Unmanned Aircraft Vehicle Assisted WSN-based Border Surveillance

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***Abstract*—We develop in this paper a novel border surveillance solution, composed of a Wireless Sensor Network (WSN) deployed terrestrially to detect and track trespassers, and a set of lightweight unmanned a quadcopters that interact with the deployed WSN to improve the border surveillance, the detection and investigation of network failures, the maintenance of the network, and the response to hostage situations. In this paper, together with the design of the proposed VTail quadcopter, we develop powerless techniques to accurately locate terrestrial sensors using RFID technology, compute the optimal positions of the new sensors to drop, relay data between isolated islands of nodes, and wake up sensors to track intruders. A simulation is conducted to evaluate the proposal.**

I. Introduction

Wireless Sensor Networks (WSNs) can be used to assist authorities in monitoring the security of critical areas such as borderlines. To provide an economical large-scale monitoring of the borderline, even it is inconvenient for humans to be present, an aerial vehicle is generally used to drop sensors. Several issues are facing the use of these networks. First, the physical location of sensors' landing points cannot be determined with a high accuracy even if advanced models for the controllable and random deployment of nodes thrown from the air, are used [2], [1]. Therefore, coverage holes may appear and some sensors could be damaged during landing. Second, after an operational period of time, some sensor nodes may go out of energy, and their sensing range may be affected by the variation vegetation surrounding them. Third, over time, threats affecting the monitored zone could vary, making the density of the nodes insufficient to guarantee an efficient detection and tracking. Due to their sensitivity, alerts generated by sensor nodes should be timely transmited to the control center, otherwise trespassers could be undetected. To guarantee a continuous and pervasive borderline monitoring and allow a timely response to intrusions, the previous problems need to be addressed. An economical and rapid intervention should be possible to timely detect, investigate, and repair failures.

Several border surveillance applications were proposed in the literature showing either the use of Unmanned Aircraft Vehicles, or terrestrial WSN, but not a cooperation between them. These solutions remain unable to guarantee neither a continuous and improved monitoring, nor a timely investigation and reaction to failures.

In [5] and [3] WSNs have been intensively used for military surveillance and reconnaissance applications. However, these WSNs does not allow a fast investigation and intervention in the case of warnings. In [4] a quadcopter UAV is designed to monitor the border area. The solution is unscalable and unable to provide a continuous surveillance, unless a high number of long distance quadcopters are used simultaneously all the time. This would make the surveillance unpractical and highly expensive. In [7], a three-layer hybrid network architecture was proposed. It uses wireless multimedia sensors, mobile sensors, and terrestrial deployed scalar sensors. Mechanisms to rapidly detect and respond to failures are not provided.

We develop in this paper a border surveillance application where a set of lightweight Unmanned Aircraft Vehicles (UAVs), in the form of quadcopters, are used to interact with a terrestrially deployed WSN in order to improve the border surveillance, the detection and investigation of network failures, the network maintenance, the tracking of trespassers, and the response to hostage situations. The prototype of the proposed VTail quadcopters is also developed and tested. In addition, green techniques are proposed to allow the quadcopters to accurately locate sensors, detect and fix coverage holes (by dropping sensors), identify and investigate sensors' failures, relay urgent data between isolated island of sensors, wake up unreachable sensors to track intruders, and transmit real photography of the crossed zone.

The contributions of this paper are three-fold. First, green techniques for the accurate localization of sensor nodes and the investigation of coverage problems by quadcopters are developed. Second, through the integration of WISP (a battery-free and wirelessly powered platform for sensing and computation) to the sensor nodes, and thanks to the use of Dual-port nonvolatile memory (an EEPROM with RFID and Serial Interfaces), the configuration state of sensor devices can powerlessly be read or updated by the quadcopters, allowing to investigate several types of failures. Third, the developed quadcopters behave as enhanced mobile sensors, which cooperate with the terrestrially deployed sensors to enhance the accuracy of the trespassers detection. They provide an economical and efficient response tool that allows to quickly respond to various types of incidents in the borderline.

The remaining part of the paper is organized as follows. In section II, a thick strip border surveillance system based on a WSN is presented. Section III discusses the improvement of border surveillance quality using quadcopters. Section IV describes the design of the quad-copter device . In Section V, we assess the efficiency of the proposed approach. The last section concludes the paper.

