A Survey and Tutorial on the Possible Applications and Challenges of Wearable Visual Lifeloggers.

Eisa Zarepour Mohammadreza Hosseini Salil S. Kanhere
Arcot Sowmya
School of Computer Science and Engineering
University of New South Wales, Sydney, New South Wales 2052, Australia
{ezarepour, mhosseini, salilk, sowmya}@cse.unsw.edu.au

Technical Report
UNSW-CSE-TR-201515
October 2015

THE UNIVERSITY OF
NEW SOUTH WALES

School of Computer Science and Engineering
The University of New South Wales
Sydney 2052, Australia

Abstract

Advances in manufacture of miniaturized low-power embedded systems are paving the way for ultralight-weight wearable cameras that can be used for visual lifelogging of minute details of people's daily lives. The ability of wearable cameras to continuously capture the first person viewpoint with minimal user interaction, have made them very attractive in many application domains. Although today the wearable cameras are available and useful, but they are not widely used and accepted due to various challenges such as privacy concerns and some technical limitations. In this paper, possible industrial, medical, martial, educational, personal and media applications of wearable cameras are highlighted. The main challenges in realizing the full potential of wearable cameras are outlined and current state-of-the-art proposals for addressing these challenges are reviewed.

1 Introduction

Digital cameras are now widely embedded in many consumer gadgets such as smartphones, tablets, laptops and even smart watches. Recent advances in camera and display technologies coupled with the increasing trend towards miniaturization have paved the way for a new category of compact wearable visual lifeloggers (WVLs) that can continuously record high quality pictures/videos from a first person perspective. Examples include Glass-ware WVLs such as Google glasses [9], Epson [8] and VUZIX [14] smart glasses; mounted-ware WVLs such as GoPro [10], Narrative Clip [12], Autographer [7] and Microsoft SenseCam [11]; and recently introduced wearables with flying capabilities such as Nixie [4]. Several of these devices also feature communication capabilities based on Bluetooth and WiFi interfaces, embedded sensors that provide support for natural human interactions via gestures and voice commands, and screens for displaying information. The hands-free nature of interaction of WVLs coupled with the ease of uploading and viewing data has made collecting and sharing pictures and videos easier than ever before.

This new generation of WVLs can support a plethora of new applications far beyond what can be achieved with conventional cameras and even smartphones. For example, it has been shown that a WVL can be used as an assistive and rehabilitative tool for people with visual, auditory, physical or mental impairments [51, 54, 66]. A WVL can also be used for real-time recording of complex surgeries from the surgeon's point of view, which has tremendous educational value for students and interesting insights for novices [56].

While there are few prior works that document the usefulness of WVLs in individual application domains such as health [33], industry [43], military [81] and education [80], as far as is known, a comprehensive review is still missing. This paper presents a broad and detailed survey of the VWL application landscape. In addition, some interesting insights into the challenges that are likely to arise, as WVLs become more pervasive in the environment, are presented. These include energy constraints, privacy issues, social restrictions and legal uncertainties. The current state-of-the-art approaches that attempt to address these challenges are reviewed, with particular focus on the challenging issue of privacy.

The rest of the paper is structured as follows. In section 2, the historical evolution of WVLs is discussed. The core building blocks of WVLs are examined in section 3. An in-depth survey of several interesting applications of VWLs is presented in Section 4. The key challenges that are likely to emerge, as WVLs see broader adoption, are summarized in Section 5, along with a discussion on how these may be addressed. Concluding remarks in section 6 end the paper.

2 History of Wearable Visual Lifeloggers

The first documented use of a wearable camera dates back to 1968 when Ivan Sutherland designed a head-mounted display with half-silvered mirrors that let the wearer see a virtual world superimposed on reality [76] (Figure 2.1.a). This device referred to as the Sword of Damocles is now widely recognised to be the first virtual reality and augmented reality system. His system was very primitive in terms of both user interface and realism. For example, the virtual

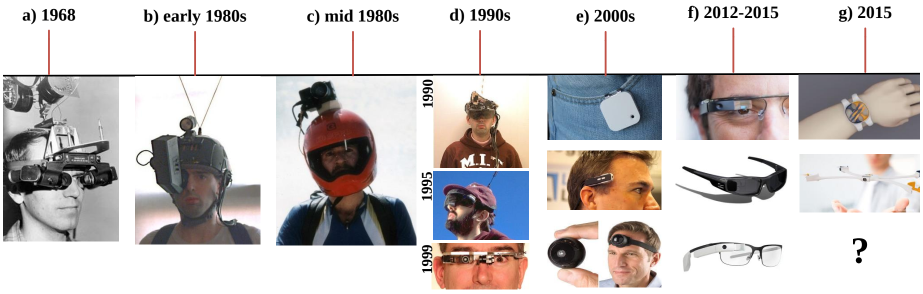


Figure 2.1: The historical evolution of wearable visual lifloggers.

environment simply consisted of wireframe rooms. It also required the wearer to be tethered to a workstation that was powered from an AC outlet. In the early 1980s, mass production of the micro-chip brought with it the potential to create smaller and lighter digital circuits than ever before. This led to the gestation of the first truly wearable camera, invented by Steve Mann, which which was a backpack-mounted computer to control photographic equipment (Figure 2.1.b) [53]. Unlike Sutherland's camera, this device did not require any infrastructure and could be powered by a DC battery which made it more portable.

In 1987 using a VHS cassette and a consumer-grade camcorder, Mark Schulze, a mountain bike enthusiast, created a *helmet camera* by rigging a video camera to a portable video recorder (Figure 2.1.c) [82]. Although the *helmet camera* was heavy and awkward, the ability to create a very exhilarating video from first-person view of this exciting sport was a highlight at that time [1].

The explosion of portable computing in the early 90s resulted in several attempts at creating wearable cameras. In the early 1980s, Steve Mann joined the MIT Digital Eye Project (DEP), improved his early wearable camera (Figure 2.1.b), and created several iterations over a period of 15 years [53]. He developed the first 'Wearable Wireless Webcam' in December 1994. The webcam transmitted images from a head-mounted analog camera to an SGI base station via amateur TV frequencies over a point-to-point connection. The images were processed by the base station and viewed on a display in near-real time. His final design built in 1999 was quite similar to today's glassware cameras (Figure 2.1.d).

Nevertheless, rapid development in manufacturing of small and smart mobile phones in the late 90s and early 2000s enforced the wearable cameras to take a back seat. A recent study in the US shows that 67% of smartphone users use their phone to share pictures, videos, or commentary about events happening in their community, with 35% of the user population doing so repeatedly [75].

