Sensor Technologies for Seeing Inside Buildings: An Overview

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ABSTRACT

In this paper, a broad overview is given of the current status of sensor technology that can be applied for obtaining inside building awareness. Different stages in obtaining inside building awareness have been identified. The first stage is surveillance of a wide area to single-out buildings of interest, followed by covert, stand-off observation of a single building. At some point, it may be required to enter the building, and intelligence of tactical nature is needed, such as a current floorplan and the number of people inside the building and their whereabouts. Finally, blue-forces may enter the building requiring real-time information on events inside the building and the location of hostiles and neutrals. For each of these stages, sensors that fulfil (part of) the information need and their level of technological maturity are discussed. Finally, in the conclusion, an outlook to sensor developments for inside building awareness is given.

1.0 INTRODUCTION

Since the 1960s, surveillance of the Earth's surface from space-borne sensors has provided a valuable source of strategic intelligence. However before 2005 despite the fact that, over the years, public awareness of overhead surveillance capabilities had increased, many illegal and terrorist activities were still routinely conducted in the open. For example, Fig. 1 shows imagery of a terrorist training camp in Afghanistan pre-strike and post-strike. It is clear that there has been very little attempt made to make the presence of this training camp covert.

However, in 2005 Google Earth became available. Suddenly, imagery of the Earth from space was easily available to the public at large. This perhaps led to a change in public consciousness with respect to the enormous capability for remote surveillance of activity in the open. Increasingly then since 2005, illegal and terrorist activity has moved from the open to covered areas, the interior of buildings or to underground compounds.

The awareness by terrorists of remote surveillance capabilities and their desire to avoid it was graphically illustrated in the case of Osama bin Laden's compound in Abbattobad. Despite the capability to take overhead images of the compound on a regular basis, as illustrated in Fig. 2, anyone who has seen the film Zero Dark Thirty will be aware of how difficult it was for intelligence agencies to confirm the presence of Osama bin Laden in this location.

This step-change in the challenge facing intelligence-gathering from space provides one compelling reason why more than ever the ability to be able to see inside buildings is a requirement for NATO military and intelligence users. However, the requirement is not just confined to the detection of terrorist activity or to space-borne sensors. There is, for instance, a requirement to detect illegal industrial activity taking place under cover or underground such as at the nuclear production site at Esfahan, Fig. 3. Other requirements include the detection of illegal storage activities, determination of building occupancy and internal layout in hostage situations and the detection of people behind walls or under rubble to support disaster relief (Fig. 3).

Many future combat scenarios involve operations in contested urban environments and it is in this arena where the ability to see inside buildings will provide essential advances in capability to support the NATO war-fighter. This paper will explore the technologies and platforms that are being developed to meet this pressing requirement.

Figure 1: Terrorist training camp in Afghanistan.

In this paper, a broad overview is given of the current status of sensor technology that can be applied for obtaining inside building awareness. Different stages in obtaining inside building awareness have been identified, each entailing specific information needs. The subsequent stages of generating and maintaining the operational picture are discussed in Sections 2 through 5. Note, however, that not all stages or all uses of technology are always applicable; applicability depends on, e.g., the actual scenario and geometry, required reaction times etc. (see, e.g., the use case descriptions in [1]). For instance, for urgent operations, such as disaster relief operations, gathering intelligence of strategic nature is of no value. In Section 6, the conclusion and an outlook to sensor developments are given.

2.0 STRATEGIC BUILDING SURVEILLANCE

The first stage of creating inside building awareness is long-term strategic building surveillance meant to single-out a building of interest within a complete district. Anything that makes a building stand out from its surroundings could be relevant information. For example, suspect people frequenting a house or goods delivered to a building which are indicative for manufacturing of drugs. In winter time, houses in which drugs are being grown can be discovered due to the lack of snow on the roof [2].

Most sensor technology relevant for long-term, strategic building surveillance already has a high level of maturity. Closed circuit television (CCTV) technology, licence plate recognition and helicopters equipped with daylight and thermal cameras are routinely used by law enforcement. Currently, the police and fire brigades are experimenting with small unmanned aerial vehicles (UAVs) equipped with daylight and thermal cameras and chemical sniffers.