II. A THICK BORDER STRIP SURVEILLANCE WSN

We consider in Fig. 1 a thick linear and hierarchical WSN which integrates three types of sensors. Basic Sensing Nodes (BSNs) are used for the detection of moving objects, the alerting, and the cooperative relaying of messages. Data Relay Nodes (DRNs) are responsible of collecting alerts from the different BSN nodes in their vicinity, and cooperating with neighbor DRNs to forward these alerts to Data Dissemination Nodes (DDNs). The latter are a set of sink nodes in charge of collecting data from their neighbor DRNs, and aggregating and forwarding them to the Network Control Center (NCC). The designed WSN follows a multiple thick line topology where the DRNs and DDNs are deployed linearly over multiple lines, while the BSNs are distributed around all the DRNs.

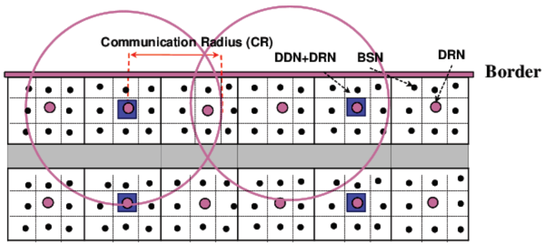

Figure 1. The WSN based subsystem architecture

Let R_c^d and R_c^b be the communication range of a DRN and a BSN, respectively, and R_s^b be the sensing range of a BSN. Every DRN node has at least two neighbor DRNs in its communication range (R_c^d). To guarantee mutual communication between successive BSNs we assume that $R_c^b \geq 2 \times R_s^b$. DDNs, representing gateways to the NCC are placed at a regular interval after a predefined set of DRNs.

In practice, BSNs and DRNs are randomly deployed using aerial vehicles. The position of the sensors' landing point is determined with respect the wind speed vector of the aircraft vehicle, the wind forces experienced by the sensors thrown from the air, and the interval separating two successive droppings times. Even if techniques, such as [2], allow to control the error related to the variation of the landing patterns, some sensing coverage holes may occur, preventing either the detection of trespassers and the generation of alerts, or the routing of received alerts toward the DRN. Holes arise because: a) As sensors are thrown from aircraft during deployment, some of them could be damaged; b) Sensors are prone to faults and malfunctioning which could decrease the detection accuracy; c) A sensor could run out of energy depending on the quantity of detected events and generated and forwarded alerts; d) Due to environment modifications (e.g., vegetation, noise) or the occurrence of transient troubles (e.g., rainy weather), several irregularities could arise on the sensing and transmission range, contributing to the creation of coverage holes. In addition to holes, threats affecting the monitored zone could vary over time, requiring sometimes to increase the density of nodes within the vulnerable area.

To guarantee an efficient detection and tracking, a WSN-based border surveillance applications should allow the prediction, detection and identification of a wide set of sensor faults, the tolerance of the monitoring system to these faults, and the ability to recover from them. Energy consumption of a sensor node, for example, should be monitored, and the instant of failure should be predicted based on the history of resources consumption. A replacement procedure should be developed so that the NCC can proactively respond to failure by replacing the sensor before it becomes faulty.

III. QUAD-COPTERS FOR BORDER SURVEILLANCE

This section discusses the use of quadcopters to improve the quality of border surveillance.

A. *Quadcopter objectives and characteristics*

The main objectives of the quadcopter are: a) Localization of terrestrial sensors and detection of sensing and transmission coverage holes; b) Detection of several types of nodes failures, such as battery depletion, and routing failure; c) Transporting and dropping of lightweight sensor nodes; d) Correction of coverage holes by dropping sensors at suitable positions; e) Relaying of data between isolated island of BSN nodes, and between isolated DRNs and the NCC; f) Tracking of objects crossing the border by capturing and transmitting real-time video of the intrusion area; g) Waking up of isolated sensors to track mobile trespassers and trace their trajectory. The use of quadcopters for enhancing the quality of border surveillance offers several advantages. First, it is able to fly over hazardous and risky areas, allowing to prevent the loss of human life. Second, it is an inexpensive platform that can be built from scratch using components available in the market, and easily assembled due to its non-complex mechanical architecture. Third, it does not rise safety and legislative issues thanks to its small dimension and ability to fly at very low altitude.

