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State-of-the-Art of Industrial Wearables: A Systematic Review

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***Abstract*—Wearable devices have been broadly studied and explored in the last ten years in many various directions such as sports, education, healthcare, transportation, military, and many others. Currently, one of the sectors widely using such devices is industries and factories interested in improving the level of labor safety as part of the broader Industry 4.0 paradigm. This paper aims to overview the current state of the wearable devices market related to this niche and highlight modern industrial wearables, new techniques, and approaches in this research field. The purpose of this article is not to criticize but to provide information for developers in this scientific field and identifying possible areas where improvements are required.**

***Index Terms*—Industry 4.0, wearable devices, industrial wearables, work safety, biosensor, survey**

I. Introduction

Many sources of danger are commonly present in the factories [1]: heavy objects, flammable substances, chemical emissions, radiation, viral infections, explosions, etc. Accidents in the workplace often lead to diseases and/or poor health of workers, which causes significant monetary losses for both the employee and employers. It should be mentioned that lethality in factories is also not rare and, at the same time, entailing much more tragic consequences. According to International Labor Organization (ILO) [2], approximately 1.9 million people lapse into illness due to harmful working conditions, and 2.3 million people die each year from work accidents, and this number reflects only recorded cases. Based on the above, we conclude that appropriate development and compliance to work safety procedures are one of the most important actions to do for the employer and his worker consequently.

Within the framework of the Fourth Industrial Revolution, or Industry 4.0, possibilities to provide and control the safety procedure at the workplaces increased significantly [3]. With the beginning of an era of industrial digitalization, the development of wearable technologies has undergone a new surge. Nowadays, wearable devices are actively used at factories and do a number of tasks that in general could be named as work safety, providing, for example: measuring of vital statistics of workers, determining the location of workers to prevent them from entering hazardous areas, monitoring the availability of personal protective equipment, etc.

The object of this paper is wearable devices, and the subject is the analysis of the state-of-the-art principles in the use of such devices in industries and factories.

This paper is organized as follows: Section II highlights the methods used to gather information related to the topic. Next, Section III presents the definition of wearable devices and a brief overview of their status in the world today. Section IV surveys modern techniques related to the industrial wearables data collection and data transmission. Further, Section V outlines the main challenges. The last section concludes the paper.

II. Methodology

This section briefly outlines the methodology and selected criteria applied to the literature review. The literature review was conducted upon the most widely used academic sources, i.e., IEEEXplore, Scopus, and Web of Science databases. In order to identify the relevant articles for the topic under consideration, the following keywords and their combinations were used: “industrial wearables”, “wearable devices”, “wearable technology”, “Industry 4.0”, “work safety”, “sensor”, “biosensor”. In addition to papers found after applying the filters above, some references provided by selected articles were taken into account. The articles selected for review should meet the following criteria:

- Original or review articles;
- The main language is English;
- The article was published no earlier than 15 years ago;
- The number of citations of articles was taken into account.

After applying the criteria, filtering grey literature, and removing the duplicates, the list was composed of 44 papers. After careful reading of the annotations, 15 articles were eliminated due to the fact that the information covered in them is either weakly related to the topic under study or is duplicated in other, more comprehensive works. Some of the remaining 29 articles were mentioned in passing, and 22 of the most complete works were selected for detailed analysis.

To cover existing wearable devices and applications in the field of industrial safety, one of the most recent and interesting articles were selected. Besides, the most impressive modern products were reviewed. In the study of theoretical approaches for methods of data transfer, localization, security, and so on, preference was given to the last published reviews.

III. A BRIEF OVERVIEW OF MODERN WEARABLE DEVICES

A. *Wearable Devices Background*

There are many different definitions of what wearable devices are. One of the most comprehensive determinations was given in [4] as “wearable devices are smart electronic devices available in various forms that are used near or on the human body to sense and analyze different types of data via applications either installed on the device or on external devices, such as smartphones connected to the cloud”.

A generalized model for the use of wearable devices consists of the following (see Fig. 1): various types of sensors collect various types of data, which are then transmitted to the central gateway node via communication protocols [5], [6], for example, Bluetooth Low Energy (BLE) [7]. A decision is made on what to do with the collected information is commonly mage on the central gateway node. In general, information can be processed, displayed on a graphical user interface, simply saved or sent to cloud service.