However, in recent years, advances in digital camera technology and miniaturization has rekindled interest in wearable cameras as lighter and better resolution versions can now be attached to the human body, for example, shirt, head; or devices (Figure 2.1.e). This new generation of wearable camera devices is promoting an entirely new mode of photography in which the camera discretely and continuously captures large quantities of opportunistic images with minimal interaction with the user. This new mode of operation, a concept known as 'lifelogging' [85] or 'visual lifelogging' [33] is now widely available to consumers through devices such as the Narrative Clip [12], Autographer [7], Microsoft SenseCam [11] and GoPro [10]. An important development in WVLs was occurred in 2012 when Google introduced its first prototype of Project Glass, now known as *Google Glass* (Figure 2.1.f). Google Glass can record and also display information in a hands-free format. It can communicate with the Internet and interact with the wearer through natural language voice commands. In recent years many other companies are making Glasses-ware cameras such as VUZIX [14], Epson [8], Lumus [3], OrCam [5], Recon [6] and Pivothead [13].

There are some interesting new developments that point to the future evolution of wearable cameras. A recent prototype called *Nixie* [4] is a wearable camera in the form of a wrist watch that can fly off the wrist and transform itself into a remote-controlled quadcopter. It captures images of the wearer and then can return to their wrist (Figure 2.1.g).

In summary, WVLs have come a long way since their inception. The increasing ubiquity of these devices is expected to create a new era of sophisticated visual sensing applications. In the next section, the key technologies that are encompassed in a WVL are discussed and the typical modes of operation outlined.

3 What is a WVL?

A WVL is a wearable device that can continually record images and/or videos from the surrounding environment. In this section, the most common hardware components and the working principles of a WVL are discussed.

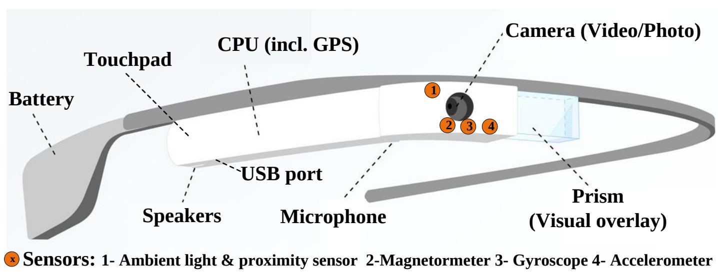
3.1 Elements of a WVL

A visual lifelogger typically includes a camera to capture the picture/video with or without a flash; a mount mechanism which may be fixed (e.g. Google Glass) or allow the user to attach it on their self (e.g. Narrative Clip); an on-board memory to save the recorded data; an export interface such as a USB port to transfer data to a computer; a battery and charging interface to power the device; and a small keyboard or touch-pad to control/set the device.

The device might also include additional facilities such as a wireless interface (Wi-Fi or Bluetooth); a microphone (for audio interaction and recording) and/or speaker; a small screen to display content; and some other components such as a water proofer cover or autonomous flying hardware [4]. WVLs, in addition, may also be equipped with some sensors such as accelerometer to determine the orientation of the device; gyroscope to track the device's rotation which can be used to increase the accuracy of detected orientation by accelerometer; and magnetometer for navigation purposes.

The typical components of a WVL shown in Figure 2.2a, and Figure 2.2b illustrates the arrangement of these hardware components in a Google glass. Recently developed WVLs have an operating system as well, mainly Android or iOS, which means that the device can be programmed. This last capability may be used to develop smart and privacy aware protocols for lifelogger devices. In the next section, the lifelogging procedure via WVLs will be described.

(a) The main hardware components for a wearable lifelogger. Camera, memory, export port, audio player/recorder, touchpad, battery/charger and screen are the main usual components in any WVL.



(b) Arrangement of the components in Google Glass [9].

Figure 2.2: Typical WVL hardware.

3.2 Working principles of lifelogging

Usually, there are six main steps in lifelogging, which are depicted in Figure 3.1:

i **Setting**: User will define the desired settings for the lifelogger, e.g. the resolution of the picture/video, frequency of capturing, etc. The privacy policies can be also set up in this step.

ii **Capture**: The physical camera captures the raw pixels.

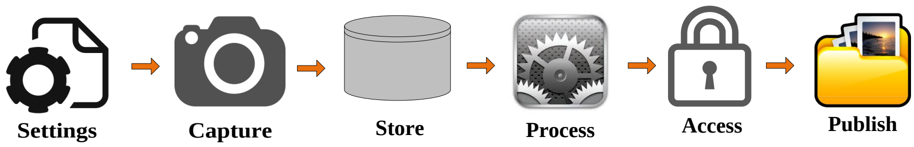


Figure 3.1: Six procedural steps in lifelogging.

iii **Store**: Captured pictures are stored in the local memory of the device and optionally also transferred wirelessly to a computer storage device.

iv **Process**: The stored pictures may be processed for image optimization either manually or automatically. Processing may be also required to enforce privacy rules that can be imposed locally on the device or externally on a remote machine.

v **Access**: Different applications can have different permissions to access to the processed pictures. For example, based on user settings, all captured pictures could be automatically uploaded to Facebook but not to Google-plus.

vi **Publish**: The processed picture/video may be published on social networks or any other locations.

Recent wearable devices can take photos at very high frequency, e.g, the Narrative Clip can capture up to 120 images per hour, while Autographer collects up to 360 per hour, which means that a few thousand photos can be collected over the course of a single day. Some other devices such as Google Glass and VUZIX can continuously capture videos as well. In the next section, possible applications for such video and high rate image recording are reviewed.

4 Applications

The ability of WVLs to continuously monitor and record the environment have made them a potential solution in a wide variety of medical, industrial, militant, educational, environmental and personal applications. In general, WVLs can be also used in augmented reality (AR) systems that allow the user to see the real world, along with virtual objects superimposed on, or composited with, the real environment [22]. This section briefly overviews the main applications of WVLs in the literature.

4.1 Health

The proposed applications of WVLs in the health domain may be categorized into four main groups: (i) early detection of disease by continuous data collection on the patient's lifestyle [38] [32]; (ii) assistance and rehabilitation of visual, auditory, physical or mental impairments such as autism [54, 40] and cognitive decline [52, 42, 65, 57, 39]; (iii) surgical applications such as real time recording of surgeries [56, 21]; and (iv) educational purposes.

