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BorderSense: Border patrol through advanced wireless sensor networks

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ABSTRACT

The conventional border patrol systems suffer from intensive human involvement. Recently, unmanned border patrol systems employ high-tech devices, such as unmanned aerial vehicles, unattended ground sensors, and surveillance towers equipped with camera sensors. However, any single technique encounters inextricable problems, such as high false alarm rate and line-of-sight-constraints. There lacks a coherent system that coordinates various technologies to improve the system accuracy. In this paper, the concept of *BorderSense*, a hybrid wireless sensor network architecture for border patrol systems, is introduced. BorderSense utilizes the most advanced sensor network technologies, including the wireless multimedia sensor networks and the wireless underground sensor networks. The framework to deploy and operate BorderSense is developed. Based on the framework, research challenges and open research issues are discussed.

1. Introduction

Border patrol systems have recently gained interest to address the concerns about national security. The major challenge in protecting long stretches of borders is the need for intensive human involvement in patrolling the premises. Conventional border patrol system consists of security checkpoints and border troops [5,27]. The security checkpoints are set up on the international roads where all vehicle traffic is stopped to detect and apprehend illegal aliens, drugs, and other illegal activity. Each border troop watches and controls a specific section of the border. The troops patrol the border according to predetermined route and time interval. Under the conventional border patrol system, even modest-sized areas require extensive human resources if manual patrolling is considered alone.

To monitor the border in real-time with high accuracy and minimize the need for human support, multiple surveillance technologies, which complement each other, are required. To address the challenges still faced by the existing surveillance techniques, we introduce *BorderSense*, a new border patrol system framework based on *hybrid wireless sensor networks*, which can accurately detect and track the border intrusion with minimum human involvements. BorderSense utilizes the most advanced sensor network technologies, including wireless multimedia sensor networks (WMSNs) [1,2] and wireless underground sensor networks (WUSNs) [3,4]. The hybrid WSN consists of three types of sensor nodes: (1) *multimedia sensor nodes* that are equipped with video cameras or night vision scopes and deployed on the surveillance towers, (2) *scalar sensor nodes* that are equipped with vibration/seismic sensor and deployed on the ground or buried underground, and (3) *mobile sensor nodes* that roam throughout the border on the surface or in air. These three types of sensor nodes

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collaborate to provide detection capabilities that cannot be provided by existing systems.

Compared with the existing border patrol techniques, BorderSense provides the following advantages: (1) the multimedia sensors provide accurate detection as well as large detection range; (2) the ground sensors provide additional information that cannot be detected by the multimedia sensors, e.g. in cases where the intruder is hidden behind an obstacle that can not be detected by the imaging sensor; (3) the underground sensors guarantee the proper system functionalities where aboveground visible devices are not preferred for concealment purposes; (4) mobile sensors provide intrusion tracking capability to track the intruders after they have been detected; and (5) by in-network processing, the heterogeneous sensors cooperatively detect the intrusion and report the results to a remote administrator. Accordingly, both the deployment and operational cost of the border patrol system can significantly be decreased.

While the potential benefits of BorderSense are significant, several research challenges need to be addressed before a practical realization. In this paper, a framework to deploy and operate BorderSense for border patrol is described. Based on this framework, research challenges and open research issues are discussed. More specifically, in the remaining of the paper, we first provide an overview of existing border patrol techniques in Section 2. The system architecture for BorderSense is presented in Section 3. Then, in Section 4, the deployment of BorderSense is discussed. The operational principles and challenges for the hybrid architecture are described in Section 5. The research challenges are discussed in Section 6. Finally, the paper is concluded in Section 7.

2. Existing border patrol techniques

Border patrol has extensively been based on human involvement. However, the relative cost for the increasing number of personnel as well as the diminishing accuracy through human-only surveillance has required the involvement of high-tech devices in border patrol. Among these, Unmanned Aerial Vehicles (UAVs) for aerial surveillance have recently been used to automatically detect and track illegal border crossing [14,13,24]. Due to the large coverage and high mobility of the UAVs, the intensive human involvement in low-level surveillance activities can be reduced. This allows valuable human resources to be allocated to decision management activities based on information from these devices. However, similar to the conventional border patrol systems, UAVs alone cannot cover the whole border at any time. There may exist times when certain sections of the border is not being monitored. Moreover, the UAVs have significantly higher costs and accident rates than those of manned aircrafts and require large human footprint to control their activities. In addition, inclement weather conditions can also impinge on the surveillance capability of UAVs.