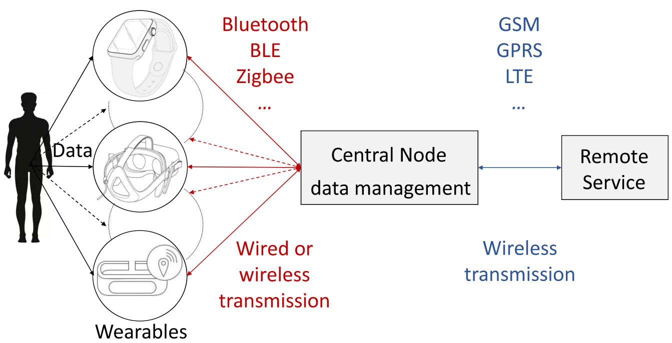

Fig. 1. Generalized model for the use of wearable devices.

According to the latest free access wearable technology database [8], 583 wearable devices were registered for 2015 in the world, and this number continues to grow. Work [9] states that the global wearable devices market is expected to grow at a Compound Annual Growth Rate (CAGR) of 11.3% from 2019 to reach $62.82 billion by 2025. This trend provides immense opportunities but, on the other hand, constitutes a vastly unexplored area, riddled with numerous research challenges, such as network security [10], which will be discussed in more detail in Section 5.

Authors of [8] classify wearable devices in seven categories depending on the purpose: fitness, lifestyle, industrial, gaming, pets and animals, entertainment, medical. Areas of market focus are presented in Fig. 2. It should be noted that, despite the fact that the number of registered purely industrial wearable devices is the smallest among all, some other types can be used for the same purpose; the lion’s share among them is formed from fitness and medical wearables.

Currently, the leading position among wearable devices is occupied by smartwatches and fitness trackers, so the main part of a human body to place the wearable device is the wrist (59% of all wearables [8]).

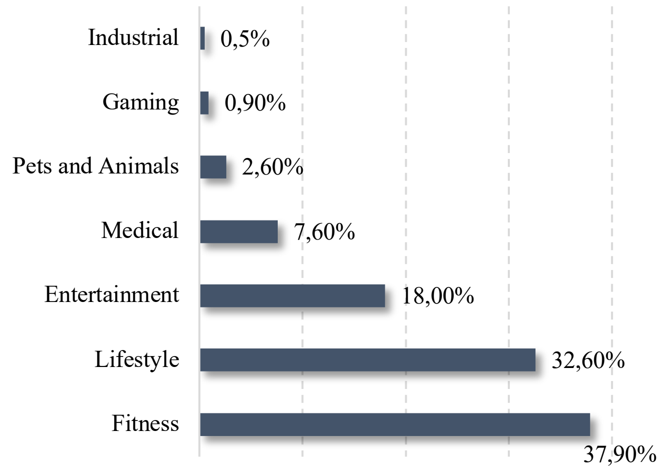

Fig. 2. Wearables depending on the purpose.

B. *Classification and Market Overview of Industrial Wearable Devices*

Industrial wearable devices classifications depend on various factors. Despite the fact that commonly such devices have wide functionality, none of those can accommodate the whole range of required functions for a certain area. The most generalized classification was given in [4]. This paper covered most of the existing wearables by means of five groups depending on the functionality: monitoring, assisting, augmenting, tracking, and delivering content:

- Monitoring group is the widest group among all. It is used to collect data about a worker’s condition at the workplace, for example, heart rate, stress level, etc. Thanks to such devices, employers can control work-related parameters of their employees. This group includes a very wide class of devices that can be presented in various forms: fitness trackers, rings, glasses, patches, and sensors attached to the body or elements of clothing, and so on.
- Assisting wearables such as exoskeletons help workers to prevent pain in the back by controlling the posture or lifting heavy objects.
- Augmenting category of wearable devices refers to work with augmented reality. It is especially useful for the training of workers. This category is presented in the form of special glasses or helmets.
- Tracking wearables are used to track mainly worker’s physical activity and their location. The first option could be helpful, for example, for sedentary control behavior and second – for forewarning workers about dangerous areas or keeping a safe distance from the others (to avoid physical contact and spreading of viruses such as COVID-19). Just like a monitoring group, this is a vast group that does not have a specific form of implementation. It can be represented by various smart clothes (for example, smart jackets, smart boots), smart bracelets, etc.

TABLE I
ENVIRONMENTAL PARAMETERS AND EXAMPLES OF SENSORS FOR MEASURING THEM

№	Environmental parameter	Sensor module
1	CO2 concentration	CozIR, IRC-A1
2	temperature	SHT11, SHT2x
3	relative humidity	BME680
4	atmospheric pressure	BMP180, BMP280
5	UV-index	SI1145,SI1146, SI1147

- Delivering content wearables, such as Smart Paper, are developed for providing just-in-time information that is useful, for example, for support services.