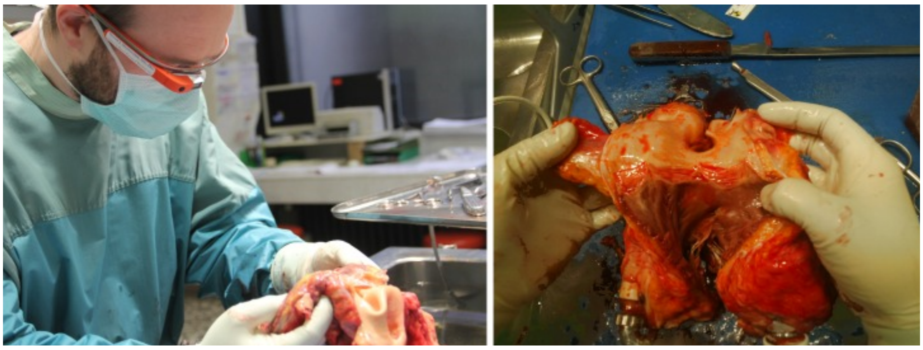


Figure 4.1: Forensics usage of WVLs. The forensic pathologist is taking a picture of the heart using Google Glass (left). The heart image taken with the device (right); adopted from [19].

In the first group, WVLs provide new insights into lifestyle behaviours enabling doctors to correctly diagnose the illness rather than relying solely on patient self-reporting which is often prone to substantial error associated with recall, comprehension and social desirability bias [32]. In this case, WVLs can be beneficial as they can provide direct observations from the day-to-day lives of patients. For example, a WVL-based solution has been proposed in [57] to monitor the instrumental activities of daily living with the ultimate goal of assessing the cognitive decline of people caused by age-related dementia. WVLs can be also used to enhance dietary assessment techniques [36, 62]. In a few studies, WVLs and their associated software analysis tools have been used to measure sedentary behaviour, active travel, and nutrition-related behaviours of patients [85, 63, 61]. In the second group of health-related applications, WVLs have been used as stand-alone or part of a solution to assist/rehabilitate patients. Although there are a number of techniques such as RFID, GPS, and sonar based systems [23] to detect the distance to obstacles, which can assist Visually Impaired (VI) persons, camera vision based systems can provide more information than only obstacle distance. Several WVL-based solutions have been proposed that not only enable the VI to avoid obstacles but also for navigation and helping to find a particular object/item in the surrounding environment [60, 49, 27]. Moreover, WVLs can be used as a text reading tool for the VI [73]. In addition, some studies have used WVLs to improve autobiographical memory [42] in a patient with limbic encephalitis [24] or episodic memory impairment [51]; as a companion tool to improve social-emotional learning in autistic individuals [54]; and as a rehabilitation tool for children with anterograde amnesia [66]. Monitoring the effectiveness of rehabilitation measures is another medical application of the WVLs. For example, a wearable camera system that is able to continuously identify hand contours and monitor hand functions, has been used to study the effectiveness of the rehabilitation process undertaken following stroke or spinal cord injuries [87].

In the third group of health related applications, WVLs have been used for surgical purposes such as remote electrocardiogram interpretation [47] and real-time recording of surgeries for training, documentation and monitoring purposes

Table 4.1: Possible applications of the wearable cameras.

Health	–Continuous monitoring of health-related lifestyle behaviors [38, 32] –Rehabilitation of the mental patients[24, 57], e.g autistic [54] and cognitive decline patients [42, 52, 57]. –Assistance to patients with visual [26], auditory, physical or mental disabilities . –Dietary Analysis [36, 62] –Real time recording of surgeries [56, 74]
Education and training	–Automatic note making from the course material. –Text reading on the go. [73] –Real-time guidance and online feedback for student . –Real-time language recognition . –Recording first person view in dangerous/expensive operations for training purposes.
Military	–To maintain clear visibility into police actions and increase accountability [81]. –To Improve soldiers post-action reports [92] –Realizing of the digital battlefield [92]. –Real time monitoring and mapping of the new battlefields [92].
Industrial and business	–Hands free operation –Remote monitoring of the technicians –Smart warehouse operations: pick-by-vision/optimized picking, warehouse planning [43] –Smart logistic, e.g., optimized freight loading and drop-off [43]. –Providing real time access to the required information for servicing agents. –Visitor estimation in exhibitions [68].
Location & activity recognition	–Place recognition using multiple wearable cameras [58] –Physical activity recognition based on motion in images [88, 59]
Disaster relief	–Real time monitoring and mapping of the disaster area [30, 31, 78, 90]
Environmental Monitoring	–Data collection in surveillance environments and urban environments
Personal	–Recording personal or family pictorial diaries. –Recording personally experienced events or sceneries. –Learning and training purposes. –Improving social interactions using real-time behavioural feedback [29]
Journalism	–Online reporting of the events. –Recording events and interviews to avoid misremembering.

[56, 74, 19]. Recording via the WVLs has three advantages over the traditional capturing methods such as using traditional camcorders or fixed cameras in the operating rooms. First, WVLs do not require an assistant to shoot the video or control the camera's location. In addition, the surgeon has complete control over what is being recorded rather than relying on a third party making that decision. Second, since the recordings are made from the surgeon's viewpoint, they offer the most unrestricted view of the procedure which can provide a lot of details and insights for novices. For instance, a commercially available head-mounted video camera has been used [56] to successfully capture high-quality recordings of trauma surgeries, including an emergency room thoracotomy for chest stab wounds and a crush laparoptomy for a severe liver injury. In another study, the feasibility of deploying Google Glass in a forensics setting for documentation purposes has been investigated (Figure 4.1)[19]. The potential uses of WVLs for health training and educational purposes will be discussed in the next section along with other educational applications.

4.2 Education and Learning

WVLs can potentially be used for many educational and learning purposes [80]. For example, using WVLs to record lectures and the contents of whiteboards could be useful for student recall of the [44]. In addition, a glassware camera such as a Google-glass, which is a kind of a microcomputer, can be used to create an integrated simulation-based training system that allows teachers and students to share information. Moreover, glassware cameras can help educators and students to search, take a picture, record a video, answer questions and translate their voice to foreign languages [83]. A WVL can also scan and detect text within pictures, which can be useful for both automatic translation and augmenting visual impairments [73]. Glass-ware WVLs are also promising for medical training and educational purposes. A recent study shows that wearable technology can improve education and patient outcomes in a cardiology fellowship program [80]. In this study, a mock trainee wearing Google-glass enacted few scenarios. The live video stream from the trainee's glass was transmitted via Wi-Fi or Bluetooth to a smartphone, tablet or personal computer that can be observed by the senior fellow i.e. supervisor. For example, in one of the scenarios, the trainee interpreted an EEG with his supervisor in real time and appropriate treatment then was initiated.

4.3 Industrial and business purposes

The service industry has already felt the impact of wearable technology, with technicians using WVLs to free up hands. Service technicians can receive real-time information about the job over the device's display while they are carrying out the service, which can increase the accuracy and performance of the technician. AR-enabled WVLs such as Atheerglass [2] can be also implemented to visually assist the technicians in quickly finding and repairing problems through a live collaborative operation [41] (Figure 4.2). WVLs can be also used for documenting the procedures undertaken by technicians, which can be used for training and verification purposes [41].