To complement the UAV activities, recently, Fiber Optic Sensors (FOSs) [22] are introduced. Seismic sensors are equipped with FOSs so that they can measure pressure waves in the earth caused by intruders. However, FOS communication depends on a single wire along the border. As a consequence, any single point-of-failure can affect very long distances. Due to the harsh environmental conditions along a border, wired sensor systems are not robust. Moreover, deployment costs of wired sensors surpass existing costs in long borders limiting their practical application.

Compared to the wired sensors, Unattended Ground Sensors (UGSs) [44,42,43] provide higher system robustness. UGSs have been intensively used for military Intelligence Surveillance and Reconnaissance (ISR) applications. UGSs can detect vibration/seismic activity or magnetic anomaly, which indicate that people or vehicles are crossing the border. Moreover, UGSs can pick up moving heavy vehicles (such as tanks) from a distance of 500 m and walking humans from 50 m [43]. However, the information provided by the UGSs can be limited and inaccurate. Therefore, based on the limited information acquired by current ground sensors, it is difficult to distinguish actual intrusion alarms from false positives, i.e., nuisance warnings caused by environment elements (insects, weather, animals, etc). According to the US department of homeland security, 90% of the alerts are caused by animals or environment impacts instead of illegal immigrants and this results in a significant amount of wasted time for the deployment of agents to check on the provided information [28]. In addition, it has been reported that the existing sensors are often damaged by insects or moisture and hence, are not robust to external impacts [28].

While scalar sensors such as vibration sensors are important to *detect* an intrusion, these sensors provide limited information to *classify* the intruder. To this end, surveillance towers equipped with video monitors and night vision scopes provide high accuracy in human detection and keep false alarms to a minimum [27]. The monitoring range is also much larger than the ground sensors. These systems, however, typically require human interaction to determine the type of intrusion. Moreover, the video monitors require the target within the line of sight. If the monitoring area consists of obstacles such as rocks, brushwood, or trees, the miss rate increases.

The existing techniques for border patrol, which include surveillance towers, ground sensors, or unmanned aerial vehicles, are deployed completely aboveground. In certain areas, aboveground components are vulnerable to the effects of the environment, vehicles or large animals. Visible devices may also be easily found, damaged, or avoided by intruders. For instance, for a system with surveillance towers, the intruders will look for areas and times not properly covered by adjacent towers. In addition to these major challenges, the existing solutions for border patrol systems lack a coherent system that coordinate various technologies to improve the system accuracy.

3. System architecture of BorderSense

Current WSNs for border patrol are based on a flat, homogeneous architecture in which every sensor has the same physical capabilities and can only interact with neighboring sensors [27]. Such a structure results in several shortcomings in border patrol such as limited coverage and high false alarm rate that require additional human intervention. Instead, we consider a hierarchical WSN architecture with heterogeneous sensor nodes as shown in Fig. 1. In this architecture, three different types of sensors are used in three different layers of the hierarchy.

As shown in Fig. 1, the system architecture of BorderSense has three layers. The unattended ground sensors and the underground sensors constitute the lower layer of the architecture, which provide higher granularity for monitoring. At the second layer, multimedia sensors improve the accuracy of the system through visual information. Finally, mobile ground robots and unmanned aerial vehicles constitute the higher layer that provides additional coverage and flexibility.