To achieve the aforementioned objectives we design a quadcopter that has the following characteristics. First, it represents a mobile sensor that is able to communicate with the WSN deployed on the ground. Second, it is able to perform a long distance communication with the NCC using a packet oriented service connection to receive navigation data, transmit the locally collected data, and relay data between isolated nodes. Third, it can be remotely piloted and controlled over thousands of meters and is able to fly at an altitude of several tens of meters. Fourth, it is equipped with a set of on-board sensors for safe flying (e.g., GPS receiver, 2D LIDAR obstacle detection). Fifth, it has an attached camera to capture high-resolution images and real-time videos of the intrusion scene (processed by a computer vision algorithm to minimize the rate of false alerts). Sixth, it can transport and drop tiny sensor nodes.

To reduce the energy overhead required by terrestrial sensors to respond to the requests generated by the quadcopter, we introduce the use of Radio Frequency energy harvesting techniques to powerlessly locate sensors and collect and modify configuration data. We integrate to every sensor a Wireless Identification and Sensing platform (WISP) which is a programmable battery-free sensing and computational platform [6] that can be powered and read by a standards compliant Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) reader. A WISP uses an ultra-low-power programmable micro-controller powered by RF energy to encode its unique ID and additional data to perform sensing and computation tasks [8]. The quad-copters use long-range RFID readers to read the WISP tags of the WSN nodes.

B. Coverage holes detection and maintenance

To compute the coordinates of a sensor node s the quad-copter proceeds as described in Fig. 2. First, it computes its coordinates (x_p, y_p) at position p (e.g., using a GPS receiver). Second, while flying at a constant speed (to another position q) in parallel to the upper boundary of the strip representing the thick border, it performs two successive measurements of the distances d_p and d_q (between itself and the sensor node) at two positions p and q, respectively. Knowing its speed and the time difference between the two instants of measurements, the quadcopter computes the distance d_{pq}. The coordinates (x_s, y_s) of the sensor s are computed by resolving the two equations: $x_s^2 + y_s^2 = d_p^2$ and $(d_{pq} - x_s)^2 + y_s^2 = d_q^2$. We obtain x_s and y_s as: $x_s = (d_p^2 - d_q^2 + d_{pq}^2)/(2d_{pq})$; $y_s = \sqrt{(d_p^2/2d_{pq}) * (d_p^2 - d_q^2 + d_{pq}^2)}$. Since the quadcopter is always flying at the upper boundary, the value of y_s cannot be negative.

To compute the distances d_p and d_q the quadcopter performs an RFID based localization by estimating the physical distance separating it to the passive WISP tag embedded in the sensor. Several techniques can be used for the distance estimation such as [9] which combines the advantages of acoustic location (high degree of precision and simplicity) and the use of RFID technology to provide a high accuracy. Using it, the WISP tag embedded on the sensor will be equipped with an acoustic tone detector. Once interrogated, the WISP powerlessly generates an ultrasound signal after the reception of an acoustic beacon, measures the acoustic Time of Flight, and stores the latter in the tag to be read by the RFID reader.

After computing sensors' positions (both BSNs and DRNs), the quadcopter checks if: a) the distance separating two neighbor DRNs does not exceed R_c^d; b) each BSN has the required number of neighbor BSNs; and c) the distance between two neighbor BSNs or between a BSN and a DRN does not exceed R_s^b. If one of these conditions is not satisfied the quad-copter drops additional nodes to overcome coverage and connectivity problems. Having computed the position of the two horizontal DRNs D_i and D_j that are unable to communicate together, the quadcopter computes the position of the new DRN to be dropped, so that it will be at the intersection of the communication coverage areas of D_i and D_j. If possible, the position of the new DRN will be also in the communication coverage of one or two vertical neighbors, so that DRNs located at different strips could communicate together to relay alerts from a border strip to another.

