Virtual Fences: A Systematic Literature Review

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Abstract. Virtual fencing is a technique for animal control where a physical infrastructure is not needed to implement a fence. Control is achieved by modifying the behavior of the animal by means of one or more sensory signals, which may be auditory and/or electrical. These signals are transmitted to the animal when it tries to cross an electronically constructed boundary. This demarcation can be of any shape that respects geometric properties. While invisible to the naked eye, it is detectable by an electronic device worn by the animal. Due to its potential, this notion of virtual fencing for the management of free-range livestock is attracting growing interest in the literature. First, he advanced ecological management by transforming physical labor into cognitive labor. It is proved that there is a considerable number of methods that rely on stress in the growth of virtual fences, which can be classified in three classes: the first one is interested in virtual fences that focus on auditory stimuli, the second one is the one that depends on electrical stimuli and the third class merges both. These three categories can be divided into two classes: the first class relates to static virtual fences and the second class relates to dynamic virtual fences. The purpose of this work is to first provide an overview of the existing approaches inherent to virtual fences while noting their technical characteristics, advantages and disadvantages. Then, we compare the different virtual fencing approaches and the associated localization/delimitation techniques. Finally, we discuss the remaining challenges for optimal animal control.

Keywords: Virtual fencing · Auditory stimulus · Electrical stimulus · Auditory and electrical stimulus

1 Introduction

On the whole of the Earth, we have approximately 25% that is being exploited by pastoralists [1]. The optimization and management of pastures requires resources and labor costs. In recent years [2,3], the growth of virtual fencing systems has facilitated change in livestock management, as it has provided herders with the

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ability to supervise livestock in a flexible manner. Having the ability to keep animals in desired areas and exclude them in other areas is crucial to effective animal husbandry in the face of expanding urban spaces [4,5]. However, the words fence are used in many notions [6]. However, they all have in common the fact that the barrier or boundary is implemented by relying on non-physical objects in the landscape to modify the behavior of the animals. The concept of virtual fence appears more and more in the works relating to scientific research [7]. The virtual fence concept does not alter the landscape by introducing physical infrastructure [8]. The virtual fence is a system that allows to define and control a given perimeter without any physical barrier. The movement of the animal in the virtual fence can be defined by decision algorithms [9].

Conservationists give specific credit to this technology because of its benefits and potentials. The virtual fence overcomes some of the drawbacks of conventional [10] fences. These include the lack of flexibility and construction costs to erect and maintain physical fences. Some virtual fence approaches not only have the ability to define and readjust grazing area boundaries quickly and at low cost, but also allow remote administration through an interface by sending commands to devices. Technologies employed. It is also possible that animals can be controlled, moved or rounded up remotely [11]. In the article [12], we find a summary dealing with the virtual fence and a very interesting overview in this field of research. The purpose of this study is to provide a more detailed overview of the different concepts and technologies related to virtual fences found in the literature.

In this article, we study virtual fences while emphasizing the different stimulus techniques used to control animals. The essential complements of our work are summarized as follows:

We present a specific classification of virtual fences taking into account the physical and logical requirements, the characteristics of the fences, the diversity of areas and seasons. Driven by advances in the field of IoT, virtual fencing covers almost every aspect of animal life. We expect a clear taxonomy to provide readers with the information needed to better understand these innovative technologies; an overview will be described on localization algorithms, the most used proactive protocols showing their strengths and weaknesses [9,13]; a technical comparison and the evolution (Cf. Fig. 1) of the different virtual location fences is presented to put their properties into perspective.

