be informed when maintenance, a regular inspection or the replacement of the PPE or parts thereof is required.

2.1 Nanofibres

Nanofibres are known for their high surface area to volume ratios, small pore size and high porosity, light weight and breathability of membranes. These synthetic and natural nanofibrous polymers have potential to be used in applications in various fields. In order to expand their use, polymer blends or incorporation of additives (fillers in form of nanoparticles) into fibres can be applied. Nanoparticles are very attractive materials to be used in functionalization of nanofibrous systems, for instance silver and zinc oxide nanoparticles exhibit wanted properties such as antibacterial effect, UV-blocking, piezoresistive properties and electrical conductivity.[7]

There are multiple techniques to spin nanofibres (summarized by Barhoum A.[8]). Generally, nanofibres can be prepared from polymer melt or solution. Electrospinning techniques and its modifications (needless electrospinning, multiple-jet electrospinning, bubble electrospinning, cylindrical porous hollow tube electrospinning, electroblowing, coaxial electrospinning, charge injection electrospinning[6, 9, 10]) are most commonly used to form nanofibres.

3. APPLICATIONS OF SMART TEXTILES IN PERSONAL PROTECTIVE EQUIPMENT

Smart textiles are part of the new technologies that have recently been explored for potential applications in PPE. Three main trends have been identified for product development: users' needs, global systems, and environmental conditions. In addition to wearable electronics that can act as physiological condition, temperature and humidity sensors, power and data transmitters, and end-of-life indicators, smart materials also provide ways to tackle the new challenges associated with these main development trends. For example, membranes with responsive permeability, including to water vapour, can be produced using shape memory polymers, polymer gels, superabsorbent polymers, grafted polymer brushes, and polymeric ionic liquids. These barrier membranes may even be made self-decontaminating with N-halamines, quaternary ammonium groups, bioengineered enzymes, metals and metal oxides, nanomaterials, and light-activated compounds. Thermal comfort can also be improved with phase change materials that can provide additional heat or coolness as the need arises.[11]

Another example of application of smart materials in PPE concerns shear thickening fluids that solidify and become shock absorbers when impacted at high rate. However, testing methods need to be adjusted to take into account these new materials. This includes the characterization of their specific properties, for instance their trigger threshold value, consumed power, magnitude and quality of the response, durability, and interaction with the user's body.

One application example is Coldwear, a clever jacket. This jacket, developed in Norway, monitors workers' health levels when they work in extreme cold (Figure 2). The readings of body temperature, humidity and perspiration, both inside and outside the suit, along with tracking the location of the worker are recorded. Coldwear, designed for arctic oil fields, goes a long way in protecting the workers in a harsh environment by sending information back to a central point.

Furthermore, the clothing can detect gas leaks and other harmful substances which may endanger your workers.[12]

Figure 2 - The ColdWear demonstration sleeve[13]

Another example is the concept developed for miner's "smart" personal protective equipment, with embedded sensors on all their PPE which includes: safety glasses, hard hats, miners' clothing, and also by wearing smart technology gadgets like smartphones and smartwatches that can monitor and inform mine personnel of potential safety hazards (Figure 2 and Figure 3).[4] This smart technology embedded in a PPE can provide safety alerts to workers in the field, remind them of specific safety procedures, and even enable an injured worker to reach out for help automatically.

