Abstract—Wireless visual sensor networks can provide valuable information of the monitored field, enriching surveillance and control applications. Critical monitoring scenarios will benefit from wireless visual sensor networks, but availability must be a major design concern. For those networks, some active visual sources may fail or run out of energy, reducing the area covered by the deployed network. As applications may define a minimum acceptable visual coverage of an area of interest, availability metrics should be computed along the network lifetime. In this paper, we define the main concepts related to availability assessment for wireless visual sensor networks, for the special case of area coverage. We derive a numerical approach for computing the application availability, which may anticipate decisions when the perceived availability gets lower than the minimum acceptable level for the application.

Keywords—Wireless sensor networks, Wireless visual sensor networks, Availability, Area coverage.

1 Introduction

A large set of monitoring and control scenarios has been addressed by Wireless Sensor Networks (WSN) technologies (Yick et al., 2008). In this context, visual sensors can be employed to enrich the retrieved information with video streaming and image snapshots, but many challenges arise when dealing with visual sensor coverage, besides the stringent requirements of image and video transmissions over resource-constrained sensor networks (Almalkawi et al., 2010; Charfi et al., 2009).

Generally speaking, failures may compromise the system quality, resulting in economic losses or putting people in danger, which turns availability into a major design issue (Silva et al., 2012; Costa et al., 2014b). Hardware and coverage failures will affect the availability of Wireless Visual Sensor Networks (WVSN), reducing the quality of retrieved data or turning ineffective the current monitoring application. Some applications in WVSN may define minimum acceptable levels of monitoring availability, indicating thresholds to be considered when planning and managing visual sensor networks (Costa et al., 2014b).

Many monitoring applications based on WVSN have a high level of criticality (Silva et al., 2012; Bruneo et al., 2010). Industrial control, traffic management, rescue operations and medical assistance are some of the scenarios that require minimum availability levels. For such applications, losses of transmitted data or reduction on the visual coverage area may severely impact the overall monitoring quality (Costa and Guedes, 2010). If the current availability level is below the defined threshold, some countermeasure may be taken, as, for example, battery recharging, sensors redeployment, dynamic repositioning and visual coverage optimization (Costa et al., 2014b; Osais et al., 2010).

Visual monitoring applications will typically experience different levels of hardware failures and coverage failures (Costa et al., 2014b). A hardware failure is resulted from energy depletion, sensors harming, connection problems or faulty conditions resulted from the manufacturing process. On the other hand, coverage failures are originated when the monitoring quality of the application is somehow diminished, for example when fewer visual data packets are received or when lower quality images or videos are retrieved from the monitored field. Putting together both parameters may help to improve the availability of WVSN.

In general, availability is a characteristic of the applications, instead of the networks. As different applications will have different require-
ments concerning visual coverage and dependability (Avizienis et al., 2004), any availability metric must account the characteristics of each visual monitoring application. In this context, the way sensors view the monitored field will directly affect such metric. In fact, visual sensors networks will typically perform one of three types of coverage: area coverage, point (target) coverage or barrier coverage (Cardei and Wu, 2006). In area coverage, we are concerned with monitoring of one or more areas of the monitored field.

In this paper, we address the problem of availability assessment in wireless visual sensor networks deployed for area coverage. We propose a numerical metric to indicate the current availability level of the network, which can be used to indicate if a particular monitoring application can be considered as available.

In the last years, many works have investigated dependability issues in wireless sensor networks, addressing reliability and availability issues (Avizienis et al., 2004; Silva et al., 2012). For WVSN, additional relevant issues are related to visual coverage and optimizations (Costa and Guedes, 2010; Osais et al., 2010; Liu et al., 2003), which are directly related to availability. However, to the best of our knowledge, numerical metrics for availability assessment in wireless visual sensor networks, for the particular case of area coverage, are still missing.

The remainder of this paper is organized as follows. Section II brings some related works. Section III presents the fundamental concepts for the proposed approach. Section IV presents the proposed availability metric when considering area coverage. Some initial numerical results are discussed in Section V. At last, conclusions and references are presented.

2 Related works

In the lat years, many research efforts have been devoted to the enhancement of the performance of wireless visual sensor networks. In general, different aspects of those networks have been addressed, as multimedia data sensing (Almalkawi et al., 2010), coding (Yick et al., 2008) and transmission (Gungor and Hancke, 2009; Lee and Jung, 2010). For some of these networks, the performed monitoring tasks may be somehow critical, potentially demanding real-time and error resilient transmissions (Avizienis et al., 2004; Costa et al., 2013). In such way, critical monitoring applications may require some level of availability for the active visual sources, assuring at least a minimum level of coverage of the monitored field (Costa et al., 2014b).