Some studies have suggested that WVLs can be widely used in the logistics and transportation business. For example, in big warehouses, an operator wear-

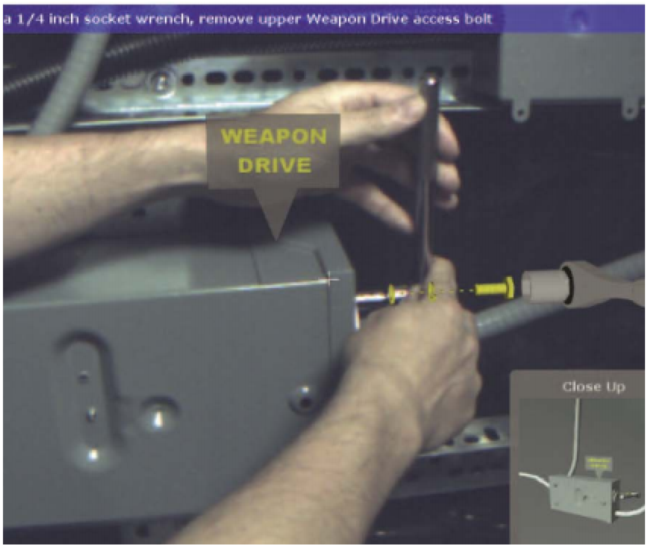


Figure 4.2: The glass-view of a mechanic wearing a AR-enabled WVL repairing a device. adopted from [41].

ing a glassware camera can smartly pick or stack items, based on a plan that been displayed on the devices' LCD which can save physical space and also time [43]. The same technique can be used for freight loading and drop off.

WVLs can be also used for visitor estimation in large exhibitions. A head-mounted camera has been used to approximate the number of attendees in exhibitions using a mathematical method [68].

Online customer service feedback is another potential capability of WVLs that can be used in many industries. For example, a camera-pinned passenger flying an airline every day can document and report any customer service issue such as dirty toilets, rude staff, delayed departures and any other inappropriate condition [69].

4.4 Military applications

Wearable cameras can help to maintain clear visibility during police actions and thereby increase accountability. Small cameras can be clipped onto officers' uniforms to record their interactions with the public. The recorded video then can be used for verification purposes if the wearer were to be accused of any inappropriate behavior [81].

In the army, WVLs can be helpful in three ways, including improving soldiers post-action reports; real time monitoring and mapping of the battlefield; and help in creating a digital battlefield, i.e, using information technology to smartly command and control the battle. First, a soldier may sometimes leave out vital observations and experiences in their after-mission report that could be valuable in planning future operations. The Defense Advanced Research Projects Agency (DARPA) has explored using soldier-worn sensors and recorders to improve the soldiers' recall and reporting capability [92]. Second, army intelligence agents

Figure 4.3: Some applications of the wearable visual lifeloggers.

can employ WVLs to gather visual data from the battlefield which can be used to create war plans and maps.

Finally, advanced WVLs capable of showing data, playing sound and wireless communication can be helpful to realize the idea of digital battlefields (DBFs)

[91]. DBFs enable infantrymen to digitally distribute orders, maps, and intelligence. The physical activity and health conditions of soldiers can be also remotely monitored in DBFs. DBFs can also improve the situational awareness of ground troops. Moreover, AR techniques can be employed to identify and tag potential foes. These data then can be shared with fellow troops that are connected to the network.

4.5 Real-time mapping of disasters

Wearable camera-based systems can be used for real monitoring and mapping of disaster areas [90]. Researchers in MIT have developed a device consisting of a camera, a laser scanner and a number of sensors that wirelessly transmit data which can be used for real time mapping of disaster areas. The laser scanner computes the distance between the wearer and a nearby physical structure, and the camera captures a photo every few metres as the test subject walks, feeding the information to a remote station. Several important features, including a location's colour pattern and contours can be extracted using special software [78]. In addition, a method for real-time simultaneous localisation and mapping purely based on the output of a single camera has been proposed [31, 30].

4.6 Location recognition

Generally user-mounted sensors such as microphones, accelerometers and cameras can be used for location detection other than the traditional approaches such as GPS and radio frequency based approaches [58]. For example, a mathematical framework which benefits from the spatial relationships between places has been used to estimate the location from a sequence of images, captured by multiple wearable cameras [58]. The recorded images via WVLs can be also used as a reliable source to re-recognise the places. For example, an image sequence matching technique has been proposed to recognise the locations and previously visited places [20].

4.7 Activity recognition

Human activity recognition (HAR) is a key component for many applications such as indoor-positioning, surveillance systems, patient monitoring systems, and a wide variety of systems that involve interactions between persons and electronic devices such as socially enabled robots and human-computer interfaces [18]. Wearable camera can be used for HAR [88, 59]. For example, a method has been developed that can recognize the user's activity purely by analysing the picture captured by a tiny front facing camera embedded in a glassware camera [88]. It starts with raw video data collection, followed by feature extraction and average pooling, time independent classification using kNN, Logit-Boost and SVM, and structured prediction with a Hidden Markov Model (HMM) to smooth the outputs at the end.

4.8 Journalism

The possibility of live-streaming from a versatile, portable, head-mounted camera can potentially change the face and even disrupt journalistic reporting as anyone who is witnessing an important event can easily record and publish the news from the heart of the incident. Moreover, in traditional news gathering, the reporter records events through text, images or audio and sends the news back to the news centre after simple editing. WVLs can help reporters to complete a series of tasks for news gathering, including acquisition of pictures, audio and video, and uploading the data, which can be accessed by the news centre [89].

that are connected to the Internet can also act as a mobile TV station and be used for reporting live news. Reporters can also use WVLs to record interviews. The "*Glass Journalism course* [16]", which is mainly about media applications of WVLs, is soon going to be a part of academia.

4.9 Personal applications

The ability to continuously capture high quality pictures without using hands has made WVLs an interesting appendage for people to record personally experienced events or scenes, and also to capture key magic moments such as a baby's first steps, first talking, etc. These are unscripted instantaneous and fleeting moments, capturing which may not be possible with a regular camera. Wearable cameras not only free the user's hands for more important tasks but also free the user's eyesight, i.e., the user does not need to stare at a screen or through a lens.

Table 4.2: Power supply and lifetime of some wearable cameras in the market. Extracted from the manual of the devices.