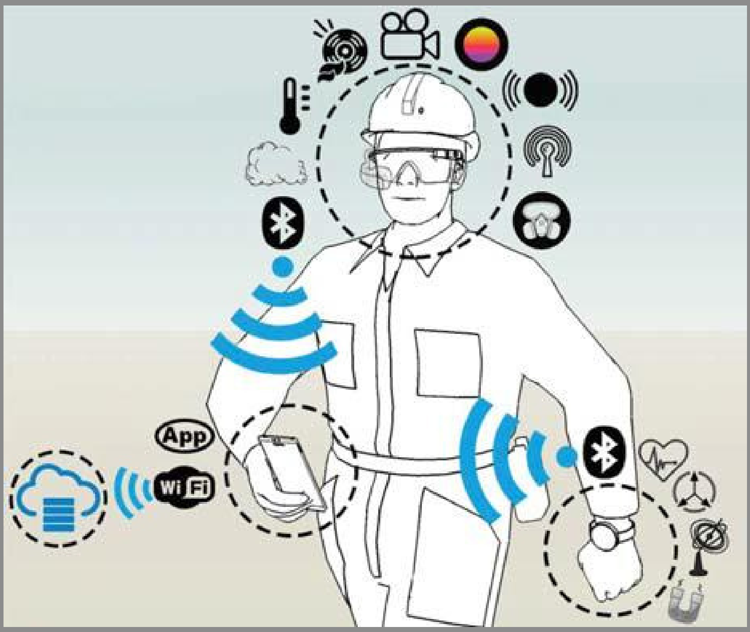

Figure 3 - Prototype system with sensors embedded in PPE interconnected with smart technology

Combining smart technology and underground mining could lead to next-generation mining; by means of digitalization this system takes advantages of active sensing, remote signal, data processing, communication, and improves the efficiency and safety of the mining process[4]. Figure 4 presents the prototype model of PPE with integrated sensors and smart technology which are interconnected with the five-layer architecture.

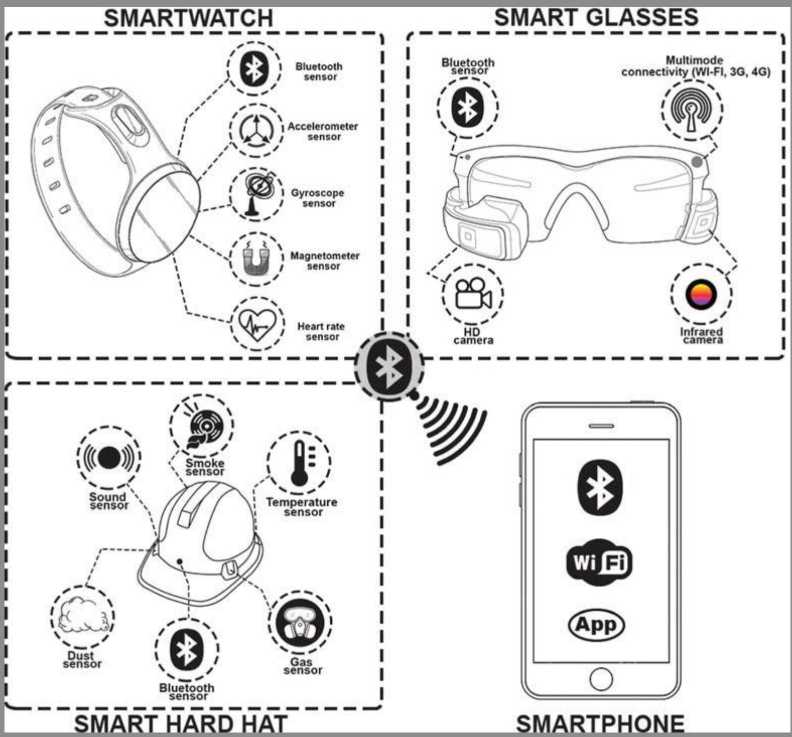

Figure 4 - Smart technology and sensor upgrades in PPE [4]

Many research projects have already been led around the world with the purpose of integrating wearable devices into protective equipment, mainly to be able to monitor physiological parameters but also to replace bulky and heavy electronic devices that are usually added to the uniforms[14].

The **Safe@sea** project had the objective of integrating sensors within fishermen's outer garment, fully waterproof, in order to detect falling overboard[15]. The GPS location of the incidence will be shown, helping the further rescue actions, and an alarm will be activated on the vessel. The suit's emergency light will also be automatically switched on and the bladder will be inflated when coming into contact with water.

Figure 5 - Safe@sea flyer

The **TIIWS project**[16] (Thin multilayered PVDF based piezo co-polymer for textile integrated intelligent wearable self-sustained monitoring and safety applications in garment and footwear) developed innovative textile sensors based on polyvinylidene fluoride (PVDF) copolymers. PVDF copolymers have excellent chemical, abrasion, heat and flame resistance as well as ultraviolet stability, making them an excellent starting material for smart textiles. Scientists optimised polymer formulations and pre-processing methods, and designed a multilayered composite consisting of active polymer, electrodes and protective layers. The textile-based piezoelectric materials are flexible, durable, reliable and show improved power generation, overcoming the limitations of traditional piezoelectric materials. Sensors and active materials were integrated into material active sensing systems, tailored for specific end-use applications.