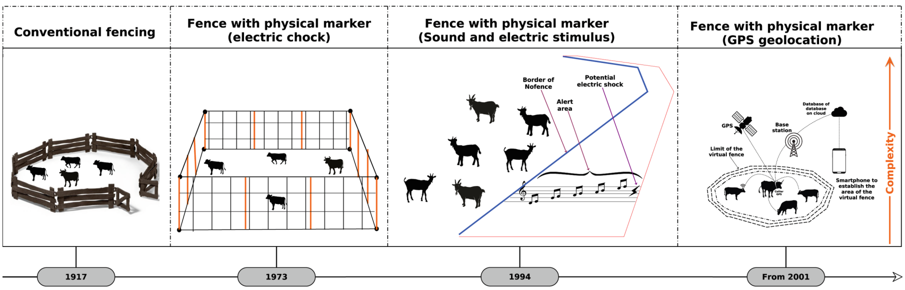

Fig. 1. Evolution of cattle fences

1.1 Study Process

It is important to overview how this research was carried out in order to better understand the documents used in the context of this review. We enumerate below the research questions. Section 1.2 explains the search process with the selection criteria for the relevant literature. The main objective of this review is to provide an overview of existing approaches to the development of virtual fences. For an article to be considered relevant, it must meet a number of criteria formulated by the following questions:

Question 1: What are the recent studies on this topic? Are there any previous studies showing the benefits of virtual fencing?
Question 2: What can be achieved by monitoring animals through technologies associated with virtual fencing?
Question 3: What are the limitations of monitoring animals using virtual fences? Are there still opportunities to explore for optimizing livestock management through virtual fencing?

The purpose of this study is to demonstrate the potential of virtual fences to achieve better management of domestic and free-ranging animal resources.

1.2 Method

To obtain articles deemed relevant for this literature review, we performed search queries on major databases (IEEE Xplore, ACM, Springer, Google Scholar, ResearchGate and ScienceDircet). Table 1 shows the results.

Table 1. Search queries for scientific databases

Databases	Queries
IEEE Xplore	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)
ACM	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)
Springer	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)
Google Scholar	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)
ResearchGate	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)
ScienceDirect	(“virtual fencing”) AND (“Livestock Tracking Or Livestock Tracking Algorithm”) AND (“Scope of virtual fencing”)

During our various researches, it was observed that it was necessary to delete certain keywords in the queries when the results obtained are not related to the theme sought. In this journal, searches were conducted from January 2022. Another criterion for retrieving relevant information was to select only papers published in indexed and abstracted journals with a high impact factor or academic repositories. The main objective is the use of Google Scholar to obtain information in IEEE Xplore, ACM, Springer.

1.2.1 Selection of Publications: The search was successful to varying degrees on the various databases mentioned above. These results are presented in the Table 2.

For each article encountered, we proceeded to read and analyze its title, its summary, its results in order to ensure its relevance and to produce a summary. We also systematically checked the impact factor of the journals in which the articles are published. The process of selecting or rejecting a scientific article after reading the above points obeys the rules below and is illustrated in Fig. 2.

Rule 1 : Select only publications whose primary purpose is to locate or monitor animals;
Rule 2 : Consider only articles selected in English;
Rule 3 : Select articles that rely on virtual fencing technology, excluding those that are not published in serious journals or sources;
Rule 4 : Do not consider virtual fencing technology used for anything other than animal monitoring or control so as not to confuse the concepts and thus prejudice the results of this study.

1.2.2 Collection of Articles: Once we have read the title and abstract of an article, and it seems relevant, the next step is to read it in its entirety (introduction, results, discussion and conclusion).

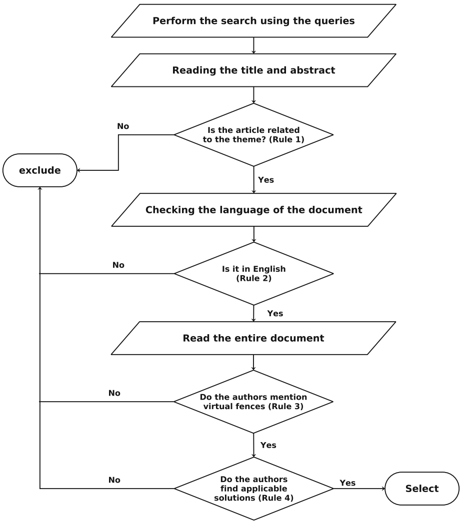

Fig. 2. Process for identifying relevant articles

Table 2. Summary of research results

Databases / logs	Number of search results	Number of documents selected for a complete reading	Number of documents deemed relevant
IEEE Xplore	37	32	29
ACM	21	13	6
Springer	26	16	11
Google Scholar	29	22	20
ResearchGate	16	11	7
ScienceDirect	57	13	2
Total	**141**	**101**	**79**

2 Related Works

The related work is shown in this section. We are indeed emphasizing the research work of the existing literature, our research on the different types of virtual fences and the most important location algorithms. Additionally, the articles explored in this study provide a practical implementation of the animal management model. We review the static and dynamic models that have been tested on cattle and others on sheep.