To respond to coverage holes, the quad-copter drops new BSNs while guaranteeing that each BSN has at least one BSN in its sensing range R_s. First, it determines the nearest BSNs of both isolated islands and selects one of them. Second, it drops the new BSN as far away as possible from the actual point, provided that the distance separating them will be equal to $R_s - \epsilon$ where ϵ is a small value representing the estimated error in computing the distance between nodes. The quadcopter repeats the same operation until no coverage hole exists.

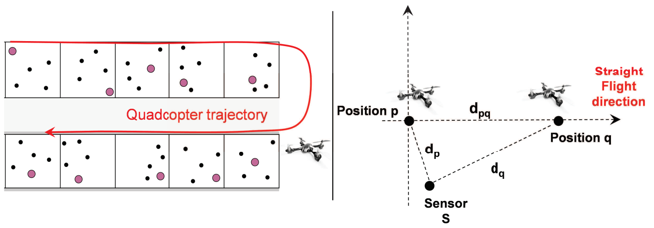

Figure 2. Quad-copter-based localization correction

C. Maintenance of failed nodes

Sensor failures occur due to several reasons such as battery depletion, manufacturing, or calibration drift. We extend the sensor node architecture by integrating to the WISP a dual Access EEPROM, which can be accessed through a wired serial port from the embedded micro-controller, or through a wireless RFID reader. The use of the RFID interface will allow the memory of the sensor to be read and updated remotely and powerlessly, even in the case of battery depletion. Therefore, the failures can be investigated even if the sensor is unable to respond to the quadcopter's requests. Each sensor node stores each period of time T its last configuration state on the dual-port access memory. Such a configuration includes: a) the routing table showing at least a route to the nearest DRN. A route is a four-uplet in the form of $\langle DRN\, id, next\, hop, distance, timestamp \rangle$, describing the id of the DRN, the identity of the next hop, the number of hops to reach the DRN, and the time of the last update ; b) the timestamped value of the remaining battery energy; c) the value of energy average consumption computed over a predefined number of hours; d) The content of alerts that remained in the sending buffer for a period of time exceeding a threshold Th_w. Failures in sending the buffered data could occur due to the unavailability of next sensors in the route towards the BSN; and e) a status flag describing whether the sensor is in active or sleeping state.

Moreover, each BSN or DRN is made able to estimate the remaining lifetime by calculating the average energy consumption in J/S over a history period. If its lifetime reaches a depletion threshold value Th_d (the energy required to keep functioning for a period of time equal to the quadcopetr's intervention time), a node forwards a notification to the NCC which will intervene by sending a quadcopter (initially deployed at the Intervention Center, IC), to replace that node and then extend the network lifetime.

To detect and investigate failures, the quadcopter uses its

RFID reader to read the content of the dual access memory. Failures can be detected as follows:

a) Detection of unreachable nodes: Some nodes could be unreachable even if they are in the transmission coverage of their neighbors, especially due to transmission impairments. This failure can be detected by noticing the availability of alerts that remained in the sending buffer for a period of time exceeding a threshold Th_w. The quadcopter copies the content of these buffered alerts and immediately forward them to the NCC. After being acknowledged, it deletes these alerts from the dual access memory.

b) Detection of out-of-coverage nodes: The quadcopter checks if the routing table is empty or contains an outdated route to the DRN. It checks if the current time value is higher than the sum of the route timestamp and the period of update. If it is the case, the NCC instructs the quadcopter to correct coverage holes as discussed in the previous subsection.

c) Detection/identification of out-of-energy nodes: The quadcopter reads the value of the remaining battery energy and checks if its is lower than a threshold. To determine whether the sensor is still active, the quadcopter checks whether the timestamp of the last update is recent, and whether the expected remaining energy has reached the zero value considering the average consumption of energy. If sensor's battery is depleted, the NCC instructs the quadcopter to drop a new sensor node in that location.

D. Tracking assistance

After detecting a trespasser, alerts generated by BSN are forwarded to the NCC through the hierarchical DRNs and DDNs. The NCC predicts the trajectory of the trespassers, instructs the DRNs on that trajectory to wake up sensors in their vicinity, and sends the quadcopter to remotely capture real-time video of the intrusion scene . In this context, the quadcopter can reduce the rate of false positives, allowing to better determine the type of the moving object. The NCC instructs also the quadcopter to check if the sensors located on the predicted trajectory are all woke up by remotely reading the dual access memory and checking the value of the status flag. If some sensors are found to be still in sleeping state, the quadcopter informs the NCC , and sends a pulse to the sensor (by writing directly to the dual access memory) to change its configuration state.

