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Industrial wearable system: the human-centric empowering technology in Industry 4.0

Xiang T. R. Kong[1,2] · Hao Luo[1] · George Q. Huang[2] · Xuan Yang[1]

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Abstract

The Industry 4.0 program and corresponding international initiatives continue to transform the industrial workforce and their work. The service-oriented, customer-centric and demand-driven production is pushing forward the progress of industrial automation. Even though, it does not mean that human can be fully replaced by machines/robots. There is an increasing awareness that human presence is not only one type of manufacturing capability, but also contributes to the overall system's fault tolerant. How to achieve the seamless integration between human and machines/robots and harness human's full potential is a critical issue for the success of Industry 4.0. In this research, a human-centric empowering technology: industrial wearable system is proposed. The aim of this system is to establish a human–cyber–physical symbiosis to support real time, trusting, and dynamic interaction among operators, machines and production systems. In order to design a substantial framework, three world-leading R&D groups in this field are investigated. Five design considerations have been identified from real-life pilot projects. The future trends and research opportunities also show great promise of industrial wearable system in the next generation of manufacturing.

Keywords Industrial wearable system · Human–cyber–physical symbiosis · Industry 4.0

Introduction

After the epic changes of the manufacturing industry caused by web-/internet-based systems and applications, new generation of industrial informatics, such as internet of things (Liu et al. 2017), cloud computing(Chen and Lin 2015), cyber physical system (Wu et al. 2017), ubiquitous computing (Luo et al. 2016; Wang et al. 2009) and wearable computing (Galzarano et al. 2016) open up a novel industrial revolution, referred to Industry 4.0 (Hofmann and Rusch 2017; Zhang et al. 2017). Local and regional governments are aware of the importance of this new industrial revolution and corresponding international initiatives have been lunched (e.g., Industrial Internet and the advanced manufacturing partnership in US, Made in China 2025) (Lorenz et al. 2015; Vogel-Heuser and Hess 2016). Meanwhile, the integration of manufacturing progress and the strengthening of autonomous capability in production systems change the framework of human works (Anastasi et al. 2009). Is the much-discussed topic "full replacement of men by machines/robots" a real? It has been a continued debating among academia, governments and industries (Lorenz et al. 2015; Romero et al. 2016).

It's no doubt that those heavy physical labour work and simple repetitive operations will certainly be replaced by machines. However, in some scenario, human's experience is non-substitutable. For example, the order picking of high variety goods in e-commerce warehousing; failure diagnosis in complex manufacturing system. There is an increasing awareness especially in manufacturing that human capabilities are fundamental and cannot be easily substituted. Even the industrial automation has well-established in some "smart factories", it does not necessarily means the absence of human beings (Liao et al. 2017). Human presence not only can be considered as one type of manufacturing capability (ability to complete specific jobs by human knowledge and experience), but also contributes to the overall system's fault tolerant (ability to address unplanned situations and accidents) (Hofmann and Rusch 2017).

✉ Hao Luo
luohao@szu.edu.cn

1 Department of Transportation Economy and Logistics Management, College of Economics, Shenzhen University, Shenzhen, China

2 HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam, Hong Kong

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To achieve a soft-landing of Industry 4.0 in manufacturing, understanding how the human can be better integrated with manufacturing system is a prerequisite. It is necessary to establish an interactive interface between humans and machines/robots, which can capture, analyse and interact with both the physical and cyber production world with high-level precision in all dimensions. In the technical aspect, Industry 4.0 has addressed the improved human–machine interaction paradigms, including the coexistence with robots or new ways to interoperate in the factory (Hofmann and Rusch 2017; Mrugalska and Wyrwicka 2017). In the socially sustainable aspect, technological transformations of Industry 4.0 should carefully consider the central role of humans. The new technology should help employees to remain in, return to or incorporate into the modern manufacturing workforces (Lorenz et al. 2015). Previous studies in inclusive manufacturing also aim to ensure the utilization of human resources lost due to automation in various other service fields by cross training their employees.

Against this backdrop, the wearable technology and its relevant IoT applications play an important role. The wearable device is widely accepted by the consumer market. However, its applications in industrial environment are still rare. In previous research, the wearable technologies in industry are scattered. They mainly focus on VR/AR-based smart glasses (Liao et al. 2017; Lee et al. 2015; Romero et al. 2016; Stanford 2002) and smart gloves (Leitao et al. 2016). According to the comprehensive interaction and interoperable requirements in Industry 4.0, a single wearable device and isolated applications are far from enough. A sophisticated and systematic paradigm should be established to support real time, trusting, and dynamic interaction among cyber system, physical world and humans. In this research, the framework of Industrial Wearable System (IWS) is thus proposed.

IWS is a human-centric connectivity and interaction system based on a set of unobtrusive body-worn devices and embedded IoT application. The aim of IWS is to achieve seamless collaboration among all manufacturing elements (Man, Machine and Material) and establish the human–cyber–physical symbiosis in industrial field. IWS is not only a communication technology but also a "human empowering technology". IWS employs smart sensors, wireless communication, multi-screen display and human intention recognition technology to augment human's perception, communication and judgement ability. In this way, the empowered operator can perform not only "cooperative work" with robots but also "work aided" by machines. The production systems can be more lean, agile, traceable, and adaptable.

The objectives of this paper are four-folded. Firstly, three representative industrial wearable projects in the world and their relevant application should be deeply investigated. Based on this investigate, their relative merits and research gap will be identified. Secondly, the specific features, requirements and considerations should be identified from real-life manufacturing and logistics domains. Thirdly, the development of a technical framework of industrial wearable system considering the close loop of human–machine interaction is required for both academic and industrial community. Fourth, several opportunities for future research should be identified with coherent connection of research perspectives and open questions.

The remaining of this paper is organized as follows. "Relevant research and development frontiers" section conducts a briefly review about frontiers of industrial wearable projects. "Design consideration of industrial wearable system" section addresses the system design considerations of IWS based on the feedback from real pilot applications. "Technical framework of industrial wearable system" section presents development of a technical framework of industrial wearable systems. The details of the proposed research perspectives are discussed in "Future research opportunities" section. Finally, this article is concluded in "Conclusion" section.

Relevant research and development frontiers

After several years of research efforts and capital inputs, several research and prototyping efforts have been developed in the domain of industrial wearable application. This section addresses three world-leading research and development groups as they had significant industry participation and are seen as lighthouse projects reflecting a wider community thinking and transition.