Device	**Capacity (mAh)**	**Continuous Video recording (30fps)**	**Continuous picturing (0.5fps)**
Google Glass	750	1.3 hours	8 hours
Vuzix Smart Glasses, M100	550 -3800 (with an external micro USB battery)	1 - 5	5-25 hours
Epson, BT-200	2720	3 hours	21 hours
Microsoft SenseCam	980	1.5 hours	9 hours
GoPro, HERO4	1160	2 hours	12 hours
Ambarella, Police Wearable	2600	4 hours	22 hours
Autographer	1100	2 hours	12 hours
Narrative Clip	125	20-35 hours - depends on the image capture rate	
Average	**1400**	**2 hours**	**10 hours**

5 Challenges of Using Wearable Cameras

While the tremendous potential of WVLs across many application domains has been outlined in the previous sections, there still exist several key challenges that need to be addressed before this technology can see wide adoption. These challenges may be broadly categorized into two main groups, namely technical issues such as power constraint i.e. lifetime of the devices, poor operation of the camera in areas of low lighting and incorrect positioning of the camera [42], and non-technical challenges such as privacy issues, social restriction and legal uncertainties [37]. The three most important challenges are highlighted, namely battery limitations, privacy issues and legal uncertainties.

5.1 Battery Limitations

Table 5.1: Proposed approaches to protect people's pictures from unwanted disclosure.

	Title	**Short description**
1	FaceBlock [86]	Allows a users mobile device to share privacy policies with nearby Glass devices using a P2P communication channel (Bluetooth), then any unauthorized picture would be blurred.
2	Visor [84]	A hardware based solution to prevent unauthorized face image revelation by adding invisible noise signals to images.
3	P3F: Personal Picture Policy Framework [28]	It enables users to express their picture privacy policy in a machine readable format and (to some extent) automatically enforce it.
4	Respectful Cameras [72]	People who wish to remain anonymous agree to wear coloured markers such as a hat or vest.
5	Offlinetags [64]	Similar to respectful camera and P3F, people declare their privacy by using some symbols which can be worn in the form of stickers or badges.
6	Privacy.Tag [25]	It consists of a QR-code to express privacy, and sharing protocols which prevent publication of unauthorized face images.
7	Negative FaceBlurring [85]	If a bystander is not happy then his/her face would be blurred.
8	Courteous Glasses [48]	It offers using low-fidelity sensors such as far-infrared devices along with the usual wearable camera to detect people faces in order to respect their privacy concerns.
9	SensorSift [34]	It proposes a framework to balance sensor data privacy and the performance/ utility of automated face recognition.
10	DARKLY [46]	It tries to protect user's pictures from perceptual applications.

Wearable cameras are necessarily small, as they must be comfortably worn by individuals. As a result there is limited real estate for all the electronics and the battery. The small size of the battery imposes unique constraints on WVLs.

The battery specifications and lifetimes of a few available wearable solutions in the market are shown in Table 4.2, based on their catalogues. With average power consumption of 1 and 2 Watts respectively for capturing high resolution pictures (20 frames per minute) and video (30 frames per second), Table 4.2 shows the maximum lifetimes of the devices assuming an output voltage of 3.5V (typical voltage). Clearly available WVLs in the market can continuously capture video and images on average for up to 2.5 and 15 hours, respectively. Simultaneous use of other device functions such as communication, audio, display and/or sensors will further decrease these lifetimes.

All in all, existing wearable solutions in the market can last for a reasonable period on a single recharge if the device is only used for capturing images at a moderate rate. However, capturing videos severely limits the operations on a single recharge. Moreover, other actions such as transferring images/videos over the communication interface, operating the LCD display, etc. can significantly reduce the lifetime. Many of the applications outlined in the previous section typically impose a greater than normal load on the wearable device. Therefore, the current crop of wearable devices may not offer sufficient lifetime for most of these applications. However, the trend in development of more efficient rechargeable batteries [37, 77, 71] provides hope that the lifetime would increase in the near future.

Table 5.2: Proposed mechanisms to address privacy of sensitive subjects and places.

	Title	**Short description**
1	PlaceAvoider [79]	A technique for owners of WVLs to blacklist sensitive spaces (like bathrooms and bedrooms).
2	Public Restroom Detection [35]	It actively probes the environment by playing a 0.1 seconds sine wave sweep sound and then detecting the place by analysing the impulse response (IR).
3	World-Driven Access Control [70]	It proposes a general, extensible framework for controlling access to sensor data on multi-application continuous sensing platforms.
4	Screen Avoider [50]	It presents a framework that controls the collection and disclosure of images with computer screens and their sensitive content.
5	MarkIt[67]	MarkIt is a computer vision based privacy marker framework, that allows users to specify and enforce fine grained access control over video feeds.
6	Blindspot [15]	It prevents the recording of still and moving images without requiring any cooperation on the part of the capturing device or its operator.

5.2 Privacy issues

Visual imagery is extremely rich in content, and leakage of image data could be particularly damaging. While all captured items by the WVLs (e.g. pictures, videos and voices) might not violate privacy rules, some sensitive information such as people's pictures, objects (e.g. screens, credit cards, etc.) and places (e.g. bedrooms and bathrooms) might be disclosed.

In recent years, several researchers have investigated the aforementioned privacy concerns and proposed solutions to address them. The most important efforts in protecting the privacy of a bystander are highlighted in Table 5.1. In most of the works, the proposed framework allows users to declare their desired privacy rules by communicating with the WVLs using an interface such as mobile phones [28, 85, 86]; or by wearing a tag [25, 28, 64] or specific cloth/colour [72].

Then, the subject of the desired policy is identified by face recognition techniques and is deleted or blurred. This could occur during the capture, access or publish phase. In some other works [84, 48, 84], some hardware-based solutions have been proposed that prevent the camera from recording any image/video in the restricted areas. In addition, many attempts have been also made to detect sensitive objects and places and different mechanisms have been proposed to protect them from unauthorized disclosure ,which are outlined in Table 5.2.

5.3 Social issues and legal uncertainties

Although many privacy-aware solutions have been already developed to avoid disclosure of unauthorized people (Table 5.1) and items (Table 5.2), people are still not be happy to be exposed to WVLs because there is no way to ensure that camera wearers will apply these techniques. Moreover, as WVLs can potentially violate the confidentiality of people's activities, they might be considered as inappropriate devices. In some cases, as can be easily found on the Internet, people have been beaten up for wearing cameras in bars and other public places (e.g., [17]).

On the other hand, camera holders may be legally required to report evidence of criminal activity to authorities, potentially without consent from people. Failing to report evidence of child or elderly abuse, for example, is a criminal offence in some jurisdictions. These consequences may also make people unwilling and uncomfortable in using WVLs.