- The ground sensors [44,42,43] and the underground sensors in the lower layer are resource-constrained, low-power scalar sensors, which perform simple tasks such as taking seismic/vibration measurements and sending the information to data sink or processing hub. The underground sensors can either communicate with the ground sensors or other underground sensors [30,31]. Due to the complex underground channel characteristics [19,38], new physical layer propagation techniques are needed to realize the communications, such as underground electromagnetic wave techniques or magnetic induction waveguides [4,33,35,34]. Different from the camera sensors in the surveillance towers or UAVs, the ground/underground sensors can detect non-line-of-sight intruders. However, as discussed in the introduction, based on the limited information acquired by ground/underground sensors, it is difficult to distinguish actual intrusion alarms from false positives. Consequently, the false alarm rate of the ground/underground sensors is considerably high.
- Mobile or stationary surveillance towers can host very powerful and reliable multimedia sensors, i.e., radars [26], cameras, and sensors, which constitute the second layer of the hierarchy. The multimedia sensors are resource-rich, high-power devices with higher processing ability and larger communication range. As a result, these components are also used as local processing hubs. The multimedia sensors are responsible for more complex tasks such as collecting the sensing reports from the ground/underground sensors, detecting possible intrusion according to the sensing reports as well as the local image/video information. As a results, the false alarm rate of the ground/underground sensors can be significantly reduced. After the surveillance towers confirm intrusion detection, they report the detection results to the remote administrator, and inform the mobile sensors the position of the intrusion for target tracking. Furthermore, the measurements and image/video information are stored for future use. There may also exist cooperations between imaging sensors to detect intrusions collaboratively. In this case, correlation-based camera selection schemes [9,10] and data compression frameworks [39] are required to reduce the redundancy among correlated cameras.
- In addition to the stationary components, unmanned aerial vehicles (UAVs) and robots provide additional capabilities at the third layer. UAVs have recently been used for several applications including environmental surveillance and infrastructure maintenance [11,14,13,24]. Drones and Remotely Piloted Vehicles (RPVs) are two types of UAVs. Drones are configured for autonomous flight with a pre-determined course and schedule. RPVs are remotely controlled by ground operators. In addition to mobility, UAVs can also be equipped with on-borad sensors and camera systems to provide additional coverage in an on-demand basis. Furthermore, UAVs can track intruders based on information from stationary sensors and help the border patrol agents catch intruders.

Due to cost and coverage considerations, the number of sensors in the first layer is much larger than that at the higher layers. Accordingly, the network is divided into several clusters. The ground/underground sensors form several clusters, where the multimedia sensors also act as cluster heads. Similarly, multiple multimedia sensors coordinate with each other to form higher layer clusters that are maintained by mobile nodes. The higher-layer information from the multimedia sensors are fused at the mobile nodes that are dispatched to locations of intrusion for

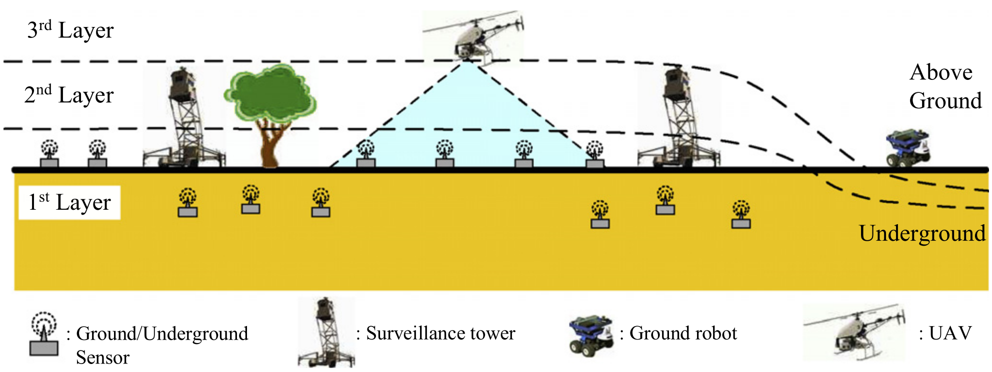

Fig. 1. Network architecture of the hybrid wireless sensor networks for border patrol.

target tracking. One cluster may have more than one cluster head according to the specific requirements of the applications.

4. Deployment of BorderSense

According to the heterogeneous architecture shown in Fig. 1, the development problem of BorderSense system is discussed in this section. In border patrol applications, the established monitoring network should cover a significantly large monitoring area. However, the sensing radius of a single sensor node is normally limited. Thus, a large number of sensor nodes are expected to fulfill the coverage requirement. Moreover, different types of sensor nodes (e.g., underground, ground, camera, and mobile sensors) provide different coverage capabilities. In addition, each sensor type is characterized by different cost, sensing radius, and sensing accuracy. Thus, an optimal deployment strategy is required to determine the number and locations of sensor nodes with heterogeneous capabilities. The primary objective of the deployment research is to find the deployment strategy using the minimum number of each type of sensors to cover the whole surveillance area and to achieve a desired intrusion detection probability.