Wearable computing group

Project highlights

Wearable computing group involves all consortium partners in the wearIT@work project led by University of Bremen (Lawo et al. 2011). WearIT@work is the largest project worldwide funded by the European Commission since 2004. They investigate both technical and business potential of wearable computing for industrial applications. This project was based on a cyclic innovation approach and the user-centred design approach. Four application domains, including emergency response (Paris Fire Brigade), production (Skoda Auto), maintenance (EADS) and healthcare (Gespag Hospital) were chosen to evaluate the specific impacts of wearable computing on the productivity of the workforce as well as the quality of work (Lukowicz et al. 2007). Production scenario is highlighted here, in which the challenge is the information integration and the intelligent information presentation using belt-computer and head-mounted display

(Maurtua et al. 2007). Previously, the process of quality assurance at the end of the car assembly line was based on a paper checklist with irrelevant and redundant information. Wearable-enabled solution was thus proposed to free workers' operation while allowing them to handle all necessary tools with dynamic checklists. System interfaces and context recognition were also improved to allow untrained users to obtain the information regarding the product and the corresponding production processes. The use of wearable computing in this scenario has reduced the training time for the individual workers (Pasher et al. 2010).

Achievements and identified gaps

WearIT@work project contributes to standardisation by a user-centred design approach, a common hardware framework and software platform for wearable computing (Lawo et al. 2007). Moreover, suitable methods for user acceptance, interaction and processes suited to wearables in real-life industrial scenarios were identified. With the creation of the open wearable computing group (i.e., involving 42 partners from 16 countries), a community building process in industry and science has been initiated as well to make more stakeholders realize the benefits of the leverage for wearable computing.

Although a lot of research has been done in wearable computing, body-worn and miniature wearable devices for context or activity recognition are still a research topic. Batteries remain an important aspect if workers use this technology for multiple working shifts. Localization is important in most industrial scenarios but previous wearable solutions are not integrating related hardware systems or sensors to endow such a function. It is also realized that there is a lack of interoperability and reliable wireless communication at the user level when testing the head-mounted display solution with users (Boronowsky et al. 2006, Herzog et al. 2007).

Wearable computer systems group

Project highlights

Carnegie Mellon University (CMU) has developed thirteen generations of wearable computers, each addressing a different class of applications. A CMU wearable computer tree has been developed based upon the operational delivery dates and application areas. As one of the typical projects, Navigator 2 aims to augment efficiency of inspection execution for mobile users through using wearable computers. Before the introduction of Navigator 2, a typical inspection checklist may have hundreds of pages that usually takes four to six hours to complete. This project has adopted a modular architecture and off-the-shelf components to develop wearable hardware device for mobile workers. Meanwhile, a speech recognition system and wearable computer interfaces were designed based on "Corporal, Attention, Manipulation and Perception (CAMP)" framework (Siewiorek et al. 2009). The speech recognition system offers hands-free inspection manner, allowing the operator to perform tasks with minimal interference from the wearable system. Several important principles were applied for user interfaces such as simplicity of function, no textual input, and controlled navigation. The before-and-after evaluations indicated 50% time reduction to record inspection information.

Achievements and identified gaps

CMU research projects contribute to a general design guideline to deal with the context detection and human-computer interaction problem in wearable computing, in terms of interface design, cognitive model, contextual awareness, and adaptation to tasks being performed. A set of wearable forms have been developed to demonstrate how wearable devices might be mounted on the body by following a simple pattern for ensuring wearability. To reduce distractions occur especially in mobile environments, an attention matrix was developed to categorize activities by the amount of attention (Anhalt et al. 2001).

These studies provide a starting point for wearable systems designers and developers; however, there is much work to be done in this area. Weight was not considered in these projects, nor were the long-term physiological effects such systems might have on the wearer's body. Similarly, context-aware information can affect the perception of comfort and desirability of wearables. How do we develop cognitive models of industrial applications and how do we integrate input from multiple sensors and map them into user cognitive states? Extensive experimentation working with end-user tests will be required to address these questions before context-aware wearable computing becomes possible.

Contextual computing group

Project highlights

Context detection is considered to be one of the most scientifically challenging topics in wearable computing. As the longest-serving technical leader on Google Glass, contextual computing group led by Prof. Thad Starner at Georgia Institute of Technology (Georgia Tech) creates real-time context-aware computational interfaces for industrial uses, especially in warehouse order picking activity (Baumann et al. 2012; Baumann 2013; Wu et al. 2015). They suggested to use head-up displays (HUD) like Google Glass to support parts picking rather than other methods including pick-by-paper, pick-by-light and pick-by-CMD (cart-mounted display) due to fewer errors and task time (Guo et al. 2015). By expanding their research, Hao and Helo (2017) demonstrated the uses of HUD-enabled cloud computing system to support operators' decision-makings and activities in a discrete factory.

Achievements and identified gaps

Georgia Tech's research group has codified a series of experimental results into roadmaps for developing and applying head-mounted wearable systems in the complicated working environment. Drawing upon their research findings, many enterprises have already incorporated the Google Glass into their enterprise resource planning (ERP) systems to get and share relevant information in a timely manner (News 2017). Heterogeneous data sources are integrated and presented in this uniform wearable format. Decision makers can thus detect anomalies, extract useful knowledge, evaluate operational risks and select an appropriate alternative during system disruptions (Peng et al. 2011).

However, the wearability of head-mounted displays is still a research issue. How to further optimize and streamline frontline decision-making for mobile works through wearable computing would be a challenging topic in future works. More efforts should also be done to design adaptable mobile workflow and context-dependent reconfiguration information to enable the wearable system to perform a wide range of tasks without any user interaction at all.

Design consideration of industrial wearable system

To make the industrial wearable system practicable, the practical problems in contemporary manufacturing enterprises must be thoroughly investigated. In this section, 15 design considerations of industrial wearable system are summarized from a comprehensive survey of typical users. The back ground of the enterprises in the survey will be introduced. Then the relevant wearable projects reviewed in "Relevant research and development frontiers" section will be evaluated by the design considerations

Enterprise background of the survey

In order to conduct an in-depth investigation and present an overall picture of current situation, a large range of survey of 25 representative enterprises in manufacturing and logistics are conducted. Following 4 aspects are considered in case enterprise selection.

(1) Industrial sector

This survey covered 7 major industrial sectors, which includes equipment manufacturing, metallurgy, chemical, warehousing, rail transit, airport and harbour. These industrial sectors can representative the general requirements of manufacturing and logistics enterprises.

(2) Application scenarios

The second aspect of case enterprise selection is application scenarios. Since the key user of wearable device frontend operators, following 6 typical frontend operation are considered: manufacturing execution, equipment management, order picking, remote assistance, asset management and warehouse operation. The manufacturing execution is the data collection in the shop floor. Equipment management focuses on the status check of large scale facilities. Order picking is the typical operation in e-commerce warehousing. Remote assistance is the scenario of AR glasses application. Asset management is the inventory check of non-production items.

(3) Current data processing method

In the selected case enterprises, the data processing method including paper working, PDA based data processing and PC based processing. Most of the asset management and equipment management scenarios use the paper working, since the management purpose is make record. The PDA is very common in warehousing operation, but the user feedback is not good enough. The PC based operation is mainly used in manufacturing execution. In this scenario, the real time data processing is not convenience.