A major output of TIIWS were the processes and techniques used to produce these smart materials, which can be applied to other products. These sensing textile systems were then incorporated into smart garment and footwear prototypes, creating new product and market opportunities for small and medium-sized enterprises working in the smart textiles sector.

Researchers tested the prototypes for their intended purpose as smart garments, and validated them against user-centric criteria such as comfort and design. TIIWS has overcome the challenges of integrating piezoelectric sensing functionality into garments and footwear with novel polymers and processing techniques. The findings of the project will improve the safety and comfort of athletes, the elderly and those working in hazardous environments.

In the **SmartPPE project**[17] innovative single-piece reusable protective equipment is developed to better empower healthcare workers fighting Ebola outbreaks. A robust ventilation system is integrated to keep healthcare workers at a comfortable temperature.

The **Smart@Fire project** led to a smart textiles prototype suit for firefighters that offered optimal protection, as well as the possibility to measure and monitor crucial information including personal parameters, e.g. heart rate and body temperature, and environmental parameters like concentration of gasses and positioning. When making the prototype, emphasis was put on being easily producible in large scale at an affordable cost. The prototype that was selected via the pre-commercial procurement process of the project shows how protective wear in general might look in the near future.

The **smartPRO suit** is based on a certified three-layer protective suit for firefighters, which is designed mainly for extinguishing interior fires under extreme conditions for temperature, fumes and/or orientation in space.

The suit is equipped with 12 active LED lights that are fixed on the main reflective tape. The integrated light sensors can also activate four different lighting systems, based on these 12 LEDs, to provide as optimal as possible light conditions, irrespective of the environment in which the firefighter is operating.

The suit is also equipped with a sophisticated electronics system consisting of sensors, an alarm and a so-called Suit Control Unit (or SCU). The system can continually monitor and evaluate the safety of the environment in which a firefighter is operating: temperature inside and outside the garment, moisture, humidity, detection of toxic gases. The suit also provides information about the physiological functioning of the person inside as well as on the exact location of the person on a map.[18]

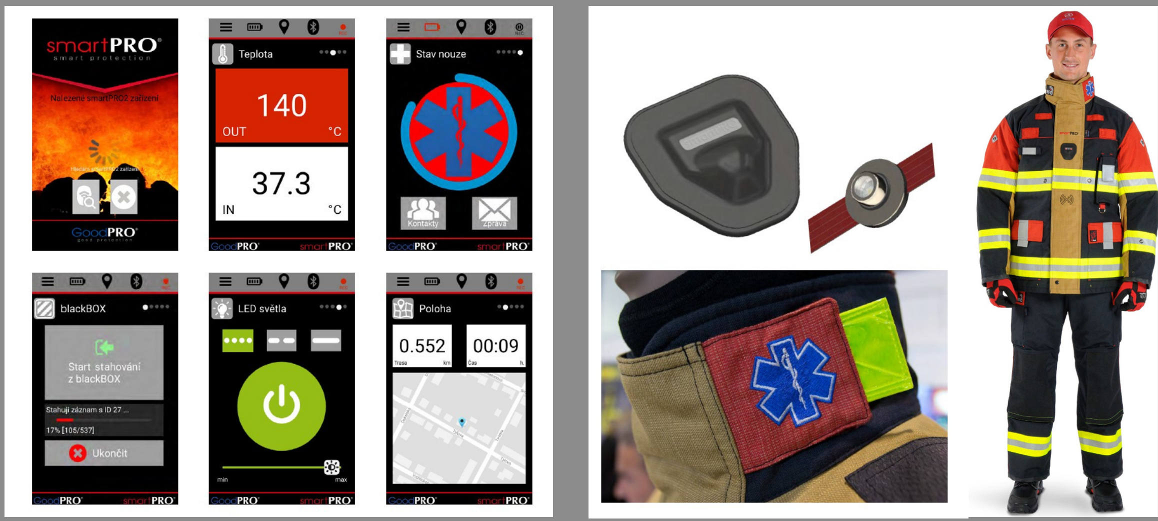

Figure 6 – The company GoodPRO (Czech Republic) developed the smartPRO suit for firefighters