IV. Prototyping the quad-copter

We chose to work with a quadcopter, which has the "Y" shaped VTail design, over the conventional "X" orientation. The VTail design, shown in Fig. 3 is modeled after the shape of the letter "Y" with a tail in the shape of the letter "V". The base setup of the VTail quadcopter contains 1240kV motors, 30Amp electric speed controllers, two 8045 and two 9047 propellers, and a 2.4GHz 8 Channel radio receiver. The major differences between the VTail and conventional quadcopters are the weight, motors, and battery. The VTail's credentials allow it to carry a heavier payload, have longer flight times, and achieve more agile flight maneuvers. This unique construction promotes a more stabilized flight, combining the natural agility of a tricopter setup, the stability of the "X" style quadcopter, and removes the disadvantage pending on servo control to turn in place.

The electrical architecture of the quadcopter is centered around the use of a flight controller called the KK2 Board which uses the Atmega324 PA, an 8-bit microcontroller operating at 20MHz with 32 general purpose input/output pins, I2C communication protocol, Universal Asynchronous Receiver/Transmitter serial communication line, and analog to digital conversion channels. The KK2 Board has a library of pre-installed software for different orientations of quadcopters, which is especially useful since the VTail form is rarely supported. This board is responsible for sending pulse width modulated signals ranging from 1.5ms to 2.0ms every 20ms to four electric speed controllers, which control the speed and therefore, thrust of each individual motor on the quadcopter. The sensors on the board include a sensitive gyroscope and accelerometer system to keep up with the VTail's unique agility and auto-levels the quadcopter in the air at a high refresh rate. A separate GPS system is employed to keep track of the UAV in relation to the Earth at all times. The quadcopter operates through a radio control frequency of 2.4GHz with the aid of a live video stream captured by a GoPro video camera and transmitted by an 800mW 1.3GHz transmitter.

A permanent magnetic ring on the bottom of the quadcopter structure will hold the top of the sensor to be deployed on the ground. The UAV drops the sensor by a stepper motor-driven threaded turning rod that passes through a hole in the base of the structure, making the platform move upwards. The rod will physically push the top of the sensor down to create enough to separate the sensor from the magnetic ring, dropping the sensor on the ground in its designated location. The stepper motor is controlled by a channel on the KK2 board.

We have tested our prototype on a test scenario with two control method setups, namely manual control and GPS based auto-control, for providing valid parameters to simulations. In the test scenario, three triangular positions (Intruder position A, and Intruder position B, and intervention center C) were arranged with GPS coordinates. Our quad-copter flights over each intruder A and B, and then flights back to C. We equipped the designed quadcopter with a 3000mAH battery. In comparison with a normal quadcopter, which has a 3300mAH battery, our quadcopter can reach a maximum flight distance of 3390 m before it has to return to its takeoff area, while the Crossfire's maximum distance is 1872 m. This difference is mostly due to the fact that the VTail is lighter, more agile, and faster than the Crossfire, overcoming the battery disadvantage. The prototype made 10 flights over intruder positions, and we measured the battery consumption, and also the flight speed, distance, and mission completion times based on GPS positions. Our quad-copter showed a top speed of 11.5m/s.

To spot a trespasser, the range of the VTail quadcopter can be extended by considering the range of the camera used to take a picture. The camera used for the simulation was a GoPro Hero 3 Black Edition, having a resolution of 12 Mega Pixels.

The range of this camera considering the need to recognize a face is given by :

$$H = r_w \times (w_m / w_p); \quad D = f \times (H/h) \tag{1}$$

where H is the width of the scene (m), r_w is the width of the resolution of the scene (px), w_m is the width of the face to detect in meters (m), w_p is the width of the face to detect in pixels (px), D is the distance to the scene (m), f is the maximum focal length of the camera (mm), and h is the width of the CMOS (mm). Obviously, experimentally finding the Optimal flight speed of the quadcopter can increase flight efficiency so that battery lifetime and flight distance can be also extended due to the phenomenon called "helicopter transnational lift". In this experimentation, we were unable to find the optimal speed of our quad copter yet because of the limited coverage of the flight speed control system currently used. Such a feature will be be developed in a future work.