(4) Data interaction level

Since the data interaction has significant influence on industrial wearable system design and application, this enterprises survey has paid more attention to enterprises with different data interaction model. There are 4 data interaction levels are defined here. Single data collection means one-way and simple format data iteration. For example, the check point data in the patrol operation. Multiple data collection is also a one-way data operation, but various data formats are collected. For example, the temperature, barcode and video data in the equipment management. Bidirectional interaction indicates that the operator not only submit the data to backend system, but also needs to get feedback instruction from the backend. The frontend decision making is the most comprehensive data interaction model. The operation should use the human experience and make on site decision based on frontend data.

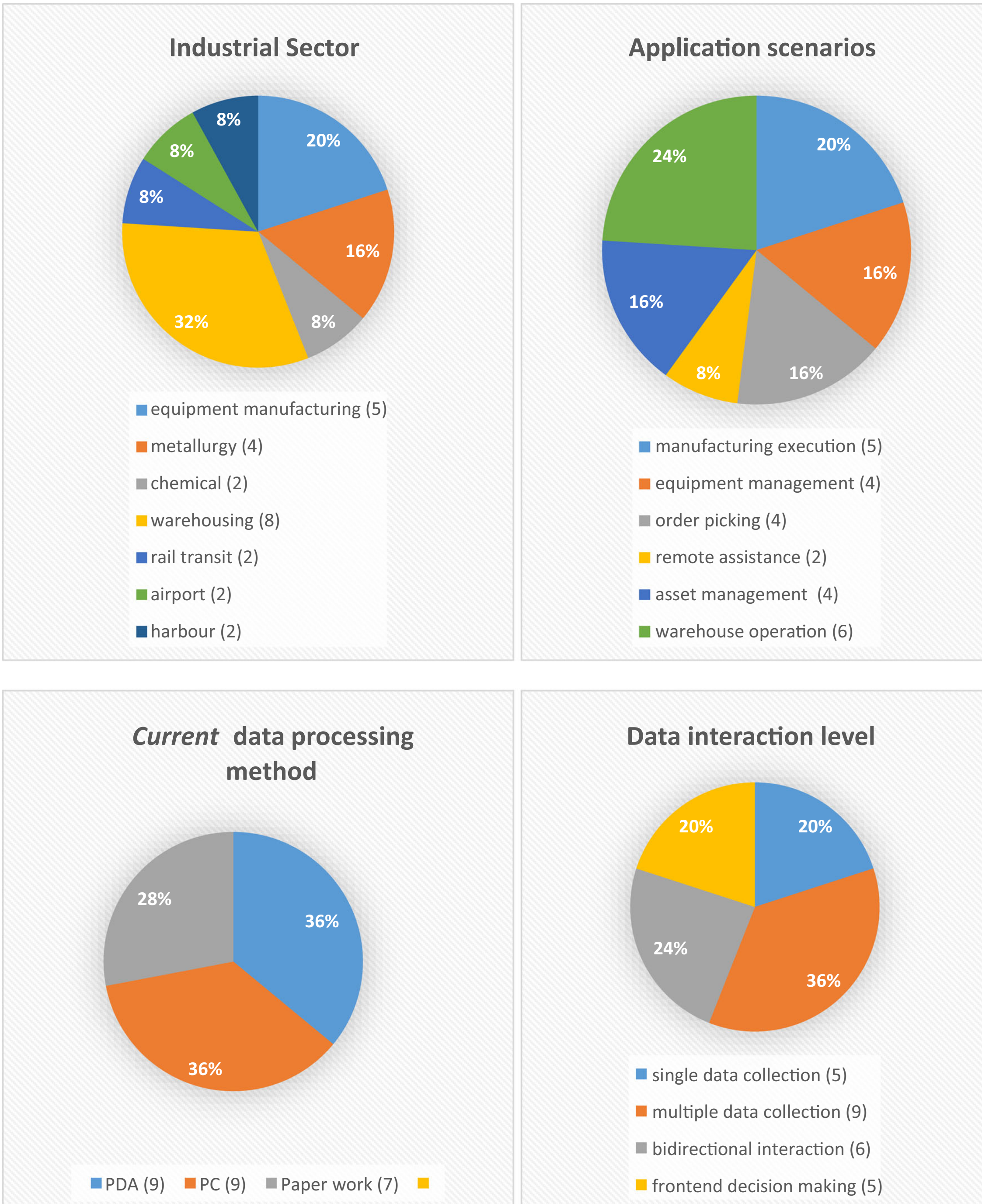

Fig. 1 Background of 25 selected enterprises in the survey

The distribution of 25 selected enterprises under above 4 aspects are shown in Fig. 1.

Design considerations

All of the case companies selected in "Enterprise background of the survey" section have collaboration projects with author's research team. A number of system development and consulting projects has been conducted in these companies. Before the implementation, we investigated the key pain spots of users by questionnaires. After the implementation, the feedback and key considerations are collected by interviews and workshops. Finally, we summarized 15 design considerations of industrial wearable system and grouped them in to following 5 factors.

Ergonomic product design

[Design Consideration (DC) 1] Weight of wearable device: Due to the special usage mode of wearable devices, especially for the head mount wearable devices, the heavy and bulk device is not acceptable. This consideration is highlighted in smart glasses scenarios.

[DC 2] Comfortable material of skin contact part: The wearable product is normally fixed on human body by belt and strap. Users are very sensitive to those skin contact part. Because the user has to wear the product for long time in the harsh environment, the moisture absorbing and breathability are quite critical features. This consideration is raised from the warehouse in which the environment can be very hot.

[DC 3] Hands free and wireless: Since the industrial wearable is a human-centred system, the operators may have lots of manual operations on the manufacturing sites. Wearable device should be developed to enhance the operation efficiency without any interruptions. So their hands cannot be fully occupied and the movement of hands cannot be restricted by any wires and cables. This consideration is highlighted by the small parts pickup and put away operation in warehouse.

Data interaction on device

[DC 4] Concise presentation of key information: In each specific working sections, the operation only need to read very limited data, for instance, the location ID of a product, or the quantity of a product. The complete information shown on the wearable deice screen may disturb the operator's focus and concentration. This consideration is raised from the high speed operation scenarios, for example, the e-commercial warehouse in peak season.

[DC 5] Less touch screen and keyboard input: The touch screen and keyboard data input are normal methods for most of data interaction scenarios. However, it is not suitable for industrial wearable system. The screen size and wearable method cannot support complicated data typing. This consideration is raised from elderly operators who are not very familiar with the mobile device operation.

[DC 6] Voice and gesture interaction: In some specific scenarios, the voice and gesture can be good supplementary data interaction methods, especially for succinct information(Kim et al. 2004). For example, using voice for one digital command, or using vibration to status alerts. This consideration is highlighted in smart glasses scenarios.

Operational stability

[DC 7] Battery life: The battery life is a critical issue for industrial wearable device. Normal, the device must work longer than 8 hours without charging. This is because in most of manufacturing the logistics company, one work-shift is 8 hours.

[DC 8] Network connection stability: In the industrial environment, the multiple wireless networks are used in the same space such as Wifi, Bluetooth, RF and 4G/GPRS. The network connection should be stable and network access should simple-to-use and easy-to-deploy. This consideration is raised from the working site with large spaces. The wireless network may cross different access points.