To overcome the problems related to livestock management, the studies carried out in the articles [11,14–20] on virtual fences have been presented to show how these are essential for grazing management.

With this in mind, we summarize recent comparative studies of virtual fences [21]. Ayesha *et al.* [22,23] discuss location-based protocols for livestock management. They explain that the problem arises when transferring data when used in mountainous or riverine areas. In addition, they point out performance issues with each deployment method.

Highland *end al.* [17,24,25] conducted a comprehensive study of positioning algorithms based on GPS (Global Positioning System or Personal Navigation Assistance System). They categorized them according to their goals and methods. Therefore, the authors provide a detailed classification of virtual fences based on existing research.

In the articles [17,26], the authors make an in-depth study of virtual fences in various applications. They describe the objectives of virtual fences for good animal management and elaborate their new classification. Beforehand, the properties of virtual fences with auditory and electrical stimulation, virtual fences with acoustic stimulation and virtual fences based on the auditory signal. The second concerns the characteristics of the virtual fence using the Internet of Things. The third point concerns dynamic and static virtual fences. They also ranked location algorithms by area to prove that virtual fences are far more valuable than traditional fences.

Zach Butler *et al.* [21,27–31] describe the solutions offered by virtual fences in animal management, taking into account their requirements. They classified the applications of virtual fences according to their properties. These properties are related to the range of the signal emitted by the electronic device, the quality of service, security and mobility. Then, considering these properties, they propose a new classification of the latter. Finally, they divided virtual fences into two categories: virtual fences with a physical marker and virtual fences without a physical marker.

Aquilani *et al.* [32,33] presented the advantages and disadvantages of virtual fences. They recommend considering both different location techniques and mobility when designing an algorithm. Danila *et al.* [34] examined the question of the location system, especially in the context of retail management using virtual fencing technology could be very effective in animal monitoring. The authors also listed virtual fence approaches based on their applications and implementation. Accordingly, they analyzed the virtual fence characteristics as a function of the battery life of device worn by the animal [35]. Dana LM *et al.* [21,36] provide a detailed study that focuses on the comparison of virtual fencing based on localization techniques and warning signs.

Otabek *et al* . [13,29] conducted an enriching review including tracking protocols and algorithms using a comprehensive performance-based comparison and application hypotheses showing their effects on animal welfare. They presented a classification of these protocols according to geolocation techniques.

To highlight the uniqueness of this study, a comparison of related work is summarized in Table 3.

Table 3. Comparative table of related works

Ref.	Brief description	Stimulus			Type of fence			Controlled Animal	Animal welfare
		Sound	Sound + Electric	Electric	conventional	Électric	Virtual		
Marini et *al.* [21]	The use of a virtual fence to restrict sheep access to pastures for effective pasture management is presented in this work.	×	√	×	×	×	√	Sheep	+ + ++
Fogarty et *al.* [35]	A quantitative and systematic methodology study is conducted to examine how sensors have been applied in precision technology to revolutionize livestock management.	?	?	?	?	?	?	Sheep	++
Umstatter et *al.* [10]	The article critically analyzes the progress made to date and highlights the benefits and challenges of virtual fences.	√	√	√	√	√	√	All	− − −

- (+) : more benefits or fewer concerns;
- (−): fewer benefit or more concern;
- (?) : Requires more research;
- (√) : Accepted or supported;
- (×) : Not accepted or supported.

In the light of comparison on the most recent related works presented in the table above (Cf. Table 3). It appears that the above-mentioned journals are very enriching in relation to this theme. There are other slightly older works, the majority of which are already taken into account in [10].