4.1. Deployment of ground/underground sensors

As discussed in Section 3, the sensing ranges of the ground/underground sensors should cover the whole border, as shown in Fig. 2. According to [43], a seismic sensor can detect moving heavy vehicles (such as tanks) from a distance of up to 500 m and walking humans from up to 50 m. To guarantee the detection of every type of intrusion, the sensing range of the walking humans is used in this paper, which is denoted as R_{UGS}. For sufficient detection accuracy and system robustness, k-barrier coverage is required for the belt region in front of the border [6,16]. The definition of the k-barrier coverage is as follows.

Definition. A belt region is k-barrier covered by a sensor network if and only if all crossing paths through the belt are covered by at least k distinct sensors.

4.1.1. Manual deployment

We first consider the case that each ground/underground sensor can be deployed at the predetermined positions. According to [16], the optimal manual deployment strategy to achieve k-barrier coverage in a belt region is to deploy k rows of sensors along a shortest path (line or curve) across the length of the region. The sensing ranges of the sensors on the same path should be consecutive, as shown in Fig. 2. By using this strategy, the k-barrier coverage of the border can be achieved with the minimum number of ground/underground sensors.

Proposition 1. *Consider a strip region in front of the border. Let d denote the length of the shortest path across the length of the region. Let the sensing range of the sensor is r. Then, the number of sensors necessary and sufficient to achieve k-barrier coverage in this region is* $k\lceil \frac{d}{2r} \rceil$.

The proof of Proposition 1 has been given in [16]. Then, according to Proposition 1, given a border area with axial distance d, the minimum number of ground/underground sensors required to achieve k-barrier coverage is $k\left\lceil \frac{d}{2R_{UGS}} \right\rceil$.

4.1.2. Random deployment

Although the manual deployment strategy stated above is the most efficient, it may be not applicable in certain scenarios. For example, the ground sensors can be deployed by dropping from aircrafts or vehicles to reduce the deployment cost. Consequently, the distribution of the sensors is random. In this subsection, we analyze the requirements of the density and the deployment area of the ground/underground sensors to achieve the k-barrier coverage when those sensors are randomly distributed.

Assume that the ground/underground sensors are distributed in the strip area in front of the border according to a Poisson point process with spatial density λ. According to [20], the following proposition applies.

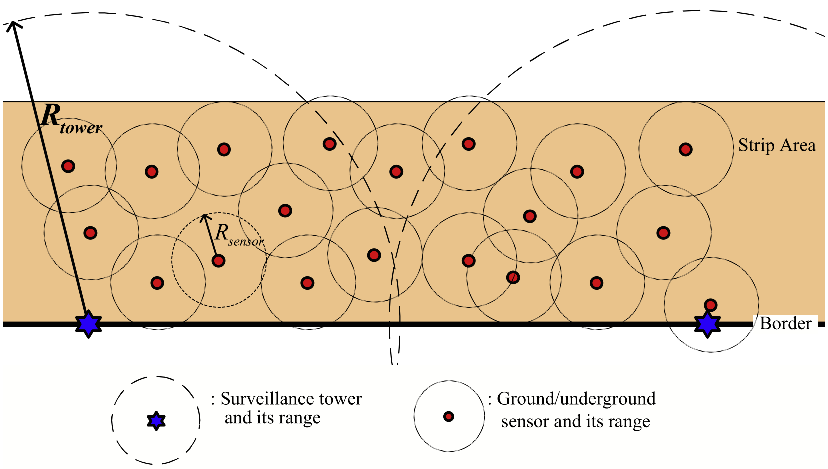

Fig. 2. Deployment of the hybrid wireless sensor networks for border patrol.

Proposition 2. *Consider the strip region in front of the border. Let d denote the length of the region and w denote the width of the region. Let the sensing range of the sensor is r. If the width of the strip is asymptotically larger than the logarithm of the length, i.e.* $w = \Omega(\log d)$*, the network is k-barrier covered with high probability when the sensor density* λ *reaches a certain value.*

The proof of Proposition 2 is given in [20]. Then, according to Proposition 2, given a border area with length d, to achieve k-barrier coverage when ground/underground sensors are distributed randomly, the following two conditions should be fulfilled.