In camera-enabled wireless sensor networks, availability will be a function of the active visual sources, concerning their covered area and the faulty probability of the sensors (Costa et al., 2014b). Thus, coverage and faulty assessment influence our work. In (Liu et al., 2008) authors propose a metric to assess the coverage quality of a deployed wireless visual sensor network. The proposed metric computes the probability of a randomly deployed network to be K-Coverage. In a different way, a metric to compute the coverage quality concerning point coverage is proposed in (Zhao and Cheung, 2007). Other relevant aspect is FoV overlapping, that happens when two or more cameras view the same area (Devarajan et al., 2006).

When computing availability, FoV overlapping may be exploited to define some level of redundancy among visual sensors. And such redundancy may enhance the availability level of visual monitoring applications, but the perception of redundancy depends on the application monitoring requirements (Costa et al., 2014b).

Active sensor nodes may go offline due to some failure. In short, a failure will be caused by transient or permanent faults (Avizienis et al., 2004). Transient faults are temporary and usually affect communication links, while most permanent faults result from hardware malfunctions, sensor damage or energy depletion (Silva et al., 2012; Bruneo et al., 2012). And those faults may affect the viewed area (coverage failure) or the sensor operation (hardware failure), with different impact to the application availability. In (Costa et al., 2014a), we proposed a availability metric for wireless visual sensor networks deployed for target monitoring, where coverage and hardware failures are considered.

WVSN deployed for area monitoring will be concerned with the effective area being covered by visual sensors, where sensing redundancy has a deep influence. Visual redundancy in WSN has been investigated in recent years, with promising results (Costa et al., 2014b; Costa et al., 2014c). In this context, we proposed a metric to indicate the availability level of a visual monitoring application deployed for area coverage, concerning hardware and coverage failures. To the best of our knowledge, such a metric has not been proposed before.

3 Fundamental concepts

Camera-enabled sensors can view an area of the monitored field, according to some characteristics as viewing angle and Depth of Field (DoF). In fact, the significance of the viewed area depends on the application monitoring requirements (Cardei and Wu, 2006). For a group of visual monitoring applications, sensors will be deployed to cover part or the entire considered monitored field, as for example in intrusion detection, industrial control and surveillance systems. It
is different, for example, from point monitoring, where a set of targets needs to be monitored and the monitoring quality will depend on the effectiveness of the network to view the targets defined by the application. Thus, for area coverage, availability will be related to the capability of the network to view and keep viewing areas of the monitored field.

In this context, the basic idea for monitoring quality enhancement is maximizing the total area viewed by all deployed visual sensors. As some visual sensors may fail along the network lifetime, the effective covered area by the visual sensor network may be reduced. Hence, the application availability is deeply related to the network visual coverage.

We then define that, for a monitored field \( M \), where \( |M| \) is its area, every application will define a minimum acceptable percentage of visual coverage over the monitored field, defined as \( MC \), where \( MC \leq |M| \). The deployed network will be composed of \( S \) active visual sensors, which may be homogeneous or be equipped with different camera types. As long as the sum of the current viewed area by all visual sensors, referred as the Network Coverage, \( NC \), is greater than \( MC \), the network might be assumed as available.

We define the concept of visual sensing and Coverage Unit to better address the issue of availability of monitored applications.

### 3.1 Visual sensing

Each visual sensor will be equipped with a low-power camera with a viewing angle \( \theta \), an orientation angle \( \alpha \) and a sensing radius \( R \) (approximation of the depth of field), defining a Field of View (FoV) \( (\text{FoV}) \) (Costa and Guedes, 2010). For simplification, we can define the FoV of a visual sensor as the sector of a circumference, which can be approximated by an isosceles triangle. Such triangle is composed of three vertices, \( A \), \( B \) and \( C \), where vertex \( A \), \( (Ax, Ay) \), is assumed as the current position of sensor \( s \), \( (xs, ys) \). Figure 1 presents a graphical representation of the sensors’ FoV.

![Figure 1: FoV of visual sensors.](image)

Using basic concepts of trigonometry, we can compute the FoV of a visual sensor \( s \), as expressed in (1).

\[
\text{FoV}_s = \frac{R^2 \sin(\theta_s)}{2}
\]

When addressing availability for area coverage, we want to assure that the deployed visual sensor network can view at least a minimal area \( (MC) \). Although it may seem natural to sum up all sensors’ FoV to achieve the network coverage area, the FoV of two or more sensors may overlap, indicating that those sensors can view the same region. This characteristic changes the fault tolerance of some areas viewed by visual sensors, pushing us to propose the concept of Coverage Unit.