[DC 9] Industrial protection: In the harsh industrial environment, the wearable device should consider the protection for extreme temperature, humidity and shock. This consideration is raised from the chemical industry and outdoor working site.

External software integration

[DC 10] Business process integration with enterprise system: The IWS cannot independently working without the connection to enterprise systems such as ERP, WMS, MES. Industrial wearable system have to be seamless integrated into current business process. This consideration is raised from the company which has their own IT supporting team.

[*DC 11]* On-site real time decision-making: The industrial wearable system should have the ability to support real-time data process and decentralized decision -makings. The data view and operation statement should be synchronized between frontend and backend systems. This consideration is raised from the frontend management user who need to make real time decision.

[DC 12] Human experience involvement: In the human-centred system, the role of human is not only just conforming to system's instruction. The human experience must be involved in the process to handle some special and disruptive cases. This consideration is raised from the frontend management user who need to deal with complicated situation.

External hardware integration

[DC 13] Data collection from equipment: The IWS should have convenient method to directly collect data from external equipment, machines or robots on the manufacturing sites. This consideration is raised from equipment management application.

Table 1 The important degree of each design consideration

Key factors	Design considerations	Important degree
Ergonomic product design	Weight of wearable product	☆☆☆☆☆
	Comfortable material of skin contact part	☆☆☆☆
	Hands free and wireless	☆☆☆
Data interaction on device	Concise presentation of key information	☆☆☆☆
	Less touch screen and keyboard input	☆☆☆☆☆
	Voice and gesture interaction	☆☆☆
Operational stability	Battery life	☆☆☆☆☆
	Network connection stability	☆☆☆☆
	Industrial protection	☆☆☆
External software integration	Business process integration with enterprise system	☆☆☆☆
	On-site real time decision-making	☆☆☆
	Human experience involvement	☆☆
External hardware integration	Data collection from equipment	☆☆☆☆☆
	Intervention and control of equipment	☆☆☆
	human–machine cooperation	☆☆

[DC 14] Intervention and control of equipment: The IWS should has the ability to execute the human–machine integrated decisions by directly control the external equipment, machines, robots or intervening operation processes. This consideration is raised from manufacturing execution application.

[DC 15] human–machine cooperation: This cooperation is a high-level human–robot symbiotic in a fenceless environment. The productivity and resource effectiveness will be improved by combing the flexibility of human and the accuracy of machines. Human can instruct robots by speech, signs, and gestures. The aim of this human–machine cooperation is to achieve dynamic task planning, active collision avoidance and adaptive robots control.

Evaluation of the relevant research and developments

Based on the feedback of pilot industrial wearable projects, the important degree of each design consideration in five design considerations are summarized in Table 1.

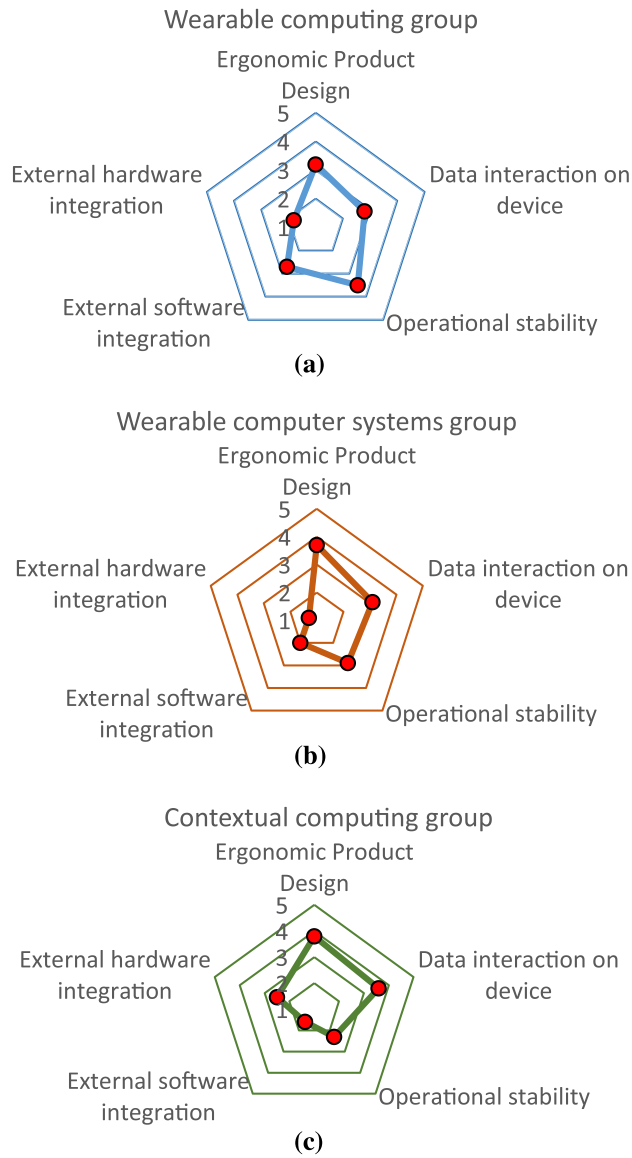

Fig. 2 Evaluation of five design consideration factors for three world-leading groups

The important degree of design consideration can act as an evaluation mechanism to review the previous industrial wearable solution. It also can act as a guideline in design the new industrial wearable system framework. Based on this evaluation mechanism, three world-leading industrial wearable projects has been reviewed. The results are shown in Fig. 2. In contrast with wearable computing group and wearable computer systems group, contextual computing group has the highest scores in the following three aspects, namely ergonomic product design, data interaction on device and external hardware integration. However, the other two factors are not mature enough due to head-mounted displays are still a research issue in terms of users' acceptance and wearability especially when wearing it for a long time.