In The Netherlands, smart meters for monitoring utility usage are presently deployed. These smart meters allow remote read-out (via internet) of electricity, gas and water usage. Other sensor technology for large-scale infrastructure monitoring is still in the development stage, such as a network of chemical sensors to monitor the sewers or the air. Within the framework of the recent European Union funded projects LOTUS and EMPHASIS, technology demonstrations have been prepared [3], [4].

For building surveillance of strategic nature, the main difficulty is getting access to the different data flows (which are likely to be controlled by various agencies), detecting relevant structures in the data, extracting information and finally compiling and maintaining the overall operational picture. Furthermore, privacy regulations may prohibit obtaining, using and/or combining data of such differing sources.

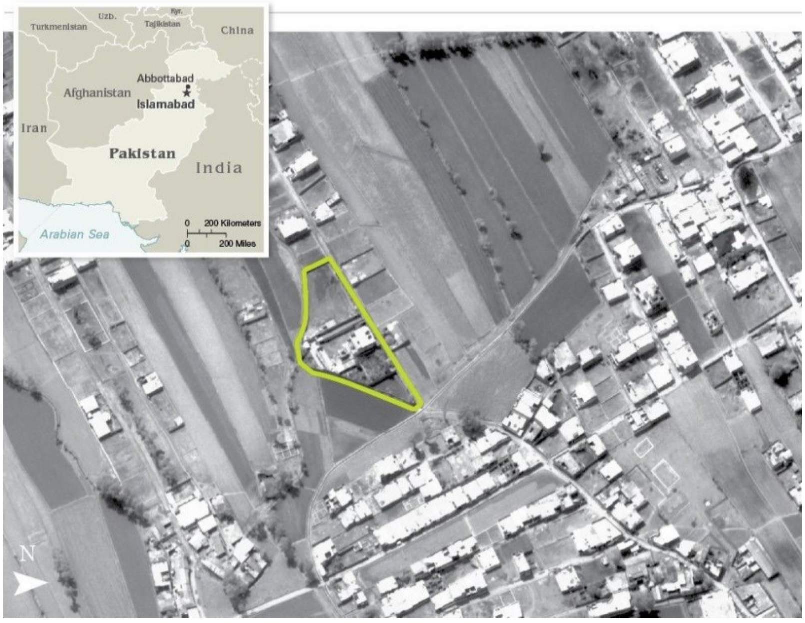

Figure 2: Osama bin Laden's compound in Abbattobad.

3.0 STAND-OFF SURVEILLANCE OF THE INSIDE OF A BUILDING

The stand-off surveillance of a single building is in the grey area between strategic and tactical surveillance. The building may be monitored for a longer period of time to gather further strategic intelligence (using conventional policing means such as telephone and internet taps, stake-outs, electronic listening devices etc.) in order to map the criminal or terrorist network tied to the building of interest (i.e., Social Network Analysis).

At the same time, information on the current situation inside the building should be gathered. First, a current floorplan should be obtained (filed floorplans, if available, may be outdated) showing the locations of infrastructure (pipes, electrical lines) possible points of entry, doors, staircases, hallways and possible barricades, but also showing the presence and location of specific goods, e.g., weapons, explosives or chemicals. In a disaster relief scenario, it is important to assess the general state of a building and determine whether it is safe for first responders to enter. Second, the number of people inside the building and their whereabouts should be known. To prevent civilian casualties, the intent of people should be established (hostile versus neutral).

A first impression of a building structure and floorplan can be obtained using (covert) through-wall radar deployed in a drive-by fashion, see for instance Fig. 4 (left) [5]. However, radar propagation is hampered by walls and furniture, thus the floorplan will be incomplete and other sensors may be needed to complement the radar measurements: thermal imaging sensors can detect dividing walls connected to the building façade due to an observable temperature difference in the façade or X-ray sensors may provide information on dividing walls and even on reinforcements, cracks or voids in the walls.