2.1 Contributions

In this work,

1° We review the various works inherent to virtual fencing, in particular for the management and monitoring of livestock, which have been proposed in the literature. We highlight the evolutions, the advantages and their disadvantages relating to the different virtual approaches.
2° We provide an extensive and detailed discussion of the various techniques and technologies that can be used for livestock tracking. We will highlight their advantages and disadvantages while specifying the relevance and challenges associated with animal localization techniques.
3° Due to recent concepts related to livestock management, we present an introduction and discuss some emerging technologies that optimize animal management. We conclude, based on our analysis, that emerging virtual fencing technologies can provide innovative solutions on pastoral management.
4° This work also discusses the applications of virtual fences and the various challenges they currently face.

2.2 Acronyms

The acronyms contained in this article are presented in the Table 4 in order to facilitate its reading.

Table 4. List of acronyms used in this review

Acronym	Description
GPS	Global Positioning System
IoT	Internet of Things
WGS84	World Geodetic System 1984
DTN	Delay Tolerant Networks
MANET	Mobile Ad hoc Network
ToA	Time-of-Arrival
TDoA	Time-Difference-of-Arrival
RSSI	Received Signal Strength Indicator
AoA	Angles of arrival
RToF	Return Time of Flight
NB-IoT	Narrowband Internet of Things
LoRa	Long Range Area
LoRaWAN	Long Range Area-Wide Network
MAC	Media Access Control
DBSCAN	Density-Based Spatial Clustering of Applications with Nois
WSN	Wireless Sensor Networks
NFC	Near Field Communication

2.3 Advantages of Virtual Fencing Comparing to Conventional Fencing

Virtual fences offer the possibility of improving the efficiency of grazing management. Their major advantages are the flexibility and optimal management of stocking density they can provide. Conventional fencing is limited and expensive when it comes to managing large areas of pasture. Conventional paddocks or electric fences are the most common primary means of livestock control in developed countries. Conventional pens or electric fencing are the most common primary means of livestock control in developed countries. Conventional fences are not scalable. This inflexibility does not accommodate seasonal changes or times when animals must be excluded in certain areas. We offer a comparison in Table 5 between the different paradigms used in animal control.

Table 5. Advantages and disadvantages of fencing

Type of fence	Advantages	Disadvantages
Conventional fencing	-Perceptible by animals.	- Difficult to modulate; - Little flexibility in its management; - Implementation is expensive; - Maintenance is expensive; - Possibility of harming wild animals; - Barbed wire can cause serious health issues.
Electric fence	- More flexible than wire fences; - Easy to implement on steep areas; - Suitable for many species; - The risk of injury to animals is reduced.	- High maintenance cost; - Absence of a remote monitoring mechanism; - Electric wires can trap animals and they can die
Virtual fence	- Can be very flexible; - Modular and manageable remotely; - Controls and monitors animals remotely; - Opens interesting perspectives.	- Difficult to see for animals; - Hazardous to humans; - Presenting risks for animals

Table 6. Technical comparison of animal fences

Réf.	Type of fence	Stimulus			Remote monitoring	Cost in terms of implementation	Localization technology	Need for Internet	Visible to the naked eye	Animal welfare
		Sound	Sound and electric	Electric						
[10]	Conventional fencing	×	×	×	×	+ + +	− − −	− − −	+ + +	+/ − −−
[37,38]	Electric fencing	×	×	√	×	++	−−	− − −	+ + /−	◑
[39,40]	Virtual Fence	√	√	√	−	?	++	+ + +	++	◑

- (+): more benefits or less worries;
- (−): less benefit or more worry;
- (?): Needs more research;
- (√): Accepted or supported;
- (×): Not accepted or not supported;
- (◑): Partially satisfactory.

Virtual fences are applied in several areas including precision agriculture and pet management [41]. We present in Table 6 the main techniques used to control the animals and compare their features.

2.4 (Types of Virtual Fences)

A virtual fence is a logical boundary with no physical infrastructure fixed to the ground. It is a particularly interesting concept because of its potential to transform livestock management, making it simpler and more flexible. There are multiple approaches to virtual fencing that provide an effective means of animal control. In the following points, we describe the different techniques used to erect virtual fences.