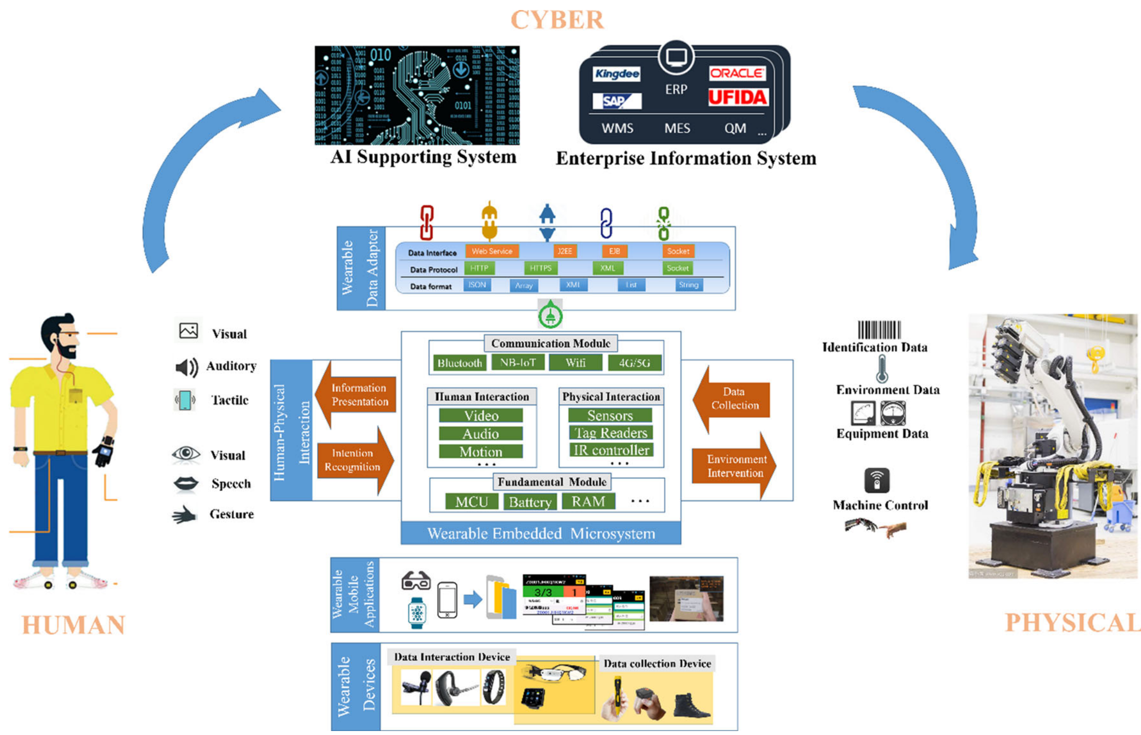

Fig. 3 Technical framework of industrial wearable system

From this evaluation, it can be found that the external hardware integration and internal software integration are still insufficient. More consideration will be put on these two aspects.

Technical framework of industrial wearable system

Based on the design consideration analysis from our pilot projects and other research frontiers, the IWS technical framework is proposed. The project types include e-commerce warehouse operation, equipment inspecting operation in chemical factory, data collection in manufacturing execution system, machine maintenance with remote expert assistance. All categories of industrial wearable devices are involved in these projects, which include smart glove, smart ring, smart glasses, smart watch and wearable printer. As shown in Fig. 3, it serves as a fundamental structure for the IWS implementation in business solutions.

The close loop of human–cyber–physical

This technical framework follows the "human-in-the-loop" paradigm (Mrugalska and Wyrwicka 2017). This paradigm contains three core components: empowered human being, perceptible physical world and cloud-based cyber system.

Empowered human being is the frontend operator who is equipped with industrial wearable devices. Their perception ability is enhanced by smart sensor and wearable data collection system. Their communication ability is augmented by wireless networks. The real-time connection can be established with other onsite operators and backend administrators. Their decision-making ability is also improved by human experience and multidimensional information supporting.

Perceptible physical world indicates that the machines, equipment, robots and materials in the industrial environment are embedded with wireless data transportation protocols or auto identification tags. The working status and operation data can be easily captured by operators. Meanwhile, such perceptible items can also be controlled and intervened by operators.

Cloud-base Cyber System consists of two parts. The first one is cloud based enterprise information system. This system is mainly responsible for business process executions. The counterpart of human and physical items are also virtually registered in this system. The second one is cloud-based computing resources. Since the human intention recognition (such as speech and gesture recognition) needs to consume abundant computational resources, the recognition processes are not accomplished on the frontend side. Most of AI recognition processes are wrapped up as web services and deployed on cloud-based services.

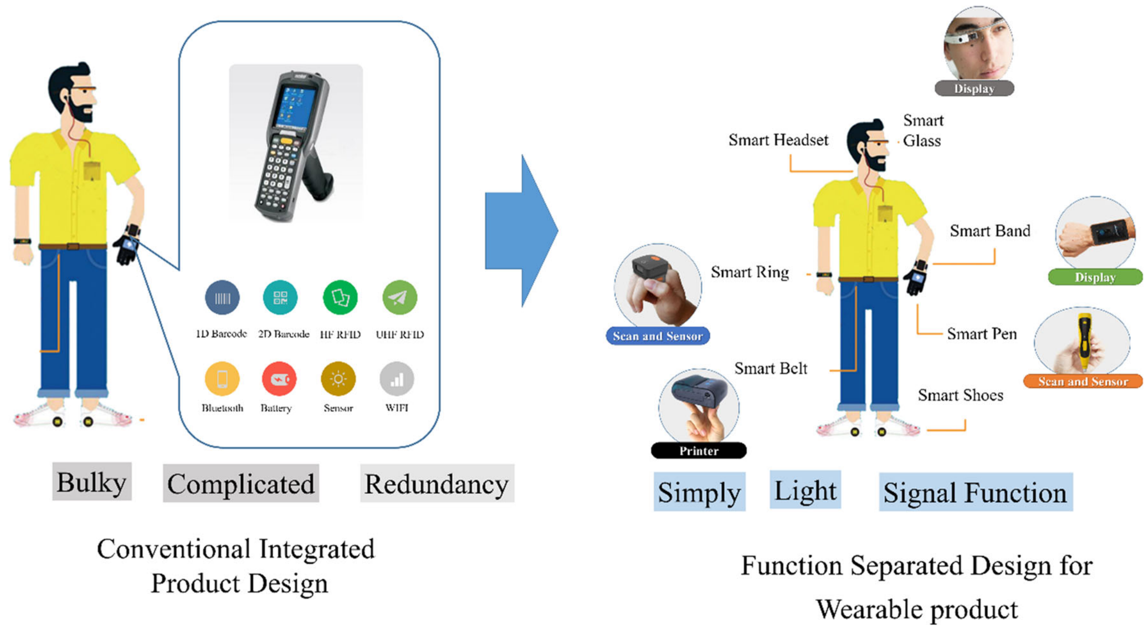

Fig. 4 Functional separated design of industrial wearable system

The Human-in-the-Loop (HitL) involves different types of human activities. It can influence the overall performance and bring flexibility to the system. The HitL scenario encompasses the following types of activities: overseeing and adjusting the set points, directly commanding the system, being a source of data (identification, early detection, reporting, etc.), introducing deviations/disturbances (errors, oversights, voluntary of involuntary deviations from the standards, etc.) (Anastasi et al. 2009). That means the human–machine interactions are supervised and controlled by adaptive control systems and based on sharing and trading of control strategies to allow a dynamic and seamless transition of function (task) allocation between human and machines, always aiming for the operator inclusiveness without compromising the production objectives (Lorenz et al. 2015).

Key components of IWS

To achieve the "human-in-the-loop" paradigm, the IWS serves as a core middleware and multiparty interface among human, physical world and cyber systems. The key components of IWS are introduces as follows.

Industrial wearable devices

The format of industrial wearable devices has two main streams: human interaction device and data collection devices. The human interaction device includes smart glasses (Sawyer et al. 2014), Pad, smart watch et al. The data collection device indicates ring scanner, smart glove (Schmuntzsch et al. 2014), RFID shoes, et al. In some case, human interaction and data collection are integrated into one device.