Longer-term surveillance of the movements of people inside the building will also add to the floorplan. The routes used through the building may provide additional information on the location of doors and staircases. The movement patterns may also reveal doors that are never used and thus may be locked. A radar system located at a fixed, stand-off position can provide through-wall detection and tracking of moving people. In addition, forward scatter radar can be applied to monitor movements in dedicated parts of the building. Further information can be extracted from radar measurements by exploiting the micro-Doppler signature of people. The gait and torso motion of a walking person changes when carrying a heavy pack or weapon. In principle this change can be extracted from the micro-Doppler signature. Also breathing invokes a specific micro-Doppler signature providing means to detect immobilised people.

Figure 3: Nuclear site at Esfahan (top left), the Iranian Embassy siege in London 1980 (top right), illegal storage activities (bottom left) and disaster relief (bottom right).

If covertness is vital for the success of an operation, passive sensors may be preferred over active systems. For instance, acoustic sensors are able to detect and track moving people behind metal walls. Daylight and infrared cameras are passive, but their operation is limited to unobscured windows, although infrared observation may be possible through curtains. Passive RF systems do have the ability of obtaining through-wall observations, but they need a transmitter of opportunity, such as a Wireless Fidelity (WiFi) access point [6] or a Global System for Mobile Communications (GSM) base station. Note that WiFi access points inside the building are easily switched-off by hostile forces and there is no control over their geometry. Another passive method to detect and track motion inside the building is radiolocation of active emitters, notably mobile phones.

An overview of stand-off radar for building mapping and motion detection can be found in [7]. Most of the developments listed, seem to have taken place within the framework of funded research projects and have low technological maturity. Only one of the listed radar systems is currently on the market [8]. Many radar-related research activities focus on improving spatial and angular resolution by employing Multiple Input/Multiple Output (MIMO) concepts, ultrawideband waveforms, Synthetic Aperture Radar (SAR) techniques etc. High resolution in three dimensions is valuable for recognition of people and objects inside the building. However, for recognition, centimetre resolution is required, which is very difficult to achieve in a heavily cluttered environment using a stand-off approach. For building mapping and people detection and tracking moderate resolution is probably sufficient. It is therefore believed that obtaining high resolution (of the order of centimetres) should not be the first focus of further developments. Significant improvements are expected in the field of information extraction and fusion. Examples are exploitation of multipath reflections of moving people (providing information on the building layout), characterisation of micro-Doppler signatures (to distinguish different people), characterisation of polarimetric signatures (to classify objects, determine wall materials or mitigate clutter and multipath effects) and exploitation of sparse representation methods (to extract building features). The requirements for the information extraction methods should also drive the further development of through-wall radar system concepts (polarimetric concepts, optimisation of the position of transmitters and receivers in a MIMO setup).