A) **Stimulus-based virtual fences**
Virtual fences have the potential to significantly change animal behavior and improve pasture management. Traditional enclosures such as chain-link fences and electric fences are widely used in many countries around the world [42]. Vidya NL *et al.* explain that this fence is expensive, difficult to implement and vulnerable to damage that can be caused by the weather. They point out that virtual fencing not only offers producers a more cost-effective, low-maintenance solution, but also an efficient way to move animals from one area to another, simply by logically readjusting the boundaries of the fence. [7,14,43]. For their part, *Juliana Ranches* and *Rory O'Connor* claim that in the different experiments, the animals are trained in advance to distinguish between the different stimuli. The auditory stimulus is applied when the animal approaches the fence and the electrical stimulus is only applied if the animal continues to move forward within the boundary of the fence despite having received the first stimulus [44].
Danila Marini *et al.* determined the importance of the auditory warning signal in an open pen and tested whether the criterion can affect the ability of sheep to learn virtual fencing [45]. They demonstrated that virtual fence training impacted the ability of sheep to learn to respond correctly to an auditory cue associated with an electrical stimulus. However, they were not able to confirm in their experiment that the character can have a change in learning. They claim that during electrical stimulus training, more than 70% of sheep appeared not to learn to respond correctly to auditory cues after several [31] trials. They conclude that animals that learned to avoid the virtual fence through auditory cues associated with electrical stimuli displayed interesting behaviors compared to animals that received only the electrical stimulus [46,47].
For their part, Marek Doniec *et al.* [48] carried out an experiment to spot cows with auditory and electrical stimuli. They proposed an algorithm for gathering by an auditory stimulus.

Algorithm 1: Gathering by an auditory stimulus

```
while |P_{cow,i} − P_{goal}| > ε do
    SOUND (t_{sound})
    WAIT(t_{wait})
```

Algorithm 2: Gathering by auditory and electrical stimuli

```
while |P_{cow,i} − P_{goal}| > ε do
    SOUND (t_{sound})
    if cow_{speed==0} then
        SHOCK(t_{shock})
        WAIT(t_{wait})
    else
        WAIT(t_{wait})
```

The authors proposed a second algorithm for herding cows with auditory and electrical stimuli. This second algorithm is the extension of the Algorithm 1 which only uses auditory signals. If the cow does not move after the broadcast of an auditory signal, the Algorithm 2 applies an electrical stimulus to it.

Still in their experience, the authors point out that it is difficult to predict the behavior of cattle during a thunderstorm using the Algorithm 2. In such a case, the electrical stimuli can bring the cows together increasing the level of stress. Based on this observation, they propose a third algorithm as an extension of the first two (Algorithms 1 and 2). The Algorithm 3 adapts the frequency and the intensity of the signals to the behavior of the animal. The algorithm has the ability to stop both signals as soon as the animal starts to react.

Algorithm 3: Gathering by adaptive sound and electrical stimuli

```
intensity = 0.1;
while |P_{cow,i} − P_{goal}| > ϵ do
    if cow_{speed==0} then
        SOUND (t_{sound})
        if intensity > 0.3 then
            SHOCK(t_{shock}, intensity)
        intensity = min(1.0, intensity + 0.1)
    else
        intensity = max(0.1, intensity − 0.1)
    WAIT(t_{wait})
```

In the article [33], the authors carried out an experiment on a group of ten cattle wearing an electronic device in the form of a collar in order to exclude them from a riparian zone. In their experiment conducted on an automated virtual fence, they found an interaction between the animals and the fence. Auditory signals and pulsed electrical stimuli vary from individual to individual [4]. The authors show that the animals learned to react differently between auditory and electrical stimuli.

In the work of Néstor Acosta *et al.* [11], the authors presented the procedures for designing a platform virtual confinement of animals based on auditory and tactile stimuli. Auditory and tactile stimuli make this platform compatible with animal welfare. They maintain that the main contribution of their work is the creation of this research platform on virtual animal confinement techniques. They also performed tests to verify that the entire system is working properly. They conclude that they are confident that after a period of training, the combination of auditory and tactile stimuli can cause cattle to remain confined inside the virtual fence.