One of the key concepts of industrial wearable devices is the functional separated design. As shown in Fig. 4, the conventional PDA is an all-in-one function design, which is bulky, heavy and redundant. For the industrial wearable device, each device should has separated and specific function. Such function should be distributed in different body parts (Lukowicz et al. 2004). The main requirements for the wearable system is to ensure the operators' hands-free (Lukowicz et al. 2004) and not to disturb their on-site operations (Chao et al. 2016).

Another key concept is the human factor engineering. One wearable device may need to fit different application scenarios. It can be achieved by the confinable and reconfigurable wearing accessories. As shown in Fig. 5, the wearable scanner can be extended to four scanning gestures with different magnetic accessories for different industrial scenarios. In addition, the textile contacting skin has to fulfil the high requirement concerning hygiene and comfort (Lorenz et al. 2015).

Wearable mobile applications

The wearable application is the watch embedded or glass embedded light software system, which aims to provide concise user interface to connect each business process. The regular wearable application format is iOS app or Android APK according to wearable terminal. The key consideration of wearable application design is the interaction user experience on small-size touch screen. The traditional inter-

Fig. 5 Ergonomic accessory of industrial wearable device

face paradigms like common line interface or previous PDA WIMP (windows, icon, menu, and pointer) interface is not suitable for wearable application. In the wearable mobile applications, the information on screen should be quite accurate and concise due to the limited space. As seen in Fig. 6, the contrast colour blocks and boldface text are used to help operator to get key information quickly and reduce human errors.

Wearable embedded microsystem

The embedded microsystem is the core structure of industrial wearable hardware. It consists of following four modularized hardware sets.

- *Physical interaction module set* includes the environment sensors (temperature, humidity), scanner module and machine remote controller module.
- *Human interaction module set* includes touch screen module, camera module, audio modules and motion sensors.
- *Fundamental module set* includes MCU, battery module, memory module and power consumption management module.
- *Communication module set* includes Zigbee, WiFi, Bluetooth, GPRS, NB-IoT and 4G/5G communication modules.

Due to the various industrial environment, the data sensing and human interaction requirements would be different. To reduce the verity of wearable devices and control the hardware design cost, the confinable and reconfigurable module structure has been proposed in the embedded microsystem. As shown in Fig. 7, the sensors, communication modules and data interaction modules are designed with standard hardware interfaces. The corresponding components for each module have the plug-and-play feature. Therefore, one wearable product format can be extend to multiple subtype wearable products.

Human–physical interaction channels

Human–physical interaction is the core issue in the industrial wearable system. The interaction has two main directions from physical to human (see Fig. 8). The IWS acts as an interface between two parts.

(1) From physical to wearable system: Data collection

The aim of data collection process is to make physical world perceptible. Data collection is mainly achieved by sensor module set. The data formation is consists of identification data (bar code, OR code and RFID), the equipment embedded data (current, voltage and instrumentation values) and environment data (temperature, humidity, vibration). The typical products including ring scanner and smart glove, and smart pen.