- The ground/underground sensors should be deployed in a strip area in front of the border with a strip width larger than w, $w = \Omega(\log d)$;
- The deployment density of the ground/underground sensors should be larger than λ, $\lambda = \frac{2(\kappa \log 6+2)}{(1-\kappa R_{\text{UGS}}/w)R_{\text{UGS}}^2}$, where $\kappa > 0$ is a constant to be determined by simulations.

4.2. Deployment of surveillance towers

To mitigate the problems caused by the high false alarm rate of the ground/underground sensors, the camera sensors equipped on the surveillance towers are activated after the ground/underground sensors detect any abnormal seismic activity in the border area. Similarly, the minimum number of the surveillance towers needs to be determined so that the total field of views of the cameras can cover the border area and improve the detection accuracy by a specified value.

Different from the deployment of the ground/underground sensors, the deployment positions of the surveillance tower should be predetermined. Moreover, the surveillance towers are deployed along the border line with 1-barrier coverage due to the much higher cost of the surveillance tower. Hence, the deployment problem of the surveillance towers can be viewed as a special case of the k-barrier coverage where $k = 1$. Assuming that the sensing range of one surveillance tower is R_{tower}. Then, according to Proposition 1, the minimum number of surveillance towers to cover a border with distance d is $\left\lceil \frac{d}{2R_{\text{tower}}} \right\rceil$. It should be noted that since the sensing range of the surveillance towers is much larger than the range of the ground/underground sensors, the required number of the surveillance towers is much less than the number of the ground/underground sensors, as shown in Fig. 2.

4.3. Deployment of UAVs

In addition to the static nodes, the mobile sensors both on the ground and in air are deployed along the border so that the mobile sensors can track the movement of the intruders after the intruders have passed the border. When an intrusion is detected by the ground/underground sensors and the surveillance towers, at least one mobile sensor is required to arrive at the intrusion position within the tolerable delay t_d so that the mobile sensor can track the movement of the intruder. Assuming that the velocity of the mobile sensor is v, the minimum number of mobile sensors required for a segment of border with length d is $\left\lceil \frac{d}{2v \cdot t_d} \right\rceil$.

5. Operational framework for BorderSense

Based on the network architecture and the deployment strategy, the operation framework is described in this section to realize the basic functionalities of BorderSense.

Since the hybrid WSN consists of three types of sensors, three types of sensing information are obtained from a spatially distributed set of sensors with different attributes. The three types of sensing information are generally complementary to each other. The multimedia sensors provide still image or video information of the border area but the intruder behind any obstacles cannot be detected. The ground sensors can sense the ground vibration as well as the magnetic anomaly caused by the intrusion. However, it is difficult to distinguish a human intruder from a large animal, hence high false alarm rate may be caused. The underground sensors can also sense the vibration of the ground, but the attribute of the sensing measurements are different from those acquired by the ground sensors. The false alarm rate of underground sensors is also high. Hence, these heterogeneous set of information should be fused at certain points in the network to improve the decision accuracy and minimize the miss rate and false alarm rate.

To detect possible intrusions with low miss rate and low false alarm rate, a two-phase collaborative detection strategy is adopted to efficiently utilize the information collected by a heterogeneous set of spatially distributed multimedia, ground, and underground sensors. In the first phase, the ground or the underground sensors initiate a collaborative intrusion detection procedure upon any suspicious reading. In the second phase, the imaging sensor improves the detection accuracy by fusing this information with the collected image and videos of the suspicious area. Only after a high confidence level is achieved, the border patrol personnel is informed. Meanwhile, mobile nodes are dispatched to the location where the intrusion is detected to track the movement of the intruder. In the above two detection phases, intensive communication between the ground/underground sensors is also involved.

According to the framework described above, the operation framework of BorderSense consists of three parts: *cooperative intrusion detection*, *intrusion tracking*, and *detection-oriented communication* as explained next.