In addition, currently, there are no specific statutes or laws in many countries that directly regulate the intrusion of WVLs into personal privacy rights [45]. Current laws on video surveillance and privacy rights can be considered as a good starting point to force WVLs holders to respect the privacy of people [45]. However, new clear legislation and/or appropriate implementation of the existing legal toolbox [55], that can explicitly declare the WVL holder's obligations and bystander's rights, appear to be a necessity.

6 Conclusions

A new generation of wearable devices such as Google Glass will soon make first-person cameras nearly ubiquitous, capturing vast amounts of imagery without deliberate human action. In this article, the exciting opportunities presented by these devices in a variety of applications ranging from healthcare to industry have been outlined. Several key challenges such as privacy concerns, battery limitations, social issues and legal uncertainties need to be addressed before wearable visual lifeloggers see widespread adoption.

Bibliography

[1] A brief history of wearable tech, http://www.wareable.com/wearable-tech/a-brief-history-of-wearables.

[2] Atheer glass, https://www.atheerlabs.com/.

[3] Lumus, http://www.lumus-optical.com/.

[4] Nixie, http://flynixie.com/.

[5] OrCam, http://www.orcam.com/.

[6] Recon, http://www.reconinstruments.com/.

[7] Autographer, http://www.autographer.com.

[8] Epson, http://www.epson.com/moverio.

[9] Google glasses, http://www.google.com/glass/.

[10] GoPro, https://www.gopro.com/.

[11] Microsoft SenseCam, http://research.microsoft.com/en-us/projects/sensecam/.

[12] Narrative Clip, http://www.getnarrative.com.

[13] Pivothead, http://www.pivothead.com/.

[14] VUZIX, http://www.vuzix.com/.

[15] *Protecting Privacy in Video Surveillance*. Springer London, 2009.

[16] Glass Journalism Course, http://www.glassjournalism.io/. 2014.

[17] A female tech writer been attacked for wearing Google Glass in a bar, http://www.dailymail.co.uk/news/article-2567548/Woman-attacked-wearing-Google-Glass-bar.html. 2014.

[18] J. Aggarwal and M. Ryoo. Human activity analysis: A review. *ACM Comput. Surv.*, 43(3):16:1–16:43, Apr. 2011.

[19] U.-V. Albrecht, U. von Jan, J. Kuebler, C. Zoeller, M. Lacher, J. O. Muensterer, M. Ettinger, M. Klintschar, and L. Hagemeier. Google glass for documentation of medical findings: Evaluation in forensic medicine. *J Med Internet Res*, 16(2):e53, Feb 2014.

[20] H. Aoki, B. Schiele, and A. Pentland. Realtime personal positioning system for a wearable computer. In *Wearable Computers, 1999. Digest of Papers. The Third International Symposium on*, pages 37–43, Oct 1999.

[21] M. S. Atkins, G. Tien, R. S. a. Khan, A. Meneghetti, and B. Zheng. What do surgeons see: capturing and synchronizing eye gaze for surgery applications. *Surgical innovation*, 20(3):241–8, June 2013.

[22] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. Recent advances in augmented reality. *IEEE Comput. Graph. Appl.*, 21(6):34–47, Nov. 2001.

[23] S. K. Bahadir, V. Koncar, and F. Kalaoglu. Wearable obstacle detection system fully integrated to textile structures for visually impaired people. *Sensors and Actuators A: Physical*, 179(0):297 – 311, 2012.

[24] E. Berry, N. Kapur, L. Williams, S. Hodges, P. Watson, G. Smyth, J. Srinivasan, R. Smith, B. Wilson, and K. Wood. The use of a wearable camera, SenseCam, as a pictorial diary to improve autobiographical memory in a patient with limbic encephalitis: a preliminary report. *Neuropsychological rehabilitation*, 17(4-5):582–601, 2007.

[25] C. Bo, G. Shen, J. Liu, X.-Y. Li, Y. Zhang, and F. Zhao. Privacy.tag: Privacy concern expressed and respected. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems*, SenSys '14, pages 163–176, New York, NY, USA, 2014. ACM.

[26] S. Cardin, F. Vexo, and D. Thalmann. Wearable obstacle detection system for visually impaired people. *VR workshop on haptic and ...*, 2005.

[27] P. Costa, H. Fernandes, P. Martins, J. Barroso, and L. J. Hadjileontiadis. Obstacle detection using stereo imaging to assist the navigation of visually impaired people. *Procedia Computer Science*, 14(0):83 – 93, 2012. Proceedings of the 4th International Conference on Software Development for Enhancing Accessibility and Fighting Info-exclusion (DSAI 2012).

[28] A. Dabrowski, E. R. Weippl, and I. Echizen. Framework based on privacy policy hiding for preventing unauthorized face image processing. In *Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics*, SMC '13, pages 455–461, Washington, DC, USA, 2013. IEEE Computer Society.

[29] I. Damian, C. S. S. Tan, T. Baur, J. Schöning, K. Luyten, and E. André. Augmenting social interactions: Realtime behavioural feedback using social signal processing techniques. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 565–574, New York, NY, USA, 2015. ACM.

[30] A. Davison, W. Mayol, and D. Murray. Real-time localisation and mapping with wearable active vision. In *Proc. IEEE International Symposium on Mixed and Augmented Reality*. IEEE Computer Society Press, Oct. 2003. (To appear).

[31] A. J. Davison. Real-time simultaneous localisation and mapping with a single camera. In *Proceedings of the Ninth IEEE International Conference on Computer Vision - Volume 2*, ICCV '03, pages 1403–, Washington, DC, USA, 2003. IEEE Computer Society.

[32] A. R. Doherty, S. E. Hodges, A. C. King, A. F. Smeaton, E. Berry, C. J. Moulin, S. Lindley, P. Kelly, and C. Foster. Wearable Cameras in Health. *American Journal of Preventive Medicine*, 44(3):320–323, Mar. 2013.

[33] A. R. Doherty, S. E. Hodges, A. C. King, A. F. Smeaton, E. Berry, C. J. Moulin, S. Lindley, P. Kelly, and C. Foster. Wearable cameras in health: The state of the art and future possibilities. *American Journal of Preventive Medicine*, 44(3):320 – 323, 2013.

[34] M. Enev, J. Jung, L. Bo, X. Ren, and T. Kohno. Sensorsift: Balancing sensor data privacy and utility in automated face understanding. In *Proceedings of the 28th Annual Computer Security Applications Conference*, ACSAC '12, pages 149–158, New York, NY, USA, 2012. ACM.

[35] M. Fan, A. T. Adams, and K. N. Truong. Public restroom detection on mobile phone via active probing. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers*, ISWC '14, pages 27–34, New York, NY, USA, 2014. ACM.