B) **IoT-based virtual fences**

The IoT is a concept that provides interconnection via the Internet of devices to collect, share and analyze data for innovative applications [49]. Bernard *et al.* asserted that the IoT is considered an evolution of the Internet. It collects, transmits, distributes, detects and analyzes large-scale [50] data. They point out that all these possibilities offered by the IoT can be exploited for good livestock management. The IoT enables remotely controlled operations with sensors to monitor animals [51]. They claim that virtual fences can be reconciled with this technology for better livestock management [19]. Luís Nóbrega *et al.* [52] set out an animal behavior monitoring platform based on IoT technology. This platform contains a local IoT network to collect animal data. It has the ability to do processing and storage while providing machine learning capabilities.

C) **Virtual fences using GPS**

Virtual fences have been studied for several years to replace the physical barriers used for animal confinement and have considerable advantages. They are generally implemented with an electronic device carried by an animal, with a GPS and means to deliver a sensory stimulus (auditory or electrical) to the animal to prevent it from crossing the pre-established limits. Azamjon Muminov *et al.* [17] presented in their work that virtual fences can be added or removed at any time and several of them can be created at once from information stored in a database. When GPS readings indicate that an animal has crossed the boundary of the fence, an auditory or electrical stimulus is triggered. They introduced an algorithm for measuring the distance between the animal and the virtual fence. They introduce the use of Google Maps and the Spherical Mercator projection method based on WGS84 in the virtual fence system [53,54].

$$\overline{AB} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{1}$$

Otabek Sattarov *et al.* [55] introduced a notion of distance estimation using GPS data. To achieve their objective, they point out that it is necessary to have a technique for measuring the distance between two GPS points. In general, the closest distance between two points $A(x_1, y_1)$ and $B(x_2, y_2)$ is calculated by the formula of the Eq. (1) presented in the article citemuminov2019modern .

To solve this problem, they turn to a frequently used algorithm called Haversine [56], and to the Google Maps API, which provides out-of-the-box functions that can be used.The Haversine [56] technique. The Haversine technique is applied to measure the length of two geolocations on the Earth's surface. To determine the distance between two points, we use the principle of the Haversine method illustrated in Fig. 3.

$$hav\left(\frac{d}{r}\right) = hav(\varphi_1 - \varphi_2) + \cos\varphi_1 \times \cos\varphi_2 \times hav(\lambda_2 - \lambda_1) \tag{2}$$

where h is the haversine function, d is the central angle between two points located on the great circle, r is the radius of the sphere, φ_1 and φ_2 are the latitude of the first and second point in radians, λ_1 and λ_2 are the longitude of the first and second point in radians [57,58].

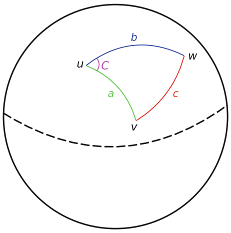

Fig. 3. Illustration of the haversine law

- u, v, and w: three points on the sphere;
- a: length (from u to v);
- b: length (from u to w);
- c: length (from w to v);
- C: the angle of the corner opposite c.

The ratio $bigg(\frac{d}{r}\Bigg)$ of the Eq. (2) allows to know the distance d [57,58].

$$d = 2r \bullet arcsin\left(\sqrt{sin^2\left(\frac{\Delta latt}{2}\right) + \cos(latt_1)\cos(latt_2)sin^2\left(\frac{\Delta long}{2}\right)}\right) \quad (3)$$

D) **Virtual fences based on wireless sensor networks**
Real-time data collection requires the use of wireless sensor networks [59,60]. Virtual fences replace physical barriers and gather cows based on stimuli (auditory or electrical signals). In the paper [61], the authors provided an overview of a wireless sensor network system to collect and analyze data collected on cow behaviors. They implemented an Algorithm 4 that runs locally on each device.