In the field of high visibility clothing smart models have been developed. Examples are jackets being developed by the Belgian company Sioen some years ago. An active lighting system based on LED is integrated into a high visibility rain jacket. It contains 6 white LEDs in front and 5 red LEDs on the back. Furthermore, a high visibility softshell jacket with integrated heating system allows the end user to regulate his own temperature depending on the surrounding temperature. The complete system is flexible, lightweight and can be washed at 30 °C (after removing batteries).[19]

Figure 7 – High visibility clothing with Left) integrated ighting system; Right) integrated heating system (developed by Sioen)

Comparable high visibility clothing with integrated lighting is also offered by other companies like MABEO France. These new products are presented to their customers from September 2017, essentially industries, building and public works and local authorities.

Figure 8 - High visibility clothing with integrated lighting, produced by Mabeo

3.1 Applications of nanofibres as smart textiles

Nanofibres layers have received considerable attention from researchers in the field of protection. In addition, nanocomposite fibres with including nanoparticles can enhance physicochemical properties (e.g. conductivity, wettability, magnetic and mechanical properties) and improve multifunctionality of the whole system.

The well-known barrier effect of nanofibrous membranes is employed for selective filtration through facepiece respirators. Respirators and facemasks are consisting of several fibrous layers with various fibre diameters. Nazir et al.[20] concluded that the addition of nanofibrous webs between the layers of nonwoven filter media remarkably improved the filtration capability, water vapour permeability, thermal conductivity and comfort properties.

Electrospun ceramic, carbon or polymeric nanofibres have demonstrated great potential for the design of gas-sensing nonwoven textile. Smart textile PPE that changes colour if it comes into contact with a hazardous substance are much promised and desired.

For instance, Kim et al.[21] developed polydiacetylene/polyurethane nanofibers web with colorimetric sensor ability for volatile organic compounds in form of solvent or gas. Vitchuli et al.[22] deposited a layer of electrospun nanofibres on a nylon/cotton blended textile to improve filtration performance against submicron level aerosol chemical and biological threats. Superhydrophobic nanofibrous membranes that are highly resistant to water and self-cleaning[23] or antibacterial and antiviruses nanofibers[24] have gained great attention due to their potential application in PPE for medical employees.

New protective clothing is also required against electromagnetic shielding, wireless signal transmission technologies or heat dissipation. Wearable smart nonwoven textile featuring high ultraviolet (UV) resistance, ease of breathability, and desirable waterproof performances, have been developed by Liu et al.[25] using a polyvinylidene fluoride nanofibrous membrane with F-TiO_2 nanoparticles. Yuan et al.[26] created a highly flexible and stretchable electrospun polyurethane nanofibers web covered by $Ti_3C_2T_x$ with delicate wrinkle structure design for effective electromagnetic wave interference shielding.

Liu et al.[27] prepared a nanofibers layer bonded with a nylon 6 fabric to improve the mechanical properties, air permeability, and moisture permeability for novel functional layers in protective clothing. Protective antiballistic composites can be reinforced with nanofibres due to the improved toughness of the composite without compromising mechanical properties.[28]

Polymeric nanofibers with incorporated magnetic nanoparticles can increase the thermal resistance.[29] Cellulose nanofibers with graphene oxide remarkable improve the flame retardancy, mechanical properties and sound absorption coefficient.[30]

4. END USER'S PERSPECTIVE – FIRST RESPONDERS

To ensure a successful development of a new technology the end user has to be involved. The user acceptance is an essential component of an effective product design and market launch. Therefore, the user-centred design is indispensable to create smart PPE.