[36] W. George, S. S. Andy, D. Barry, M. J. P., and C. G. L. Assessment of energy expenditure in elite jockeys during simulated race riding and a working day: implications for making weight. *Applied Physiology, Nutrition, and Metabolism*, 38(4):415–420, 2013. PMID: 23713535.

[37] J. B. Goodenough and K.-S. Park. The li-ion rechargeable battery: A perspective. *Journal of the American Chemical Society*, 135(4):1167–1176, 2013. PMID: 23294028.

[38] C. Gurrin, Z. Qiu, M. Hughes, N. Caprani, A. R. Doherty, S. E. Hodges, and A. F. Smeaton. The smartphone as a platform for wearable cameras in health research. *American journal of preventive medicine*, 44(3):308–13, Mar. 2013.

[39] K. Ha, Z. Chen, W. Hu, W. Richter, P. Pillai, and M. Satyanarayanan. Towards wearable cognitive assistance. In *Proceedings of the 12th Annual International Conference on Mobile Systems, Applications, and Services*, MobiSys '14, pages 68–81, New York, NY, USA, 2014. ACM.

[40] G. R. Hayes, S. Hirano, G. Marcu, M. Monibi, D. H. Nguyen, and M. Yeganyan. Interactive visual supports for children with autism. *Personal Ubiquitous Comput.*, 14(7):663–680, Oct. 2010.

[41] S. Henderson and S. Feiner. Exploring the benefits of augmented reality documentation for maintenance and repair. *Visualization and Computer Graphics, IEEE Transactions on*, 17(10):1355–1368, Oct 2011.

[42] S. Hodges, L. Williams, E. Berry, S. Izadi, J. Srinivasan, A. Butler, G. Smyth, N. Kapur, and K. Wood. Sensecam: A retrospective memory aid. In *Proceedings of the 8th International Conference on Ubiquitous Computing*, UbiComp'06, pages 177–193, Berlin, Heidelberg, 2006. Springer-Verlag.

[43] B. T. Holger Glockner, Kai Jannek, Johannes Mahn. Augmented Reality in Logistics. *DHL Customer Solutions & Innovation*, 2014.

[44] J. Ikonen and A. Knutas. Exploring Wearable Cameras for Educational Purposes. In *International conference on e-learning.*, pages 70–76, Valparaiso, Chile, 2014.

[45] S. S. Intille and A. M. Intille. New Challenges for Privacy Law: Wearable Computers that Create Electronic Digital Diaries. Technical report, MIT Technical Report.

[46] S. Jana, A. Narayanan, and V. Shmatikov. A scanner darkly: Protecting user privacy from perceptual applications. In *Security and Privacy (SP), 2013 IEEE Symposium on*, pages 349–363, May 2013.

[47] O. M. Jeroudi, G. Christakopoulos, G. Christopoulos, A. Kotsia, M. A. Kypreos, B. V. Rangan, S. Banerjee, and E. S. Brilakis. Accuracy of remote electrocardiogram interpretation with the use of google glass technology. *The American Journal of Cardiology*, 115(3):374 – 377, 2015.

[48] J. Jung and M. Philipose. Courteous glass. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, UbiComp '14 Adjunct, pages 1307–1312, New York, NY, USA, 2014. ACM.

[49] S. Kammoun, G. Parseihian, O. Gutierrez, A. Brilhault, A. Serpa, M. Raynal, B. Oriola, M.-M. Mac, M. Auvray, M. Denis, S. Thorpe, P. Truillet, B. Katz, and C. Jouffrais. Navigation and space perception assistance for the visually impaired: The {NAVIG} project. {*IRBM*}, 33(2):182 – 189, 2012. Numro spcial {ANR} {TECSANTechnologie} pour la sant et l'autonomie.

[50] M. Korayem, R. Templeman, D. Chen, D. J. Crandall, and A. Kapadia. Screenavoider: Protecting computer screens from ubiquitous cameras. *CoRR*, abs/1412.0008, 2014.

[51] M. L. Lee and A. K. Dey. Providing good memory cues for people with episodic memory impairment. In *Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility*, Assets '07, pages 131–138, New York, NY, USA, 2007. ACM.

[52] M. L. Lee and A. K. Dey. Lifelogging memory appliance for people with episodic memory impairment. In *Proceedings of the 10th International Conference on Ubiquitous Computing*, UbiComp '08, pages 44–53, New York, NY, USA, 2008. ACM.

[53] S. Mann. Wearable computing: A first step toward personal imaging. *Computer*, 30(2):25–32, Feb. 1997.

[54] G. Marcu, A. K. Dey, and S. Kiesler. Parent-driven use of wearable cameras for autism support: A field study with families. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, UbiComp '12, pages 401–410, New York, NY, USA, 2012. ACM.

[55] R. Mathys. Legal Challenges of Wearable Computing. In *2014 World Technology Law Conference*, New York, USA, May, 2014.

[56] S. Matsumoto and K. Sekine. Digital video recording in trauma surgery using commercially available equipment. *Scandinavian Journal of Trauma*, pages 1–5, 2013.

[57] R. Mégret, V. Dovgalecs, H. Wannous, S. Karaman, J. Benois-Pineau, E. El Khoury, J. Pinquier, P. Joly, R. André-Obrecht, Y. Gaëstel, and J.-F. Dartigues. The immed project: Wearable video monitoring of people with age dementia. In *Proceedings of the International Conference on Multimedia*, MM '10, pages 1299–1302, New York, NY, USA, 2010. ACM.

[58] K. Min, S. Lee, K.-E. Kim, and J. H. Kim. Place recognition using multiple wearable cameras. In H. Ichikawa, W.-D. Cho, I. Satoh, and H. Y. Youn, editors, *UCS*, volume 4836 of *Lecture Notes in Computer Science*, pages 266–273. Springer, 2007.

[59] M. Moghimi, P. Azagra, L. Montesano, A. C. Murillo, and S. Belongie. Experiments on an rgb-d wearable vision system for egocentric activity recognition. In *CVPR Workshop on Egocentric (First-person) Vision*, Columbus, OH, June 2014.

[60] N. Molton, S. Se, J. Brady, D. Lee, and P. Probert. A stereo vision-based aid for the visually impaired. *Image and Vision Computing*, 16(4):251 – 263, 1998. Vision-Based Aids for the Disabled.

[61] Moynagh, Brian, Gurrin, Cathal, Albatal, Rami, and Tengqi, Qi. Real-time behavioural analysis using google glass. Aug 2014.

[62] G. O'Loughlin, S. J. Cullen, A. McGoldrick, S. O'Connor, R. Blain, S. O'Malley, and G. D. Warrington. Using a wearable camera to increase the accuracy of dietary analysis. *American journal of preventive medicine*, 44(3):297–301, Mar. 2013.