It is also worth noting that it is rarely possible to meet representatives of the above groups individually. Most often, there are combined industrial wearable devices that are capable of performing several functions at once. Examples of such combined devices are, in particular, helmets, developed by Realwear and Honeywell companies: hands-free technologies that provide a remote connection and are equipped with a visual display that reacts to voice and shows various types of information like urgent notifications, vital and location data.

IV. STATE-OF-THE-ART TECHNIQUES IN THE FIELD OF INDUSTRIAL WEARABLE DEVICES

A. Data Collection

There are many different parameters required to be monitored in order to maintain the safety level in industries. For the corresponding measurements, the wearable system may apply an array of sensors connected to a central processing unit with firmware for continuously monitoring [11]. All of the parameters can be thus divided into two large groups: environmental parameters and parameters related to the body of the worker.

The sensors from the first group measure the environmental parameters at the workplace and allow the wearable device to register dangerous changes in a timely manner and promptly notify employees and the employer about this. Evidently, the more sensors in a wearable device, the lower are the risks to harm the worker, but the final dimensions, weight and power consumption of the device make developers think carefully about the choice of measured parameters, leaving the most necessary, and applying various low-power strategies to provide long life to the device's battery. The most essential and frequently measured indicators of the first group are presented in Table I with widely known examples of sensors for measuring them.

Some sensors can measure several parameters at once, for example, the SHT21 sensor used in [11] is applicable for both temperature and relative humidity measurements.

Literature shows many examples of various sensors' combinations in wearable devices utilized for environmental monitoring. For example, the authors of [12] have presented a wireless wearable network for environmental monitoring that can estimate CO2 concentration, temperature, and relative humidity. Work reported in [11] presents smart, low power, wearable multi-sensor data acquisition systems that, in addition to the previous parameters listed in [12], also measure readings of Earth's magnetic field.

The authors of [13] present an integrated sensor system for monitoring of temperature, humidity and Volatile Organic Compounds (VOC), the latter of which is a wide class of organic compounds, including hydrocarbons, aldehydes, alcohols, ketones, terpenoids, and other substances, that has a fatal impact on the human's health, but is still used in large amounts in industries and factories [14].

The second group considers such parameters as heart rate, pressure, stress level, brain activity, the temperature of the body, etc. The sensors of this group are usually called biosensors [15], an exhaustive list of which, with the corresponding biosignals, is given in [16].

The biosensor group, in turn, can be divided into two categories. The first one includes biosensors for measuring pressure, pulse, temperature, body movements, and oxygen saturation. This category is widely developed and relatively easily accessible due to the great popularity of fitness bracelets. The second category relates to the biosensors that measure such parameters as heart sounds, brain, and muscle activity. These biosensors, as a rule, are rare, expensive, and access to them can often be obtained only in health facilities.

Indeed, the listed groups of sensors are interrelated, e.g., high levels of carbon dioxide in the room are directly related to respiratory diseases, according to [17]. In this connection, one wearable device could combine different types of sensors in order to track the influence of the external factors of the environment on the human body.

B. Data Transmission

According to the general model mentioned above, there are two transmission processes: from sensors to the central node and from the central node to the remote services.

In the first case, a connection could be both wired or wireless. However, the wired transmission is not in the main focus anymore because it is less convenient and can restrict the movement of a person, which can be critical during work in the danger zone. Wireless transmission at this stage naturally results in the creation of a personal area network (PAN) [16]. The most widely used PANs are 802.15.4 (Zigbee) and IEEE 802.15.1 (Bluetooth). Nowadays, more popular than basic Bluetooth protocol is its simplified low-energy version BLE [18]. Regarding the power consumption, according to [19], BLE consumes between 2–100 times less than conventional Bluetooth, depending on the case [20].

The comparison between Bluetooth and Zigbee protocols is presented in Table II.