### 3.2 Coverage Unit

An active visual sensor will view an area of the monitored field, contributing to the network coverage \( (NC) \). That area may not be viewed if the corresponding sensor becomes inactive due to some permanent failure. However, a particular area may be viewed by two different sensors and thus both sensors must fail if that area will not be viewed anymore. In such way, the application availability will be concerned to the covered areas, and not directly to the sensors.

In order to assess availability in area coverage, we propose the concept of Coverage Unit. A coverage unit \( U = (A, s_1, ..., s_n) \) is a tuple composed of an area \( A \) and a set of \( n \) sensors that completely view the area \( A \), under any perspective, where \( 0 < n \leq S \). The area \( A \) will not be viewed if and only if all set of sensors fails.

Figure 2 graphically presents some coverage units. Note that eight different coverage units are defined, where four of them are associated to only one sensor, three are associated to two sensors and only one is associated to three visual sensors.

![Figure 2: Coverage units.](image)

When a sensor \( s_1 \) is viewing the monitored field with no overlapping, it will define an unique coverage unit, which is \( U = (\text{FoV}_{s_1}, s_1) \). However, when there is some overlapping, more than one coverage unit will be defined. In general, the area \( A \) of a coverage unit \( U \) must to be the largest
area of a FoV that is viewed by the defined set of sensors. And the value of NC is computed considering only active visual sensors, summing up the areas of all coverage units.

Coverage units are computed considering sensing overlapping. Two or more sensors’ FoV overlap when the defined triangles intersect, resulting in an area that is being concurrently viewed by all those sensors. This may only happen if the Euclidean distance between any pair of visual sensors $s_1$ and $s_2$ is less than $R_{s_1} + R_{s_2}$, or $2R$ for homogeneous visual sensors, assuming $s_1 \neq s_2$.

Figure 3 presents some examples of FoV overlapping.

![FoV overlapping](image)

**Figure 3: FoV overlapping.**

FoV overlapping between visual sensors will be computed considering the vertices of sensors’ FoV, where overlapping is defined by the intersection of the considered FoV triangles (Alaei and Barcelo-Ordinas, 2010). The overlapped areas are defined by intersection vertices between sensors FoV and by vertices that are inside the FoV of other sensors.

The first step to compute the intersection vertices is finding all vertices of the sensors’ FoV, as presented in (2).

\[
\begin{align*}
Bx &= Ax + R\cdot\cos(\alpha) \\
By &= Ay + R\cdot\sin(\alpha) \\
Cx &= Ax + R\cdot\cos((\alpha + \theta)\mod 2\pi) \\
Cy &= Ay + R\cdot\sin((\alpha + \theta)\mod 2\pi)
\end{align*}
\]

(2)

With the vertices we can find the line equations of the sides of the FoV triangles, as defined in (3).

\[
\begin{align*}
\Delta A_v t B_v &= (Ax_v(By_v - y_v) + Bx_v(y_v - Ay_v)) \\
&+ x_t(Ay_v - By_v)) \\
\Delta A_v t C_v &= (Ax_v(y_v - C_{yv}) + x_t(Cy_v - Ay_v)) \\
&+ Cx_v(Ay_v - y_v)) \\
\Delta B_v t C_v &= (x_t(By_v - C_{yv}) + Bx_v(Cy_v - y_v)) \\
&+ Cx_v(y_v - By_v))
\end{align*}
\]

(3)

An intersection vertex $V$, $(Vx, Vy)$, can be found solving the line equations, for any number of neighbor visual sensors.

After finding the intersection vertices, we must check if some vertex of one considered triangle is inside the FoV of other visual sensor, as expressed in (Costa et al., 2014c), for a pair of visual sensors $s_1$ and $s_2$.

The overlapped area (if any) defined by visual sensors $s_1, s_2, ..., s_q, q \leq S$, will be formed by the intersection vertices $(V)$ and the FoV vertices that are inside the FoV of the compared FoV triangles. The overlapped area will be a polygon, $OAs_1(1,...,sn)$, composed of three, four, five or six vertices resulted from the intersection of the FoV of two or more sensors. The area of the defined polygon with $m$ vertices, $3 \leq m \leq 6$, the overlapped area can be computed according to the formulation presented in (??).

\[
OA = \frac{\sum_{i=2}^{n}(Vx_{(i-1)},Vy_{(i-1)}) + (Vx_n,Vy_1 - Vx_1,Vy_n)}{2}
\]

(4)

Then, a coverage unit that represents the area covered by both sensors $s_1$ and $s_2$ will be $U = (OA(s_1,s_2), s_1, s_2)$. In the same way, if the overlapped area is viewed by three sensors $(s_1, s_2$ and $s_3)$, we achieve $U = (OA(s_1,s_2,s_3), s_1,s_2,s_3)$. On the other hand, if sensor $s_1$ defines only one overlapped area with other sensor $s_2$, the coverage unit defined for the area exclusively viewed by sensor $s_1$ is $U = ((FoVs_1 - OA(s_1,s_2)), s_1)$.