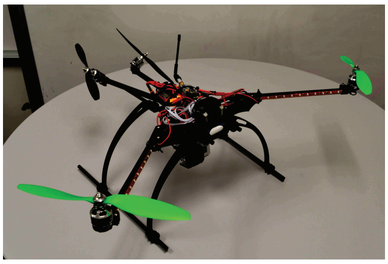

Figure 3. VTail quadcopter: Bird view

V. Simulation

We describe in this section the simulation conducted to assess the performance of the designed system.

A. Simulation Model

We consider a thick line WSN of length 6000 m and width 150 m. A DRN is placed each 150 m. The distance between two BSNs is set to 30 m. The IC is located in the middle of the intervention zone and on border line. We assume that: (a) during the operation period of the network, a sensor can be replaced several times thanks to the use of the quadcopter, which is able to repair one or several failures simultaneously; (b) the energy consumption of a sensor depends on the number of alerts generated and forwardedand on the duration of sensing period; (c) the monitored area can be divided into adjacent and non-overlapping intervention areas (each area is under the control of one quadcopter); and (d) a set of trespassers are crossing the border line starting from a point of entrance p, by following a linear trajectory and using a constant velocity $v = 1m/sec$. Due to the geographical characteristics of the border areas, the intruder's trajectory could be inclined vertically at an angle α. For each intruder, the point of entrance p and the vertical inclination α are chosen randomly (following an uniform distribution), where $p \in [O, 6000]$ and $\alpha \in [-\frac{\Pi}{6}, +\frac{\Pi}{6}]$. As long as a moving trespasser is in the sensing range of a BSN, it generates an alert with a constant rate of $1\, packet/sec$. Such an activity will lead to an energy consumption considering the following parameters: Transmission ($59.2 \mu J/Byte$), reception ($28.6 \mu J/Byte$), sensing ($6 \times 10^{-3}\, \mu J/msec$). The used battery has an initial power equal to $8640\, J$, and the alert datagram size is equal to 36 bytes. The time of intervention of the quadcopter is the total time required to: a) fly to the suitable zone; b) compute the position of the new BSN to drop; c) drop the new BSN and wait for its attachement to the network; and e) read the WISP of the BSN to check whether it has a new route to the DRN. The simulation we conducted was done using the Matlab tool.

B. Estimation of the BSNs' lifetime span

The first simulation we conducted aims to evaluate the average rate of BSNs' lifetime span in terms of quadcopter's intervention time, considering differents lengths of the intervention area. Let T_i be a period of operational time between the $(i-1)^{th}$ and i^{th} failure (In particular T_0 denotes the operation time proceeding the first failure). Then the average rate of BSNs' lifetime span, denoted by L, is given by: $L = (\sum_{i=1 \ldots n} T_i)/(Simulation\, time - T_0)$.

Based on Fig.4, we notice that the average rate of BSNs' lifetime span rises with the increase of the number of quad-copters. Therefore, the more quad-copters we have, the better network lifetime gain we obtain. We notice that for any number of quad-copters the curves decrease with the growth of the intervention time. In fact, when the quad-copter is able to reach the failed nodes rapidly (i.e. intervention time < 15 minutes) the gain is considerably important regardless of the number of quad-copters. As long as the intervention time is getting higher than 15 min, the gap between the average rates increases with the increase of the number of quad-copters.