[63] G. O'Loughlin, S. J. Cullen, A. McGoldrick, S. O'Connor, R. Blain, S. O'Malley, and G. D. Warrington. Using a wearable camera to increase the accuracy of dietary analysis. *American Journal of Preventive Medicine*, 44(3):297 – 301, 2013.

[64] F. Pallas, M.-R. Ulbricht, L. Jaume-Palasí, and U. Höppner. Offlinetags: a novel privacy approach to online photo sharing. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 2179–2184. ACM, 2014.

[65] K. Pauly-Takacs, C. J. A. Moulin, and E. J. Estlin. SenseCam as a rehabilitation tool in a child with anterograde amnesia. *Memory*, ahead-of-p:1–8, 2010.

[66] K. Pauly-Takacs, C. J. a. Moulin, and E. J. Estlin. SenseCam as a rehabilitation tool in a child with anterograde amnesia. *Memory (Hove, England)*, 19(7):705–12, Oct. 2011.

[67] N. Raval, A. Srivastava, K. Lebeck, L. Cox, and A. Machanavajjhala. Markit: Privacy markers for protecting visual secrets. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, UbiComp '14 Adjunct, pages 1289–1295, New York, NY, USA, 2014. ACM.

[68] A. Razavian, O. Aghazadeh, J. Sullivan, and S. Carlsson. Estimating attention in exhibitions using wearable cameras. In *Pattern Recognition (ICPR), 2014 22nd International Conference on*, pages 2691–2696, Aug 2014.

[69] A. Razavian, O. Aghazadeh, J. Sullivan, and S. Carlsson. Estimating attention in exhibitions using wearable cameras. In *Pattern Recognition (ICPR), 2014 22nd International Conference on*, pages 2691–2696, Aug 2014.

[70] F. Roesner, D. Molnar, A. Moshchuk, T. Kohno, and H. J. Wang. World-driven access control for continuous sensing. Technical Report MSR-TR-2014-67, May 2014.

[71] P. Saha, M. K. Datta, O. I. Velikokhatnyi, A. Manivannan, D. Alman, and P. N. Kumta. Rechargeable magnesium battery: Current status and key challenges for the future. *Progress in Materials Science*, 66:1 – 86, 2014.

[72] J. Schiff, M. Meingast, D. Mulligan, S. Sastry, and K. Goldberg. Respectful cameras: detecting visual markers in real-time to address privacy concerns. In *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, pages 971–978, Oct 2007.

[73] R. Shilkrot, J. Huber, W. Meng Ee, P. Maes, and S. C. Nanayakkara. Fingerreader: A wearable device to explore printed text on the go. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 2363–2372, New York, NY, USA, 2015. ACM.

[74] J. A. Slade Shantz and C. J. H. Veillette. The application of wearable technology in surgery: Ensuring the positive impact of the wearable revolution on surgical patients. *Front Surg*, 1:39, Sep 2014. 25593963[pmid].

[75] A. Smith and D. Page. U.S. Smartphone Use in 2015. Technical report, PEW RESEARCH CENTER, 2015.

[76] I. E. Sutherland. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, AFIPS '68 (Fall, part I), pages 757–764, New York, NY, USA, 1968. ACM.

[77] J.-M. Tarascon and M. Armand. Issues and challenges facing rechargeable lithium batteries. *Nature*, 414(6861):359–367, Nov 2001.

[78] S. Teller and C. Science. Automatic building mapping could help emergency responders. *PHYS.ORG*, (September):1–3, 2012.

[79] R. Templeman, M. Korayem, D. Crandall, and A. Kapadia. PlaceAvoider: Steering first-person cameras away from sensitive spaces. In *Proceedings of The 21st Annual Network and Distributed System Security Symposium (NDSS)*, Feb. 2014.

[80] S. Vallurupalli, H. Paydak, S. K. Agarwal, M. Agrawal, and C. Assad-Kottner. Wearable technology to improve education and patient outcomes in a cardiology fellowship program - a feasibility study. *Health and Technology*, 3(4):267–270, Oct. 2013.

[81] M. D. White. Police Officer Body-Worn Cameras. Technical report, 2014.

[82] H. Winchester. A brief history of wearable tech, 2015.

[83] T. Wu, C. Dameff, and J. Tully. Integrating Google Glass into simulation-based training: experiences and future directions. *Journal of Biomedical Graphics and Computing*, 4(2):49–54, Apr. 2014.

[84] T. Yamada, S. Gohshi, and I. Echizen. Privacy visor: Method for preventing face image detection by using differences in human and device sensitivity. In B. De Decker, J. Dittmann, C. Kraetzer, and C. Vielhauer, editors, *Communications and Multimedia Security*, volume 8099 of *Lecture Notes in Computer Science*, pages 152–161. Springer Berlin Heidelberg, 2013.

[85] T. Ye, B. Moynagh, R. Albatal, and C. Gurrin. Negative FaceBlurring : A privacy-by-design approach to visual lifelogging with Google Glass. In *ACM CIKM14*, pages 2036–2038, Shanghai, China., 2014.

[86] R. Yus, P. Pappachan, P. K. Das, E. Mena, A. Joshi, and T. Finin. Demo: Faceblock: Privacy-aware pictures for google glass. In *Proceedings of the 12th Annual International Conference on Mobile Systems, Applications, and Services*, MobiSys '14, pages 366–366, New York, NY, USA, 2014. ACM.

[87] J. Zariffa and M. Popovic. Hand contour detection in wearable camera video using an adaptive histogram region of interest. *Journal of NeuroEngineering and Rehabilitation*, 10(1), 2013.

[88] K. Zhan, F. Ramos, and S. Faux. Activity recognition from a wearable camera. In *Control Automation Robotics Vision (ICARCV), 2012 12th International Conference on*, pages 365–370, Dec 2012.

[89] J. C. Zhang, W. Yujun, and P. Zhang. Research on Application of Google glass in the field of journalism. *Applied Mechanics & Materials*, pages 631–632, 2014.

[90] Y. Zhang, C. Luo, and J. Liu. Walk and sketch: Create floor plans with an rgb-d camera. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, UbiComp '12, pages 461–470, New York, NY, USA, 2012. ACM.

[91] M. Zieniewicz, D. Johnson, C. Wong, and J. Flatt. The evolution of army wearable computers. *Pervasive Computing, IEEE*, 1(4):30–40, Oct 2002.

[92] M. J. Zieniewicz, C. Douglas, D. C. Wong, and J. D. Flatt. The Evolution of Army. *PERVASIVE computing*, (30-4), 2002.