User-centred design

In the "traditional" development of technical products, the first step is to identify the relevant problem of a particular utilisation cycle. The aim is to eliminate the weak points with the help of technical solutions and new tools in order to meet the requirements of the user. In a first step, the requirements are defined and described to achieve the goal. However, the problem with this "traditional" development is that the user requirements are insufficiently met because the user is not involved in the development process. This problem can be solved with the help of user-centred design. The human-centred approach helps to better identify the user requirements. The following steps are examples of a user-centred design:

- Understanding and description of the user context
- Concretisation of the usage requirements
- Designing design solutions that meet the requirements of use
- Evaluation of the designed design solutions from the user perspective

User-oriented product development offers both economic and social benefits. The economic benefits include, for example, the reduction of costs for training and support. A social benefit is the reduction of user discomfort and stress (the user knows the product and its functions and knows how to use it). For an efficient product design with regard to the human-centred design iterations have to be made. This allows uncertainties regarding the product or the user to be removed and the product to be specified and optimised. Risks can thus be reduced by the reactions of the user feedback.

User survey: smart PPE for firefighters

Due to the above-mentioned advantages of the user-centred design a user survey for smart PPE for firefighters was conducted by Institut für Textiltechnik of RWTH Aachen University, Aachen in cooperation with Kommission für Arbeitsschutz und Normung e.V., Sankt Augustin and Institut für Feuerwehr-und Rettungstechnologie Dortmund, Dortmund.[34] With the help of the answers of the survey participants, it is shown how far smart PPE with intelligent functions meets with acceptance of the firefighters and which sensors should be integrated.

The firefighters interviewed are members of the professional fire brigade, the voluntary fire brigade and the plant fire brigade in Germany. A total of 150 people took part in the survey. The questionnaire includes the evaluation of various characteristics of the current PPE, the question whether a smart PPE meets with acceptance and which environmental and personal parameters should be determined with the help of sensors. In addition, the participants were asked how far monitoring by smart functions would go and who would be allowed to process and evaluate personal data. About 95 % of the participants consider smart PPE as useful. But most of the firefighters did not have any contact to PPE with intelligent functions. The firefighters consider that especially their position (85 %) and pulse (70 %) should be monitored using sensors. Monitoring the body core temperature was mentioned as another useful function. With regard to environmental parameters, the participants considered that it is useful to determine the ambient temperature (85%) and to detect harmful or toxic substances in the air.

Various methods can be used to warn firefighters of danger during an operation. The participants could choose between haptic (vibration), optical (lights) and acoustic signals. All three options received roughly the same response, with values between 60 and 70 %. In addition, the firefighters suggested a display in the respiratory mask. Just under 60 % of the participants considered an automatic emergency call in a hazardous situation as useful.

Only 15 % regard this function as critical. One reason given was data protection, another was the fact that people's vital functions are individual. Thus, a generalisation of critical values is not or only with difficulty possible. Another important point is that there is often no other option at a deployment point than to stay and help. Therefore, replacement would not be an option. Around 55% of the survey participants would trust the intelligent functions more than their own personal perception. The majority (around 60%) would like to decide for themselves on the collection, analysis and forwarding of the resulting personal data. Only about 10% agree to a long-term evaluation by third parties, such as insurance companies or accident and health insurance companies.

Overall, the user survey shows that there is an interest in smart PPE for firefighters. However, as the majority of those questioned have never had contact with smart PPE, it is necessary to hold information events. Workshops can be held to present prototypes and to explain the benefits to staff. This can lead to increased user acceptance. Fire drills with smart PPE can also increase acceptance. The user-friendliness and wearing comfort can be tested and optimisations can be carried out.

The processing of personal data represents a challenge. It is therefore necessary to clarify these issues in advance.

The survey reveals the desire for tracking and localisation possibilities. Smoke and fog make the visibility of the emergency services considerably more difficult and a loss of orientation can be the result. A positioning function enables firefighters to determine their position and that of their colleagues. With current technologies, however, it is only possible to a limited extent to locate firefighters indoors. For this reason, the development of smart PPE should focus on this in particular. Another important point is the wearing comfort of PPE. This must not be further restricted by the integrated intelligent functions.[35]

5. OPPORTUNITIES AND TRENDS

The production, use and maintenance of PPE are highly regulated, with numerous national, multi-national, and international standards. The application of smart technology or integration of electronics in PPE is still relatively new. Improving user safety is the most important purpose for PPE and safety should never be impaired in any PPE. However, none of the existing standards has dealt with the safety aspect of integrating electronics into PPE.[1] Standards related to smart PPE are under construction by experts at CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Institute for Telecommunications Standards) and are subdivided in numerous committees.