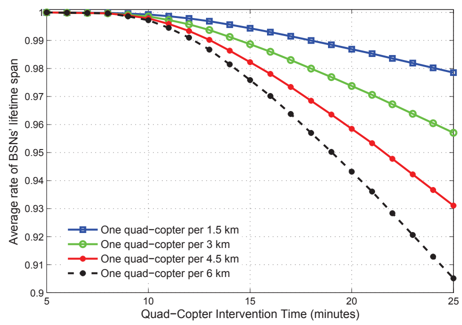

Figure 4. average rate of BSNs lifetime span vs. intervention time

Fig. 5 shows the evolution of the average rate of BSNs' lifetime span with respect to the number of intruders, considering different values of the quad-copter intervention time. The rate of gained network lifetime decreases with the increase of the number of intruders crossing the monitored borderline. The higher is the frequency of intrusions, the more the quad-copter fails to reach BSN nodes before becoming out of energy. We also notice that the negative impact of the number of intrusions/hour on the rate of gained lifetime, becomes more and more important with the increase of the intervention time. In particular, when the quad-copter is able to reach the failed nodes rapidly (intervention time $\leq$ 10 minutes), the gain remains considerably important regardless of the number of intruders/hour. When the quad-copter takes more than 10 min to reach the BSN nodes, the gap between the obtained rates for the same number of intruders is important. This gap increases significantly with the increase of the number of intruders.

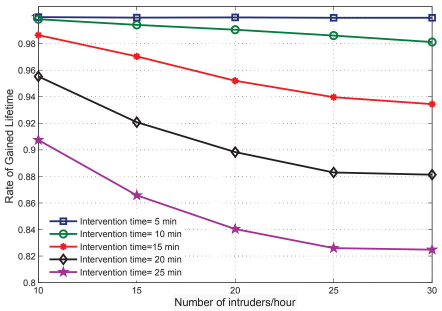

Figure 5. Average rate of BSNs lifetime span vs. number of intruders/hour

C. Estimation of the rate of non spotted trespassers

We simulated the percentage of failures in spotting intruders with respect the number of trespassers per hour. The simulation time spans 100 hours. We set the values of r_w, w_m, w_p, f, and h to $4000px$, $0.2m$, $36px$, $28mm$, and $6.248mm$, respectively. We also fixed the altitude of the UAV to 10 meters. Therefore, based on Eq. 1, the distance that can be added to the radius of the VTail is 99.08 meters measured on the ground and derived from Pythagorean theorem $sqrt((99.586m)^2 - (10m)^2))$. The result of the simulation are described in Fig. 6 considering two different lengths of the zone under the control of one quadcopter, namely 3000 and 6000 m. For each simulation, we varied the thickness of the WSN considering a border width of 60 m, 120 m, and 240 m. We use one UAV having a top speed of 11.5m/s. The results show that the failure rate of UAV detection increases with the increase of intruders per hour. In fact 1 UAV will not be able to keep up with the demand of detecting intruders across the border if the intrusions occur frequently, even with the battery being replaced when the UAV returns to its IC. We also notice that the rate of failure decreases faster with the increase of border thickness, which increases the total time that the intruder takes to cross the border under the WSN coverage, and reduces the time constraints for the UAV to move and spot the intruder successfully. The longer the distance is to the intruder, the longer the UAV is busy detecting the intruder, increasing the number of intruders that pass by undetected.

VI. Conclusion

We developed in this work a border surveillance application using quadcopters as a tool for the proactive and reactive

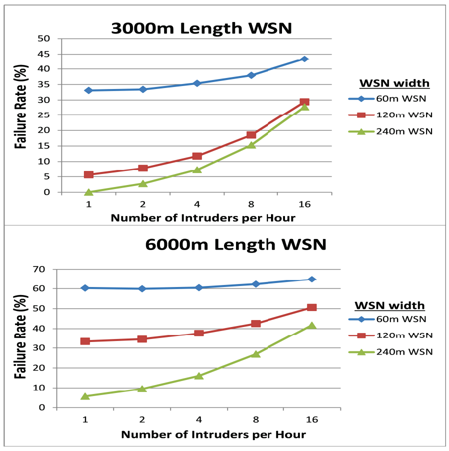

Figure 6. Failure rate w.r.t. number of intruders per hour

response to failures and intrusions, to improve the quality of detection and tracking of trespassers crossing a border supervised by a wireless sensor network. A V-tail quadcopter is designed to improve the terrestrial functions executed by the deployed WSNs to detect and track intruders, and also to enhance the reliability and increase the time span of the deployed sensors. The quadcopter detects coverage holes, identifies and investigates failures, drops new sensors at the suitable positions, relays urgent data, captures real-time video of the scene, and wakes up sensors located on the trajectory of the intruder. A quadcopter prototype was designed and tested, and served to set the parameters of the simulation.

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