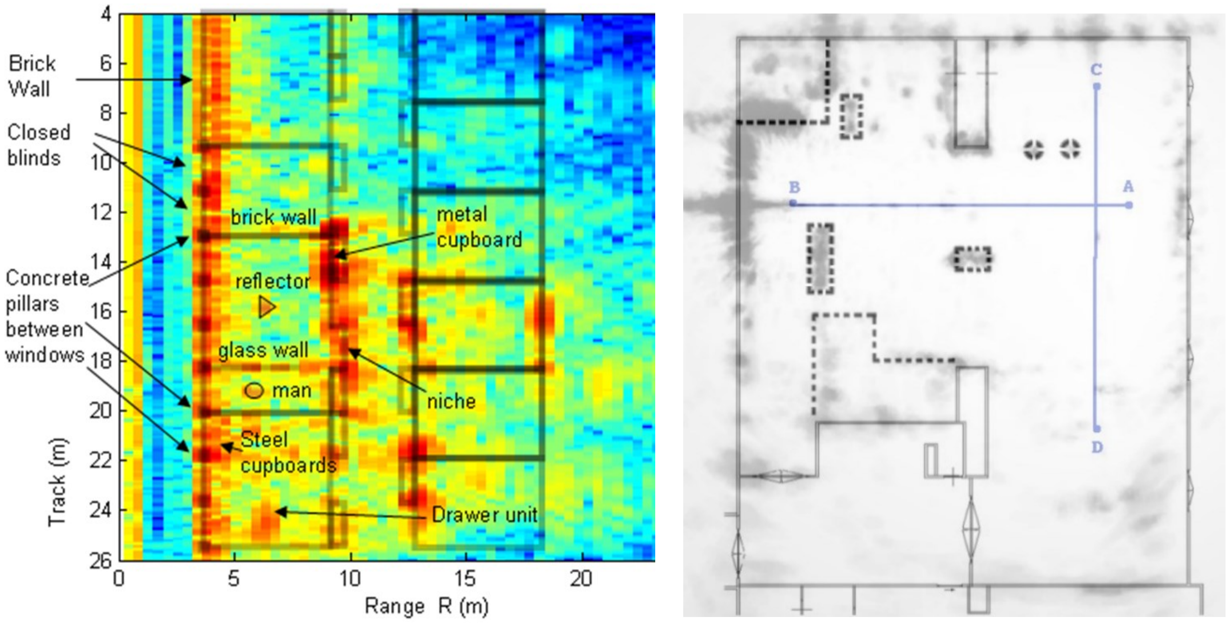

Figure 4: Left: example of a 2D building map obtained with stand-off, through-wall radar. The overlay shows the actual building floorplan. Right: example of an indoor radar SLAM image. The radar system was mounted on a ground-moving vehicle driven from ‘A’ to ‘B’ and then from ‘C’ to ‘D’. The shadowy detections show the radar map, the overlay shows the actual room layout. The room’s dimensions are 20 by 30 m.

The mentioned non-RF sensors are already in operational use, albeit for different applications. For these applications stand-off capability is usually not a requirement. For instance X-ray sensors for nondestructive testing of concrete and magnetic sensors to detect power cables are small hand-held sensors with a limited field of view. Acoustic and X-ray scanners to find people and illicit goods, are developed for surveillance of shipping containers and cargo trailers (lorries and trains). For this application the stand-off distance is typically very short. Thermal imagers are able to image a complete building façade. The information they provide seems of high quality indicating temperature differences between rooms and some details on the building structure.

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4.0 IN-SITU SURVEILLANCE OF THE INSIDE OF A BUILDING

At some point, it may be required to enter the building, e.g., to stop illegal and/or dangerous activities. The floorplan obtained with stand-off sensors is likely to be incomplete, such that it is still insecure for blue-forces to enter the building. Therefore, sensors need to brought into the building, using unmanned platforms, to unravel the remaining white spots in the floorplan. Additionally, in-situ sensors should provide current information on locations and movements of people in those parts of the building that are obscured from the stand-off sensors. In support of their primary surveillance task, the sensor platforms need to know where they are, where they should go and where the other sensor platforms are (when several platforms are sent into the building). This information should be made available at a central mission control room as well.

The unmanned platforms can be remotely piloted or they may be autonomously moving through the building. For specific tasks, Remotely Piloted Vehicles (RPVs) are preferred. For instance, RPVs equipped with robotic arms are used to pick up things, clear rubble, disarm bombs or simply open a door. For these types of relatively difficult tasks, direct feedback to and from an operator will probably lead to faster and better results. For general surveillance and mapping tasks, one or more autonomously navigating sensor platforms are better suited. For instance, a swarm or wolf pack of autonomously navigating drones can quickly spread inside a building without the need for an individual operator for each drone. Indeed drones are an appropriate platform to quickly explore a building, since they are fast, not hampered by rubble on the ground and able to ascend through stairwells and elevator shafts. However, the payload of a drone, suitably sized to enter a building, is limited. To carry a robotic arm or another heavy tool, high-end sensors, such as a high-definition camera, or emergency aids into the building, some ground vehicle is mandatory. Another aspect influencing the choice for a specific platform type is covertness. Ground vehicles and drones are not particularly covert (multicopter drones are very noisy), although they may take a concealed (stationary) position to prevent detection. If covertness is essential, Micro Air Vehicles (MAVs), which can be as small as insects, can be deployed. Of course, the payload of MAVs is severely limited, but they can still carry a small microphone or camera. Note that, by bringing them into the building, the sensor platforms themselves are at risk, which may also impact the platform choice.