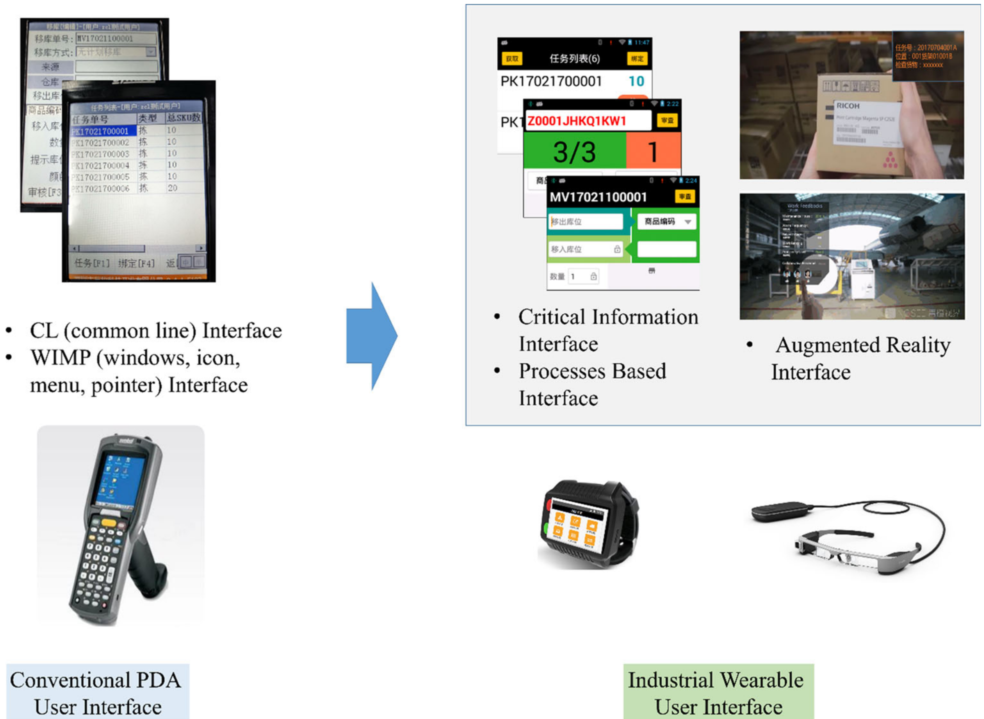

Fig. 6 Industrial wearable user interface for industrial mobility

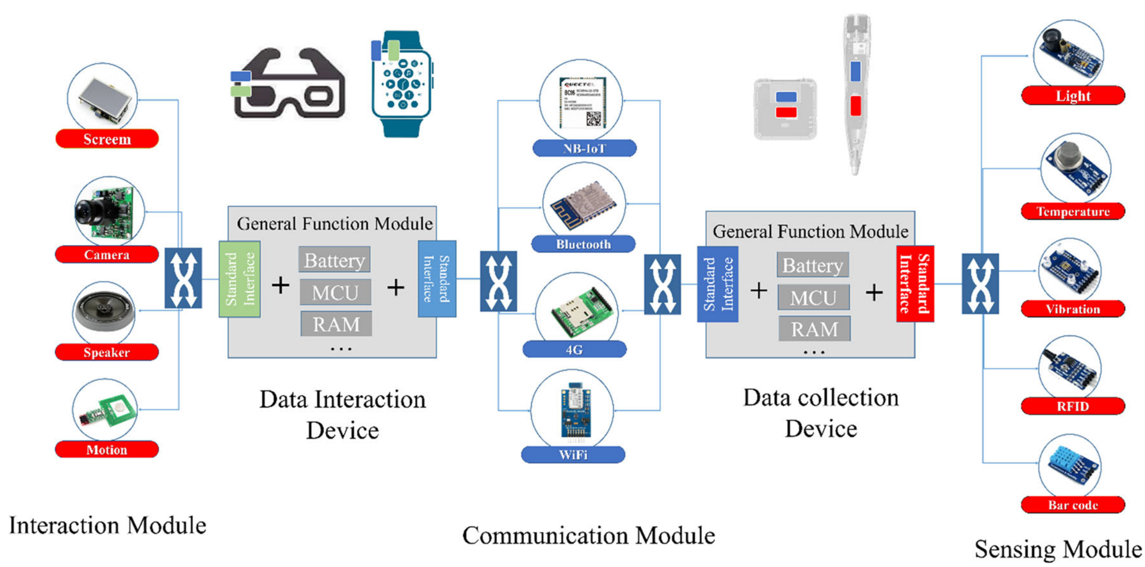

Fig. 7 Confinable and reconfigurable wearable hardware module structure

(2) From wearable system to Human: Information presentation

The key concept of information presentation in wearable system is human perception empowerment. The data collected from the physical world is converted to image, voice and vibration, which let human to acquire critical information in the most natural way. The visual sense, auditory sense and tactility sense of operator can be enhanced the by those wearable products. The typical products including AR glass, smart watch wireless earphone and smart wristband.

(3) From Human to wearable system: Intention recognition

The key requirement of human input in wearable system is to make system to know human's intention more naturally. Artificial intelligent (AI) technologies are widely used in the industrial human–machine interaction. The AI technologies are focusing on the image recognition, semantic recognition and gesture recognition. Since the AI support-

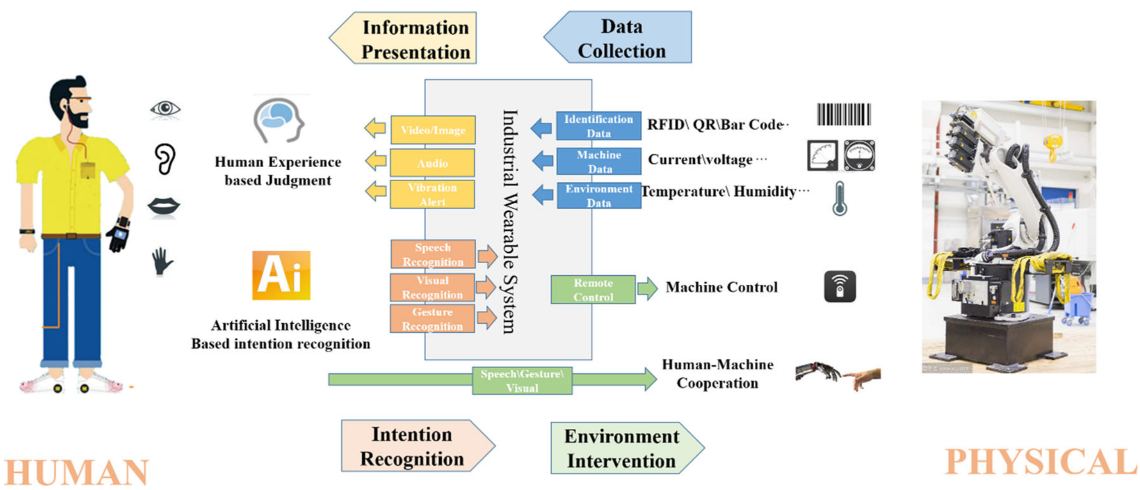

Fig. 8 Human–physical interaction channels

ing need to consume abundant computational resource, such recognition processes are not accomplished on the front end client side. Most of AI recognition processes are wrapped up as web services and deployed on SaaS structure.

(4) From wearable system to physical: Environment intervention

The last step of human–physical interaction is to intervene the machine and process in the industrial environment. There are two ways to achieve such intervention. The first one the indirect control. The machine can be operated by remote controller embedded in the wearable device, for instance, the Bluetooth or infrared remote controller. Another way is direct human–robot interaction. Human can teach robot "by holding the robot arm".

Wearable data adapter

The industrial wearable device must have a seamless connection with existing enterprise information system (EIS), such as ERP, MRP and MES. The wearable data adapter acts as middleware to connect the frontend wearable applications and backend EIS. The typical portals (Web Services, J2EE, EJB, Socket) and typical data formats (Json, Array, XML, List, String) are packaged into wearable data adapters as standard AIPs. Such data adapter design can make the system integration more efficiently.

According to the technical framework of IWS proposed above, the design considerations discussed in "Design consideration of industrial wearable system" section can be addressed in following Table 2.

Future research opportunities

The increasing integration of manufacturing processes and the strengthening of the autonomous capabilities of manufacturing systems make investigating the role of humans as a primary research objective. It is going to attract more and more research efforts, at least, in the following 5 years. Combining the proposed technical framework in "Technical framework of industrial wearable system" section, this section offers a research agenda for the identification of knowledge gaps with four significant research perspectives in future.

The perspective of wearable embedded microsystems and power management

An industrial wearable device is a typical embedded microsystem. This system houses the complete electronics for signal conditioning, digitization, processing and wireless transmission of vital parameters along with the localization data (Chan et al. 2012). In industrial applications, user requirements of up to eight hours of use without recharging are common (Hung et al. 2004; Anastasi et al. 2009). However, there is always a trade-off between miniaturized wearable device size and power management. To achieve this, a sophisticated and efficient power management of all components and wireless data communication is required, such as, data compression techniques and bandwidth balance optimization. As the devices are frequently used, a hot swappable exchange of batteries is needed.

Furthermore, the heterogeneity of possible industrial contexts demands for the data fusion of various wearable sensors (Tröster 2005; Mukhopadhyay 2014; Zhu et al. 2015). How to design a reconfigurable embedded microsystem incorporating plug-and-play feature is a key research topic as well (Yao et al. 2005). Plug-and-play architecture features a modular, open and scalable design for multi-sensor control and data transmission by leveraging shared resources and operating at different functional combinations. However, such a structure is vulnerable to node failure or signal priority inequality.

Table 2 Key components of IWS addressing the design considerations

Design consideration		Ergonomic product design			Data interaction on device			Operational stability			External software integration			External hardware integration		
		DC1	DC2	DC3	DC4	DC5	DC6	DC7	DC8	DC9	DC10	DC11	DC12	DC13	DC14	DC15
The close loop of human–cyber–physical											☆		☆	☆	☆	☆
Key components of IWS	Industrial wearable devices	☆	☆	☆						☆						
	Wearable applications				☆	☆					☆					
	Wearable embedded microsystem	☆						☆	☆					☆	☆	☆
	Human–physical interaction Channels			☆		☆	☆				☆			☆		☆
	Wearable Data Adapter								☆		☆	☆	☆			

How to carry out effective signal and wireless data transmission control is the foundation of this architecture. In terms of next-generation power management, it is worth exploring the possibility of harnessing the energy expended during the user's everyday actions to generate power for wearables that eliminates the hurdle of batteries (Starner 1996).