5.1. Cooperative intrusion detection

If the unattended ground/underground sensors are deployed according to the strategies described in Section 4, the miss rate of intrusion detection can be controlled at a low level. However, as discussed previously, it is difficult to distinguish between intrusions and nuisance warnings caused by environment elements (e.g. insects, weather, and animals) according to the limited information acquired by ground/underground sensors. Hence, the false detection rate of the ground/underground sensors is high.

In conventional wireless sensor networks, the false alarm rate can be lowered by the joint-detection of multiple adjacent sensors. Specifically, since the belt region in front of the border is *k*-barrier covered [6,16] by the sensors according to the deployment strategy, an intruder may be detected by multiple ground/underground sensors as the intruder passes through the belt region. An abnormal event is confirmed only if multiple sensors detect the event at the same time. Another scheme to decrease the false alarm rate in traditional WSNs is to increase the detection threshold. However, both schemes also increase the detection miss rate at the same time. Moreover, conventional detection schemes can only detect the intrusion but cannot accurately characterize the intruder, e.g., human or a wild animal.

In BorderSense, by the cooperation between the ground/underground sensors and the multimedia sensors on the surveillance towers, the false alarm rate can be lowered while the miss rate can be also kept at a low level. In particular, the information reported by the ground/underground sensors is fused with the collected image and videos of the suspicious area. Accordingly, the human intruder can be accurately distinguished from other objects. If the suspicious area is within the line-of-sight of the camera sensors, the camera sensors can accurately distinguish the real intrusion and the nuisance warnings. If the suspicious area is blocked by obstructions and cannot be detected, the camera sensor can either inform other camera sensors to detect the suspicious area or search the not blocked areas near the suspicious area since the intruder may move into those areas.

Although the camera sensors have high detection accuracy, the images and videos collected by the cameras still require human involvement to distinguish the intrusion from the nuisance warnings. To reduce the human involvement, two methods could be utilized.

- Centralized object detection: In this scheme, cameras take images of the suspicious areas detected by ground/underground sensors, perform image compression locally, and send the compressed data to remote processing center equipped with high computation capacities, where pattern recognition algorithms are performed to automatically detect intrusion based on the received images. This centralized scheme can yield accurate recognition results since sophisticated pattern recognition algorithms, which require computation intensive operations, can be performed by the powerful remote processing center. However, to ensure timely detection, this scheme demands high network bandwidth for high-volume image transmissions. To encounter this problem, advanced image processing approaches, such as distributed image compression [1,39] and wavelet image transform [8], are favored. Distributed image compression allows neighboring cameras jointly compress their captured images without exchanging actual images between each other, given a prior knowledge of the correlation structure among cameras. Different from the image compression scheme, wavelet image transform scheme [8] allows image decomposition into separable subbands in multiple levels of resolution. Therefore, image data can be divided into priority levels that correspond to those of the resolution. In this way, all image data with the lowest level of resolution are sent intact, while others can be transmitted partially on demand.
- Distributed object detection: In this scheme, camera sensors collaboratively perform object detection and recognition without involving the remote processing center. Since exchanging images among cameras consume considerable energy and spectrum, light-weight and distributed detection schemes are preferred. For example, in [36], the address event image sensors are introduced to achieve energy efficient object/human detection. An address event image sensor has a bank of pixels. A pixel can be designed to detect specific features (e.g light saturation, motion and contours). Each pixel generates an event when its conditions are satisfied. Different from conventional cameras, address event image sensors selectively extract and output only a handful of features of interest from the visual scene such as location, motion, direction of motion and lighting. These features form a symbolic representation of the visual scene that is much easier to process on resource constrained camera nodes. With this symbolic representation, far less bandwidth is required for cameras to communicate with each other and perform collaborative reasoning about an event.

5.2. Intrusion tracking

After an intrusion is detected by the unattended ground/underground sensors and confirmed by the multimedia sensors on the surveillance towers, at least one UAV or ground robot is dispatched to track the intruder so that the border patrol troops can effectively catch and control the intruder.

In traditional wireless sensor networks [15,25,37], the target tracking can be achieved by utilizing the detection results from each sensor. Specifically, each sensor reports the detection information to the monitoring center in real-time. The monitoring center then fuses the information spatially and temporally. Finally, the trace of the target can be derived and the future movement of the target can be predicted. Besides the centralized tracking strategies, distributed tracking based on collaborative signal and information processing can also be utilized [18,21,40]. Bayesian filtering and Kalman filtering are used to predict the future movement of the target based on its past and current positions.