Other protocols, such as infrared (IrDA), ultra-wideband (UWB), or Z-Wave, are less common with wearable devices in the studied literature [21]. In the second case, just a wireless connection is sufficient. There are a lot of different long-range

TABLE II
COMPARISON OF PAN WIRELESS TECHNOLOGIES

№	Parameter	Bluetooth	BLE	Zigbee
1	Frequency band	2.4 GHz	2.4 GHz	868 MHz, 915 MHz, 2.4 GHz
2	Maximum data rates	1–3 Mbps	125 kbps–2 Mbps	20 kbps, 40 kbps, 250 kbps
3	Range	100 m	100 m	100 m
4	Topology	Point-to-point (including piconet)	Point-to-point (including piconet), broadcast, mesh	Star, tree, mesh

wireless solutions available, such as WLAN, GSM, GPRS, UMTS, LTE, and WiMax [22]. The comparison between them, as well as modern techniques related to the positioning and data processing in wearable devices, will be considered in future work.

V. MAIN CHALLENGES

Despite the fact that the market for wearable devices has developed significantly in the last decade, this field is very attractive for further research and improvement. The specifics of the problems vary from device to device depending on the purpose, but the following questions remain unchanged for all kinds of wearables:

1) Technological challenges:
   - Problem of finding a compromise between, from one side, dimensions, weight, and from the other side, functionality, accuracy, energy consumption, communication capacity of the device.
   - Problem of an adjustment of the same model of a wearable device for different users and various external conditions, that is essential, for example, in healthcare facilities, where a limited budget does not allow to order a new wearable device for each new patient.
   - Problem of processing and analyzing a huge amount of data.
2) Economic challenges. Nowadays, most wearable devices have a relatively high cost, not to mention the fact that some devices require integration with other gadgets.
3) Privacy challenges. Still, the confidentiality of the data is a big question in such kind of devices: due to limited bandwidth and processing power, wearables provide less security compared to other computing devices [23]. Thus, wearable devices are subject to a wide range of external attacks, which are most often caused by the fact that the wearable device is not a standalone device and, in order to provide greater functionality, it communicates with other devices [23]. Currently, more attention and budget are being spent on eliminating technological issues, while improving the mechanisms for protecting user data is being taken to the background.
4) Social challenges. Wearable devices are still considered a relatively new technology that can induce resistance on the way of its acceptance. During Apadmi's survey [24], respondents were asked what they would do if their employer required them to use wearable technology at the workplace, and just 24% said they would be pleased. There are three main issues here:
   - The low initial technical skills of users do not always allow working with such devices, which require simpler interfaces and more detailed manuals, especially for older people who need constant monitoring of their health.
   - High dependency on a wearable device can cause a person's inability to act without it when necessary and possible confusion or incapability to solve a potentially solvable task due to the lack of systematized information.
   - The lack of data security and data ownership issues induce mistrust to users of wearable devices. According to the results of a survey on 4000 adults in the UK and US conducted in 2013 by Rackspace Hosting [25], 51% of respondents consider that privacy is a key barrier to the adoption of wearables.

Besides the above-mentioned challenges, there are a number of additional issues that are specific for industrial wearables. First of all, the problem with the usage of wearable devices in an environment with harsh extreme conditions is added to the list of technological challenges. Industrial wearables must be much more resistant than conventional wearable devices to withstand external hazards that could arise at the workplace in industries. Secondly,the work [26] states that workers do not feel comfortable to be monitored all the time. Monitoring in hospitals also raises concerns about the safety of personal data. However, patients see a clear connection between the need for such monitoring and recovery. Therefore confidentiality issues recede into the background. In opposite, in industries, workers usually do not know for what the employers collect the data about, for example, their stress level or blood pressure, and it makes them worry, firstly, that they might be fired, based on the data collected, and, secondly, that this data will be disclosed. Moreover, even if the employer explained the purpose of continuous monitoring at the workplace and assured employees of the confidentiality of the information collected, they still feel inconvenience because "someone is constantly watching over their shoulders" [26].

Some of the above problems found local solutions in some places, but nevertheless, all of them still are research agenda for the coming decades.

VI. CONCLUSIONS

The purpose of this paper was to give an idea about the market of wearable devices in general and about one of its domains, namely industrial wearable devices, which are currently experiencing a new leap in development, due to the concerns of factory and enterprise owners about increasing the work safety. The classification of industrial wearable devices, depending on their functions with examples, was presented. The main promising techniques and technologies related to the collection and transmission of data were also highlighted. In addition, the main challenges on the way of adoption and implementation of industrial wearable devices were considered.

In future work, modern methods related to geofencing, positioning, and data processing will be examined. In addition, state-of-the-art producers of industrial wearables and their products will be reviewed. Then it will be possible to create a comprehensive impression of the modern condition of this fast-developing category of wearables and provide main ideas to overcome existing challenges.

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