Buchweiller et al.[31] indicated that no methodology has been developed to answer the safety questions arising from integrating electronic circuits into PPE and proposed a new method to address this issue. To make smart clothing succeed in the PPE market, a safety assessment methodology for different PPE products must be developed. Following the assessment methodology, the standards for smart PPE need be developed and approved by government agencies, international nonprofit organizations, or industrial trade associations.

The term “Internet of Things” (IoT) is a new trend where a number of embedded devices and sensors employ communication services offered by different Internet protocols.[4] Many of these devices (smart objects) are not directly operated by humans, but exist as components in the environment. IoT technology offers the possibility to transform the industry by providing and increasing the availability of information throughout the working cycle using networked sensors.

Opportunities which could be enabled by the use of smart textile in PPE that are interconnected with smartphones and smartwatches are summarized below[4]:

1. Protection from invisible risks – PPE with gas, dust, sound, smoke and temperature sensors can monitor both the external environment and the user, alerting them in time about hazardous environments and alerting supervisors if workers are in unsafe conditions.
2. Connectivity and locating system – tracking systems that are attached to every smartphone connected to network can enable the identification of the location of each user.

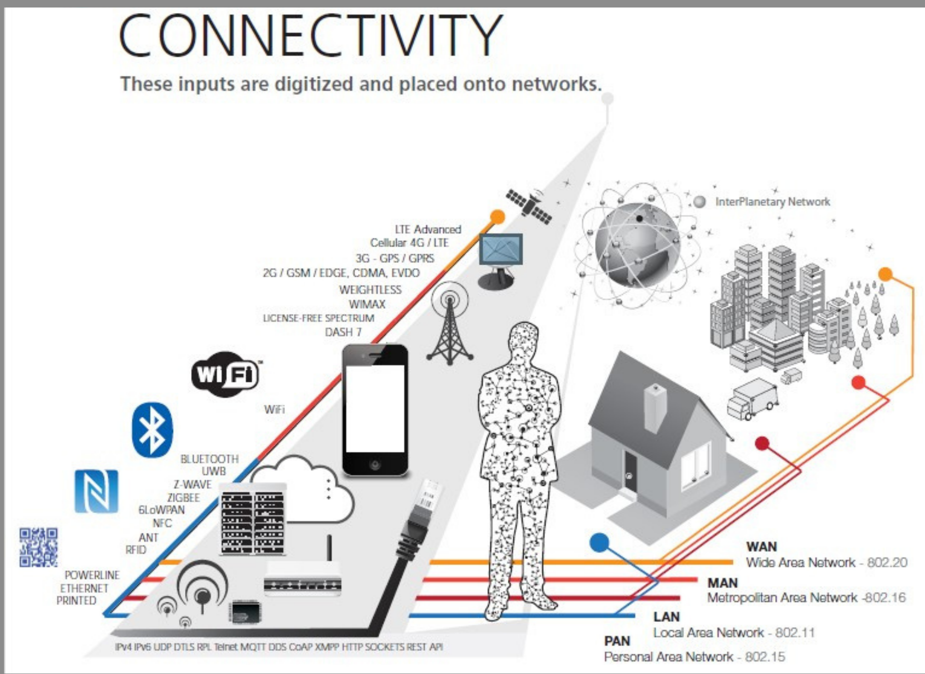

Figure 9 – Tracking systems[32]

3. Real-time data analytics – this would enable an immediate alert to a worker if he enters a potentially hazardous zone or somehow risks his safety.
4. Smart communication systems – the interconnected sensors and smartphones could provide fast and effective communication in loud or low-visual environments.
5. Smartphone app alerts – sensors connected to apps can send crucial alerts about emergency situations and also auto send emergency rescue messages.
6. Improve performance and reduce error – smart PPE improves productivity through connectivity, live updates and remote communication that can save lives and actively prevent workplace accidents.
7. Smart health – monitor workers' heart rates and physical work overload.

5. CONCLUSIONS

Smart PPE promises a higher level of protection, safety and more comfort through the use of smart elements and their combination. Smart PPE are still in the development phase. The upscaling and the industrialisation process is on one hand blocked by lack of technology needed for a serial production, while on the other hand there are no standards available yet.