However, different from the traditional WSN-based target tracking systems, BorderSense has a long strip network topology. Therefore, the intruder tracking cannot be achieved by using the stationery sensors since the intruder can pass the strip-like sensing area very quickly. Hence, the UAVs or ground robots are employed to provide intrusion tracking. In particular, first, the location of the intrusion is reported to the nearest UAV or ground robot through the surveillance towers in a multi-hop fashion. Then, the surveillance towers continue to monitor the movement of the intruder. Those surveillance towers report the direction and velocity of the intruder to the dispatched UAV or robot. After receiving the updated information of the intruder, the UAV or robot can adjust its moving direction to track the intruder. The UAV or robot is expected to reach the intruder before the intruder gets out of the monitoring area of the surveillance tower.

5.3. Detection-oriented communication

To facilitate timely and accurate object detection, efficient and effective communication protocols are required to support two types of transmissions: sensor-camera transmission and camera-remote center transmission. Sensor-camera transmission allows ground/underground sensors to report suspicious events to camera towers, while camera-remote center transmission enables camera towers to convey captured images to the remote control center, as explained next:

5.3.1. Sensor-camera transmission

Generally, sensor-camera transmission is based on many-to-many communication paradigm since multiple events can be detected simultaneously by ground/underground sensors, and these events have to be reported to the corresponding camera towers whose field of views cover the locations of the detected events. The conventional many-to-many communication schemes [7,17] aim to reduce the energy consumption or network congestion when multiple sources send packets to multiple sinks. More specifically, in [7], the many-to-many communication problem is modeled as the multi-commodity network design problem with an objective to minimize the number of links that constitute source-sink paths. Accordingly, a distributed protocol is provided to maximize the overlapping among source-sink paths. This leads to increased network lifetime and reduced contention on the wireless medium. In [17], a grid-based hierarchical routing is proposed to address the problem of routing from multiple sensors to mobile sinks, focusing on schemes to reduce the communication overhead caused by sink mobility. In this scheme, a grid structure is established after the sensor deployment. Then, a cluster head is randomly selected from the sensors within each grid and this cluster head represents the whole grid to receive the updated information regarding the sink mobility.

In contrast to the conventional many-to-many communication schemes, the sinks in the BorderSense architecture are also camera towers, which have limited coverage. This means that ground sensors need to send alarms to the specific towers that cover their location. Therefore, the number of source-sink paths are limited by the relative locations between ground/underground sensors and towers as well as the field of view of the cameras. This constraint may reduce network throughput. Thus, new many-to-many communication protocols are required. One possible scheme is to design detection-oriented communication schemes that leverage the extended coverage area of the camera towers. More specifically, instead of letting every sensor report its detected event to the towers, sensors, which are covered by the same camera tower, initiate a single event even if they detect different objects simultaneously. This approach can significantly reduce the amount of data relayed to the towers and save the spectrum resources. However, this scheme requires more sophisticated pattern recognition algorithms to identify multiple targets in a single image.

5.3.2. Camera-remote center transmission

As introduced in Section 5.1, both centralized and distributed object detection schemes require timely and reliable data/image transmissions from camera towers to the remote control center. To facilitate distributed detection scheme, the scalar data, i.e., the local detection/recognition results, are required to be forward to remote control center. Since the camera towers form a one-dimensional chain, this leads to a linear network topology. Under such topology, the communication protocols [23,29,41] are favorable since they are specifically designed for linear networks that deal with scalar data. However, to support the centralized detection scheme, all captured images have to be forwarded to the remote control center. Therefore, the design of QoS-aware communication protocols is of importance to ensure the quality and timeliness of the received images.

6. Research challenges

Based on the deployment and operation framework of BorderSense, the following challenges emerge.