One of the main challenges with respect to sending unmanned platforms into a building are setting up and maintaining a command, control and communication network. Such a network is mandatory to be able to obtain an overall operational picture at the central mission control and disseminate this picture to all agents (unmanned platforms and later blue-forces). If a pack of platforms is deployed, each individual platform can act as a the communications relay and some designated platforms may act as main communications hub and remain at a fixed position. In this case, information can be transmitted from platform to platform until the central mission control room is reached, i.e., the platforms form a layered, ad-hoc network.

Another main challenge is maintaining sense-and-avoid and navigation functionality in a possibly vision and Global Positioning System (GPS) denied environment. Based on a-priori information, for instance a partial floorplan, navigating inside the building is possible to some extent. While navigating through the building, the white spots in the floorplan can be filled applying Simultaneous Localisation and Mapping (SLAM), an example of an indoor radar SLAM image is shown in Fig. 4 (right) [9]. The main aid for navigation is an Inertial Measurement Unit (IMU) supported by information obtained with a daylight or infrared camera, an ultrasonic range finder, a (3D) laser scanner or a miniaturised radar system. These sensors also provide the measurements for the sense and avoid and SLAM functionalities. In a smoke or dust-filled and dark building, the performance of cameras and laser sensors will be limited. While exploring the building, the platforms can detect and record the presence of explosives, chemicals, toxic fumes and fires with the aid of chemical sniffers and temperature sensors and survey the electromagnetic spectrum to detect the presence of electronic equipment such as laptops and mobile phones.

The technological maturity of RPVs is already high; robots were for example used to reconnoitre the Fukushima nuclear power plant. Also drone technology is comparatively mature. Directly controlled by an

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operator they are routinely used for, e.g., television recordings. Self-organising swarm methods for drones, including communications, navigation and SLAM are still at low technological maturity. A wide variety of small sensors, suited for use on board a drone with limited payload, is already on the market including daylight cameras, infrared cameras, chemical sensors, ultrasonic range finders, temperature sensors, accelerometers, gyroscopes etc. Developments for smart phone applications and add-ons drive the further proliferation of miniaturised sensors. Also miniature (one-chip) radar systems are in development. This development is driven by the gaming and consumer electronics industry, applying miniature radar in audio and television equipment and gaming consoles to measure motion and gestures. The first miniaturised radar systems for sense-and-avoid functionality and surveillance suitable for use on board drones are on the market [10]. With respect to navigation and SLAM applications for drones, the maturity of solutions based on miniaturised radar is probably still low. The maturity of miniaturised sensors for electromagnetic spectrum surveillance is low.

5.0 BLUE-FORCES ENTERING THE BUILDING

Blue-forces entering the building need real-time information on movements of people inside the building and an indication of their intent (hostile, neutral). Furthermore, they need real-time information on events occurring, such as fires, explosions, shots fired, barricades being erected etc.

Comparable to the unmanned platforms deployed inside the building, blue-forces need to navigate (to know where they are, where they could go) and communicate (where are other blue-force squads, what's the operational picture etc.). For both navigation and communication they can rely on their own equipment or become part of the ad-hoc sensor and communication network already set up by the unmanned platforms deployed inside the building. Unmanned platforms fixed at key cross points inside the building can act as navigation way points.

A wide variety of hand-held sensors is already available off-the-shelf [11], such as through-wall radars, thermal imagers and daylight and night vision cameras. Due to the broad development of technology, applications and add-ons for smart phones, a further variety of sensors becomes available; temperature sensors. ultrasonic range finders, laser range finder, chemical sniffers, physiological sensors etc. Even a through-wall sensor is available for smart phones [12].