Nanofibrous layers as a part of the whole system can improve multifunctionality of PPE, however the compatibility with several different textiles materials still need to be investigated.

6. REFERENCES

[1] Cao, H., Smart technology for personal protective equipment and clothing, Chapter of Smart textiles for protection, Woodhead Publishing Limited, 2013, 229-241
[2] Berry C, McNeely A, Beauregard K, Haritos S. A guide to personal protective equipment. Raleigh, NC, USA: N.C. Department of Labor; 2008. Retrieved December 16, 2008, from: http://www.nclabor.com/osha/etta/indguide/ig25.pdf
[3] P. I. Dolez, T. Vu-Khanh; Recent Developments and Needs in Materials Used for Personal Protective Equipment and Their Testing, International Journal of Occupational Safety and Ergonomics, 15:4, 2009, 347-362, DOI: 10.1080/10803548.2009.11076815
[4] Adjiski, V., Despodov, Z., Mirakovski, D., Serafimovski, D., System architecture to bring smart personal protective equipment wearables and sensors to transform safety at work in the underground mining industry, In: The Mining-Geology-Petroleum Engineering Bulletin, 2019, 34, 1, 37-44, DOI 10.17794/rgn.2019.1.4
[5] Thierbach; EU OSHA - Discussion paper: Smart personal protective equipment: intelligent protection for the future
[6] CEN/TR 16298:2011 'Smart textiles - Definitions, categorisation, applications and standardization needs'
[7] S. M. Costa, D. P. Ferreira, A. Ferreira, F. Vaz, R. Fangueiro; Multifunctional Flax Fibres Based on the Combined Effect of Silver and Zinc Oxide (Ag/ZnO) Nanostructures. Nanomaterials, 2018, 8, 1069; doi:10.3390/nano8121069.
[8] A. Barhoum, K. Pal, H. Rahier, H. Uludag, I. S. Kim, M. Bechelany, Nanofibers as new-generation materials: From spinning and nano-spinning fabrication techniques to emerging applications, Applied Materials Today, 17, 2019, 1-35.
[9] M.M. Bubakir, et al., Advances in melt electrospinning technique, in: Handbook of Nanofibers, Springer, 2018, pp. 1-32.
[10] L. Haichao, et al., Engineering nanofibers as electrode and membrane materials for batteries, supercapacitors, and fuel cells, in: A. Barhoum, M.Bechelany, A. Makhlouf (Eds.), Handbook of Nanofibers, Springer International Publishing, Cham, 2018, pp. 1-27.
[11] Dolez, P.I., Mlynarek, J., Smart materials for personal protective equipment, Chapter of Smart Textiles and their Applications, Editor Chapman R., Woodhead Publishing, 2016
[12] Young, C., PPE makes use of smart sensor technology, May 2019, Available at: https://www.ishn.com/articles/110687-ppe-makes-use-of-smart-sensor-technology
[13] https://www.coldwear.com.sg/
[14] Decaens, J., Vermeersch, O., Wearable technologies for personal protective equipment, Chapter of Smart Textiles and their Applications, Editor Chapman R., Woodhead Publishing, 2016
[15] https://cordis.europa.eu/project/id/229334
[16] https://cordis.europa.eu/project/rcn/107651/brief/en
[17] http://smartppe.org/