### 3.3 Hardware failures

When estimating the overall availability level of area monitoring applications, the areas defined by coverage units will be associated to the different failure probabilities of the associated sensors.

Generally, sensors may fail due to some energy, operation or connectivity failure (Avizienis et al., 2004). Energy discharging may be modelled in different ways, considering, for example, the Peukert’s law (Omar et al., 2013) as a reference. Hardware failures originated from the manufacturing process may also be relevant. At last, when visual sensors are employed to retrieve image snapshots or video streams from the monitored field and also to relay data packets, some failure in a particular visual sensor may affect other sensors that are relying on it to relay their packets. In (Costa et al., 2014a), we modeled connectivity failures using a Fault Tree, since a faulty node may disconnect other sensors when it is acting as a relay node.

Different monitoring scenarios may have different fault conditions, and each one may be modelled in a particular way. As our proposed metric is centered at the concept of coverage unit, hardware failures may be accounted in a generic way,
since they should be adjusted for the particularities of the deployed WVSN and the way failure conditions will be modeled.

In this context, we define that each sensor $s$ has a hardware failure probability of $f_s$, which uniquely represents energy, operation and hardware failures (Costa et al., 2014b; Silva et al., 2012). It may consider energy depletion behavior, the hardware Mean Time to Fail (MTTF), the Fault Tree considering the connectivity associations and any other hardware failure. Nevertheless, we expect that $0 \geq f_s \leq 1$.

4 Proposed metric

The area covered by all active visual sensors is achieved summing up all coverage units. But each coverage unit may fail along the time, according to the failure probabilities of all sensors associated to the considered coverage unit. Then the application availability will be computed considering hardware failures of all visual and scalar sensors that directly or indirectly participate in at least one coverage unit.

We define $AU_i$ as the availability of a single coverage unit $i$, $0 < i \leq C$, for $C$ coverage units, relating the area covered by it and the failure probabilities associated to the defined set of sensors, as expressed in (5), where $A_i$ is the area of the $U_i$ viewed by $n$ sensors.

$$AU_i = A_i \times (1 - \prod_{j=0}^{n} f_j) \quad (5)$$

The overall application availability for area coverage, $MA$, will be computed as expressed in (6), which will indicate a percentage. Typically $MA \leq NC$. With that, we can assume that the network is available as long as $MA \geq MC$, indicating that the network is viewing at least the minimum area required by the application. It is important to note that the value of $f_s$ may change along the time, turning $MA$ as a metric for a specific instant of time.

$$MA = \prod_{i=0}^{C} \frac{AU_i \times 100}{|M|} \quad (6)$$

5 Initial results

The availability level of monitoring applications will depend on visual and hardware characteristics of the deployed sensors, as well as the network topology of the WVSN. In order to relate such parameters to the computed availability, $MA$, we verified different configurations and assessed the achieved results.

Figure 4 presents the value of $MA$ for different values of viewing angle ($\theta$) and sensing radius ($R$). We simulated the deployment of visual sensors in a grid-like topology where the distance between neighbor sensors in the same row or column was settled in 20m, in a desired monitored field of 300m x 300m. In that verification, we assumed a homogeneous value for hardware failure in the considered period of time, which was settled as $f_s = 0.01$. Although considering the same value for $f_s$ is an unrealistic decision, we were initially concerned with the impact of viewing parameters in the computed availability.

Figure 4: Availability for area coverage.

The viewing angle and sensing radius will affect the covered area, directly impacting the value of $MA$, as can be seen in Figure 4. Obviously, the final monitoring availability will be also impacted by the hardware failure probabilities of each visual source node and the remaining nodes that compose the active transmission paths. For this verification, we considered random orientations ($\alpha$) for the sensors, and only the average results for $MA$ after 10 consecutive tests are presented.

6 Conclusions

An overall availability metric for WVSN is hard to achieve, mainly because visual monitoring applications may have different requirements. For the special case of area coverage, the proposed metric brings a valuable resource for network design, deployment and operation.

This problem is not concluded yet. New failures conditions will be evaluated. Connectivity dependency among visual sensors will be also considered. Transient coverage failures will be evaluated, as well as permanent coverage failures as occlusion.

Acknowledgment

The authors would like to acknowledge the support of the Brazilian research agency CNPq (grant numbers 482548/2013-4 and 441459/2014-5), that partially funded this work.
References