6.0 CONCLUSION

From the previous sections it is clear that for overall inside-building awareness, a mix of sensors is required, deployed both inside and outside the building. Many of the required sensor types already have high technological maturity, such as temperature sensors, chemical sniffers, cameras, thermal imagers and X-ray scanners, albeit that some of them are typically used for different applications. Consequently, novel information extraction and fusion methods may need to be developed to extract the information particularly relevant for generating inside building awareness and combine it into a single integrated operational picture, e.g., methods should be developed to synthesise a current building floorplan from all retrieved sensor information.

Regarding further development of sensor technology for inside building awareness, it is expected that the best progress can be made with RF technology. RF technology is versatile and offers capabilities that allow a large contribution to the operational picture: through-wall radar (building mapping and stand-off surveillance), communication, emitter direction finding, navigation support, transponder interrogation etc. All these capabilities need to perform in the same indoor environment, including penetration of walls. For this reason, the same frequency band is commonly used for all of these capabilities, providing a compromise between bandwidth, angular resolution and the ability to propagate through walls. Therefore, integrating various capabilities into a single, multifunctional RF system seems efficient (e.g., reuse of components).

Notwithstanding that such an integrated RF system provides a wide range of capabilities, the use of a single frequency band will result in parts of the building being shielded (e.g., due to materials impenetrable for this particular frequency band). Therefore, the integrated RF system must be part of a multisensor suite including other sensors with 'gap filling' capabilities, such as thermal imagers, acoustic sensors or even X-ray scanners. Ultimately, to complete the operational picture, in-situ observations are needed.

Entering a building, however, constitutes a major risk for blue-forces. This risk may be greatly mitigated by deploying unmanned sensor platforms first. For successful deployment of multiple platforms (in a swarm or wolf pack) development in the fields of, among others, dynamic system architectures, artificial intelligence, machine learning, machine to machine communication, ad-hoc networking and SLAM is required. Another relevant development is the miniaturisation of sensors to make them suitable for use on board small unmanned platforms and integration in hand-held devices (e.g., smart phones).

REFERENCES

[1] L. Ericson, J. Hayes, C. Huffman, J. Fuller and V. Libonati, "Through-the-wall sensors (TTWS) for law enforcement: use cases scenarios," U.S. Department of Justice Contract 2010-IJ-CX-K024, Tech. Rep. v1.3, May 2014.

[2] http://www.telegraph.co.uk/news/worldnews/europe/netherlands/11402633/Dutch-police-catch-cannabis-growers-after-spotting-snow-free-roof.html

[3] H. Önnerud, S. Wallin and H. Östmark, "Localisation of threat substances in urban society – LOTUS," Proc. EISIC, Athens, Greece, September 12-14, 2011.

[4] F. Schnürer, M. Heil, M. Rieger, A. Eberhardt, J. Aniol and H. Krause, "Localisation of IED manufacturing facilities by detection of explosives in sewage water," Proc. Security Research Conference, Berlin, Germany, September 15-17, 2015.

[5] J.J.M. de Wit, W.L. van Rossum, and F.M.A. Smits, "Principal Scatterer Detection in Buildings with SAPPHIRE," Proc. EUSAR, Aachen, Germany, June 7-10, 2010, pp. 921-924.

[6] F. Adib and D. Katabi, "See through walls with Wi-Fi," Proc. SIGCOMM, Hong Kong, China, August 12-16, 2013.

[7] R.J. Miller, W.L. van Rossum, L. Hyde and J.J.M. de Wit, "Radar technology for inside building awareness," EDA Contract 11.R&T.OP.131 RIBA, Tech. Rep. TES 109834 - 1, December 2012.

[8] http://www.srcinc.com/what-we-do/radar-and-sensors/o-pen-radar.html

[9] J.W. Marck, A. Mohamoud, E. van der Houwen and R. van Heijster, "Indoor radar SLAM," Proc. EuRAD, Nuremberg, Germany, October 9-11, 2013.

[10] http://aerotenna.com/sensors/

[11] "Through-the-wall sensors for law enforcement market survey," U.S. Department of Justice, Tech. Rep., October 2012.

[12] http://walabot.com/