[18] Buyle, G., Eufinger, K., Baxa, M., Cleeren, S.; Smart Textiles. The future of protective clothing, Health & Safety International Magazine, April 2017, Available at: https://www.hsimagazine.com/article/smart-textiles/
[19] Proceedings of Smart Textiles Salon, 2013, vol. 3, 40-43
[20] A. Nazir, N. Khenoussi, T. Hussain, S. Abid, L. Schacher, D. Adolphe, A.l Zahir, M. B. Qadir, Z. Khaliq, A. Shahzad; Enhanced filtration and comfort properties of nonwoven filtering facepiece respirator by the incorporation of polymeric nanoweb, Polymer Bulletin, 2019, DOI: 10.1007/s00289-019-03009-1
[21] M. Ok Kim, M. Q. Khan, A. Ullah, N. P. Duy, C. Zhu, J.-S. Lee, I. S. Kim; Development of VOCs gas sensor with high sensitivity using colorimetric polymer nanofiber: a unique sensing method, Material Research Express, 2019, 6, DOI: 10.1088/2053-1591/ab42a5.
[22] N. Vitchuli, Q. Shi, J. Nowak, M. McCord, M. Bourham, X. Zhang; Electrospun ultrathin nylon fibers for protective applications, J. Appl. Polym. Sci., 116, 2010, 2181, DOI:10.1002/app.31825
[23] Kurusu, RS; Demarquette, NR. Surface modification to control the water wettability of electrospun mats, International Materials Review, 2019, 64, 249-287, DOI: 10.1080/09506608.2018.1484577
[24] Mohammadi, MA; Rostami, M; Beikzadeh, S; Raeisi, M; Tabibiazar, M; Yousefi, M; Electrospun nanofibers as advanced antibacterial platforms: A review of recent studies., International Journal of Pharmaceutical Sciences and Research, 2019, 10, 463-473. DOI: 10.13040/IJPSR.0975-8232.10(2).
[25] Liu, K; Deng, L; Zhang, TH; Shen, K; Wang, XF; Facile Fabrication of Environmentally Friendly, Waterproof, and Breathable Nanofibrous Membranes with High UV-Resistant Performance by One-Step Electrospinning, Industrial & Engineering Chemistry Research, 2020, 59, 4447-4458. DOI: 10.1021/acs.iecr.9b05617
[26] Yuan, WJ; Yang, JZ; Yin, FX; Li, YB; Ye, Y. Flexible and stretchable MXene/Polyurethane fabrics with delicate wrinkle structure design for effective electromagnetic interference shielding at a dynamic stretching process, Composites communications, 2020, 19, 90-98. DOI: 10.1016/j.coco.2020.03.003
[27] Ya Liu, X. Wang , Nana Li, X. Wang, L. Shi, E. Wu, R. Wang, M. Shan, X; Zhuang; UV-crosslinked Solution Blown PVDF Nanofiber Mats for Protective Applications, Fibers and Polymers, 2020, Vol.21, No.3, 489-497. DOI 10.1007/s12221-020-9666-5
[28] P. M. Gore and B. Kandasubramanian, Functionalized Aramid Fibers and Composites for Protective Applications: A Review, Ind. Eng. Chem. Res., 2018, 57, 16537-16563
[29] Ozaytekin, I; Oflaz, K.; Synthesis and characterization of high-temperature resistant and thermally conductive magnetic PBI/Fe3O4 nanofibers, High Performance Polymers, 2020, DOI: 10.1177/0954008320911985.
[30] Pinto, SC; Silva, NHCS; Pinto, RJB; Freire, CSR; Duarte, I; Vicente, R; Vesenjak, M; Marques, PAAP.; Multifunctional hybrid structures made of open-cell aluminum foam impregnated with cellulose/graphene nanocomposites, Carbohydrate polymers, 2020, 238, DOI: 10.1016/j.carbpol.2020.116197
[31] Buchweiller, J.-P., Mayer, A., Klein, R., Iotti, J.-M., Kusy, A., Reinert, D., Christ, E.; Safety of electronic circuits integrated into personal protective equipment (PPE), Safety Science, 2003, 41, 395-408

[32] Burghart M.; CEN-CENELEC Sector Forum Personal Protective Equipment, D, uvex Safety Digital Business Innovations, Smart garment & equipment, 7 September 2017
[33] [EN ISO 9241-210] Norm EN ISO 9241-210:2010: Ergonomie der Mensch-System-Interaktion- Teil 210: Prozess zur Gestaltung gebrauchstauglicher interaktiver Systeme: Berlin, 00.01.2011
[34] R. Krause; Smart protective equipment for the fire services: what is needed, and useful?, KANBrief, 2020, Available at: https://www.kan.de/en/publications/kanbrief/mobility-in-our-time/smart-protective-equipment-for-the-fire-services-what-is-needed-and-useful/
[35] R. Krause, M. Kemper, J. Jordan, T. Gries; Erstellung eines Leitfadens zur Entwicklung smarter persönlicher Schutzausrüstung, BePr (Betriebliche Prävention), 2020, DOI: 10.37307/j.2365-7634.2020.10.06