The perspective of wearable user interface and context recognition

Most of previous wearable system applications are characterized by their unimodal interactions such as mechanically input by keyboard or touch screen. In nowadays manufacturing, worker mobility and system complexity is increasing at the same time. Meanwhile, there are various kinds of manufacturing information, such as design specifications, logistics and inspection information, assembly tools, etc. In a distributed and complicated manufacturing environment, it is crucial to provide different views of a product to users in different task domains.

To accommodate for these new requirements, the design of augmented context-sensitive user interfaces is significant (Smailagic and Siewiorek 2002). First, manufacturing information should be efficiently classified and displayed so that information can be retrieved at the appropriate time and superimposed at the appropriate locations (Ong et al. 2008). It should allow active information filtering and only provide the users with information and interaction possibilities relevant to their current tasks, behaviours or locations. Second, in addition to the natural interaction that occurred on the basis of dialogue-driven voice control and gesture recognition, a substantial amount of information can be coherently visualized by means of virtual and augmented reality (VR/AR) to build up augmented manufacturing environment (Coburn et al. 2017) (Starner et al. 1997; Paelke 2014; Posada et al. 2015). More studies are worth being examined in augmented manufacturing, for example, the AR-aided wearable applications for walking workers in assembly islands (Baumann et al. 2011). Third, the wearable user interfaces must adapt to changing environment conditions (e.g., light, noise, use of hands, necessary movement) and take actual work context information into account. Finally, current approaches to evaluate a wearable interface requires elaborate procedures with scores of subjects, usually taking several months. The quick evaluation methodology is critical research topic, especially focusing on decreasing human errors and frustration.

The perspective of user acceptance and wearability

For industrial wearable systems to be adopted and utilized, they must first gain acceptance from the intended users. Users' acceptance is significantly affected by human factors. Buenaflor and Kim (2013) identified six groups of factors that play a key role in the acceptance of wearable computing technology. Some of these factors can be interrelated with each other and also influence other factors. Stein et al. (1998) summarized the detailed development process of a commercial wearable data collection system and ergonomics is considered as one of major technical challenges. Weaver et al. (2010) provided an empirical study for the comparison of various mobile computing interfaces and paper-based methods to support the warehouse order picking. The results showed that using the head-mounted displays was significantly faster than other picking up methods. However, head-mounted displays are still a research issue in terms of users' acceptance. Especially when wearing it for a long time. More detailed ergonomic evaluation should be conducted by looking at its quantitative effects.

User wearability is defined as the interaction between the human body and the wearable system, which may be also influenced by human body in motion. Design for dynamic wearability usually considers the physical shape/weight of wearables and their active relationship with the mobile workers. Researchers have explored different wearable designs and specific accessories in the last few years. Dipietro et al. (2008) surveyed glove-based systems and applications while providing a roadmap of the evolution of this technology. Wolf and Willaredt (2015) introduced PickRing, a wearable device that allows seamless interaction with other devices through the pick-up detection. Preliminary experimental results are promising but a number of user wearability issues still need to be solved such as how to define and evaluate appropriate wearability design attributes and wearable forms.

The perspective of cross-cutting collaboration for advanced business intelligence

With the increase of workers and assets' mobility as well as material processing complexity, the use of wearable information technology should be horizontally collaborated or vertically integrated with other new technical systems to further improve efficiency and effectiveness of enterprise decision intelligence.

The horizontal collaboration indicates that the wearable technology will integration with other parallel information technology, for instance, AI, VR, IoT and Could computing, to achieve multidimensional data operation. The vertically collaboration means that the wearable technology will embedded into enterprise information systems, for example, ERP, MES, and WMS, to linkage the business process from upstream to downstream.

In terms of horizontal collaboration, wearables might not be absolutely integrated with other technical components, whereas to realize a certain level of tasks as interoperable systems. There are several limitations for wearable applications in the real-life working environment like constrained spaces, water and heat, and corrosive products. Issues like security, safety and confidential rules have also to be considered. Therefore, context awareness requires the accompanying assistance sensors in body or in the environment such as indoor positioning sensors or integrated cameras to notify the worker about which steps to take and which security measures they must adhere to in operations (Gorecky et al. 2014). Moreover, because of recent advances in wireless communication technologies (e.g., wireless body area networks), human movements and postures can be dynamically monitored (Farella et al. 2008). Therefore, workers' workload, stress and behaviour can be analysed in each operation for enhanced task allocation optimization (Timm-Giel et al. 2006).

In terms of vertical collaboration, wearables must be integrated with other technical components as a whole decision support system. For example, a lot of heavy and repetitive works could be assigned to robots while wearables can empower mobile works to deal with more dynamic and complicated jobs for industrial frontline operations. In addition, emerging technologies such as big data, cloud computing and artificial intelligence can be integrated with wearables to produce greater value especially when a large amount of data has been collected.

More future works should be done to explore the impacts of both horizontal collaboration and vertical collaboration on enterprise performance improvements. For instance, to process real-time heterogeneous data and deal with complex industrial workflow management, an open operating system operated on smart wearables should be designed. Such pen operating system should inherit the characteristics of mobile operating system such Android and iOS (Hall and Anderson 2009; Fang et al. 2013). The technical challenges in its implementation need to be solved and discussed as well.

Conclusion

The main objective of this research is to review and analyse the academic progresses in topics related to the industrial wearable systems in a systematic manner, to provide insights into the past, present and future of this topic.

As the first stage result, this paper presented the systematic literature review for three world-leading research groups within the IWS subject based on the general design consideration factors and investigation of prominent research projects, journals and popular conferences. Knowledge and development gaps of existing studies have also been analysed.

Then, special attention has been given to structuring new technical framework of industrial wearable systems with following three aspects: (1) the design of scalable, reconfigurable and robust IWS architecture to connect the physical world, humans/assets and cloud-based cyber systems as a common platform allowing standardization while offering a unified approach for the wearable-enabled application developments; (2) the list of key components that more frequently appeared in real-life industrial implementations has been summarized, focusing on the (re)configuration and (re)combination of different modules to fit different industrial environment; and (3) the incorporation of Human-in-the-Loop paradigm into the IWS structure to build up a close-loop human–machine interaction, decisions, feedback and execution.

Finally, several opportunities for future research were identified with coherent connection of research perspectives and open questions. These research perspectives are not only concerned with technology issues of wearable hardware and software, but also with cognitional and operational issues for the enhanced user wearability and business intelligence. Several new observations can be used as the basis for future research in evaluating the impacts of IWS on Industry 4.0 and related areas.

When considering the results of the present study, several limitations should be noted. First of all, papers were collected from the 2 decades because the field of IWS is still emerging and related articles are currently limited in research community. Furthermore, although both practical challenges and research questions have been unravelled in this systematic study, our propositions require testing by further quantitative methods.

Future works should be extended in several ways. In addition to the enhanced development of wearable hardware, software and users' ergonomics, we recommend that future researchers look at the opportunities that the connection between wearable computing and other innovative technologies (e.g., big data and deep learning) should be developed. The majority of the existing studies are still based on laboratory experiments and future IWS studies applied in real-life industrial environment should be encouraged to gain more concrete managerial insights.

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