6.1. Adaptive detection for ground/underground sensors

The BorderSense architecture requires intensive camera sensor involvements, since a great amount of suspicious intrusion information collected by the ground/underground sensors needs to be validated by the camera sensors. Due to the limited number of the surveillance towers and the limited bandwidth, the number of events generated by the ground/underground sensors and sent to the camera sensors should be minimized. To minimize the number of events while satisfying detection accuracy, an adaptive detection algorithm for the ground/underground sensors is needed. Specifically, the number of events generated by the ground/underground sensors can be effectively reduced by increasing the detection threshold or increasing the number of ground/underground sensors involved into the decision making. However, if the detection threshold is too high or the number of the involved ground/underground sensors is too large, the detection miss rate will be unacceptably large. The optimal detection threshold and number of involved ground/underground sensors are different from case to case due to the different environmental and weather conditions. Therefore, the algorithm should adaptively determine the detection threshold as well as the number of ground/underground sensors involved into the decision making based on the final detection results made by the surveillance tower.

6.2. Coordination between camera sensors

The camera sensors play an important role in the intrusion detection and tracking. As discussed previously, although the camera sensors can detect the intrusion with much higher accuracy, they cannot detect the non-line-of-sight intruders (e.g. the intruder behind obstructions). Therefore, the coordination between multiple adjacent camera sensors is required to detect and track non-line-of-sight intruders. Moreover, in the BorderSense framework, the camera sensor is expected to have a disk coverage range, as shown in Fig. 2. The semi-circle range in front of the border is used for intruder detection, while the semi-circle range behind the border is used to provide target tracking functionalities before a UAV or robot catches up with the intruder. However, most current camera sensors can sense only in the direction of its orientation. To solve this problem, rotating directional camera sensors that can change the orientation of the camera at a certain rotational speed can be employed. The rotating camera sensors can cover the whole disk monitored area periodically but also cause the uncovered time of certain monitored area [12]. To minimize the uncovered time, a joint analysis of the coordination between adjacent camera sensors are required to determine the initial phase of the camera directions and camera rotating velocity. In addition, according to the BorderSense framework, the camera sensors are activated by the suspicious events detected by the ground/underground sensors. The phase of the rotating camera sensors may be changed by those events. Therefore, the coordination between the rotating camera sensors and the ground/underground sensors should also be analyzed.

6.3. QoS-aware adaptive communication protocols

The BorderSense system will be deployed in both soil and aboveground, these different media exhibit significantly different channel characteristics [4,30–32,34]. Thus, the designed communication solutions should adopt suitable protocols in both soil and air medium and provide seamless protocol transition at the medium boundaries. Moreover, due to the limited power, computation, and communication capabilities of existing sensors nodes, low-complexity protocols are desirable for extended lifetime and high system efficiency in distributed sensor networks. On the other hand, the border patrol applications demand strict requirements in terms of accuracy and timeliness with these low-end devices. Thus, the design of low complexity and high efficiency protocols is non-trivial in this case. Accordingly, the configurable communication modules are favored, which can adaptively adjust the system parameters, e.g., modulation strategies, coding rates, and channel contention time, such that the sensor energy consumption is minimized while satisfying the quality of service requirements, e.g., detection accuracy, latency, error rate, and jitter.

7. Conclusion

In this paper, we introduce BorderSense, a hybrid wireless sensor network architecture for border patrol to reduce the intensive human involvement and to improve the detection accuracy of current border patrol systems. BorderSense is a coherent system that coordinates various technologies, including unmanned aerial vehicles, unattended ground/underground sensors, and surveillance towers equipped with camera sensors. The hybrid WSN architecture combines the advantages of existing border patrol techniques. In particular, the camera sensors provide accurate detection results as well as large detection range; the ground/underground sensors provide detection functionality when the intrusion is not in the line-of-sight region of the camera sensors; and the mobile sensors provide intrusion tracking capability to track the intruders after they have been detected. The network architecture of BorderSense is first described. Moreover, the deployment strategy of the ground/underground sensors, the surveillance tower, and the UAVs and robots are discussed. Based on the network architecture and deployment strategies, the intrusion detection strategy, the intruder tracking algorithm, and the detection-oriented communication protocols are explored. Finally, the research challenges and open research issues are discussed. The future works involve the simulation evaluations of the proposed deployment and operation framework of BorderSense system. Then a testbed will be developed and field experiments will be conducted to test the performance of BorderSense system in the real border patrol applications.

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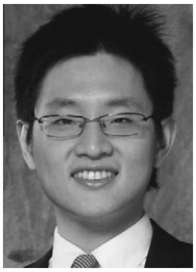

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