Algorithm 4: Data processing on each device

procédure
Update bin count $\forall i \in B$
$x_{i,t} \leftarrow \gamma . x_{i,t-1} + b(i, z_t)$
Update bin distribution (simplify) $\forall i \in B$
$y_{i,t} \leftarrow x_{i,t} / \sum_{i \in B x_{i,t}}$
$y\prime \leftarrow$ *previous significant distribution at time* $t\prime$
if $\exists i \in B : \left| y_{i,t} - y\prime_i \right| > \epsilon \ or \ t - t\prime \geq t_{heartbeat}$ **then**
  Update $y\prime \leftarrow y_t$ and $t\prime \leftarrow t$
  Estimate new state
  $s_{t\prime} \leftarrow f(DT, y_t)$
  Eventful ?
    Yes, if state differs from last update
      Store in Flash state s t and time t

To validate the method they proposed, the authors collect the data on three axes at a sampling rate 1 Hz. The data collected is X, Y when the animal is throughout the l axis, and Z when placed horizontally on a flat surface. These data are used to calculate the acceleration of each animal along the axes X, Y and Z by the following formula:

$$a_{total} = \sqrt{a_X^2 + a_Y^2 + a_Z^2} \quad (4)$$

Ryo Yamamoto *et al.* [62] brought a new information localization method for the dissemination of geolocation data with ad hoc communication. They also suggested a new local storage architecture to accomplish information dissemination using the geo-fence concept [63], using DTN and MANET technologies [64].

Each endpoint moves according to a specific policy while being able to communicate with others. In addition, each terminal contributes to the development of the network and regularly exchanges *HELLO* messages with the other terminals.

E) **Dynamic virtual fence** *vs* **Static virtual fence**

Virtual fences are little explored concepts. It is a computer-animal interaction based on many [29] concepts. These are devices that impel stimuli (auditory or electrical signals) to an animal based on its position relative to one or more fence lines. The establishment of virtual fences is done with a computer device sensitive to the movement made by the animal, called a smart collar. Apart from the dynamic virtual fences which ensure the continuity of pasture management service and the static ones which are fixed to the ground, there are also virtual fences that support nomadism. Unlike dynamic virtual fences, these do not allow continuity of service when changing location.

(a) **Dynamic virtual fences**

In the work of Zack Butler *et al.* [29], the authors explain that the real power of virtual fences emerges when they are dynamic and can move in the landscape. They point out that this is a problem of animal movement planning. They tested dynamic virtual fences. Their test resulted in interesting prospects. The results they obtained are confirmed by the work of Magnus Fjord Aaser *et al.* [65]

Z. Butler *et al.* [15] described that a Virtual fence is created by applying a warning stimulus to an animal when it approaches a predefined boundary. It is implemented by a small computer system carried by the animal with a GPS receiver. This approach makes it possible to consider animals as agents with controllable natural mobility and to have a planning of animal movement. It should be noted that dynamic virtual fences can have variable dimensions and several geometric shapes [66].

(b) **Static virtual fences**

Virtual fences are technologies that use the GPS device built into an electronic collar worn by an animal to keep it in a given area. MO Monod *et al.* [4] stated a virtual fence based on a principle of electromagnetic coupling. The fence is a looped insulated wire unrolled on the ground around the animals. An electromagnetic field is created and coupled to

a device (collar) worn by each animal. When the signal from the fence is detected by the collar, a behavioral algorithm decides what action to apply to the animal to prevent it from crossing the wire. They point out that they have found that the animals need to be trained for half a day in order to familiarize them with the fence.
In order to put related work into perspective and determine their strengths and weaknesses, we propose in the two Tables 7 and 8 a technical comparison of different types of fences and a summary of the advantages and disadvantages of virtual fences compared to the different notions mentioned above in Sect. 2.4 (Fig. 4).

Table 7. Technical comparison of different types of fences

Réf.	Type of virtual fences	Localization technologies	Data storage	Ground device	Visibility	Type of stimulus
[46,67]	Sound stimulus	GPS	Local	No	No	Auditory signals
[67]	Electrical stimulus	GPS	Local	No	No	Electrical signals
[42,67,68]	Sound and electrical stimuli	GPS	Local	No	No	Auditory or electrical signals
[69]	IoT	GPS	Local	No	No	Auditory or electrical signals
[11,22]	GPS	GPS	Central server	No	No	Auditory and electrical signals
[15,16]	Dynamics	GPS	Local/cloud	No	No	Auditory and electrical signals
[16,70]	Static	GPS	Local/cloud	No	No	Electrical signals
[61,62]	WSN	GPS	Cloud	No	No	Auditory or electrical signals

Table 8. Advantages and disadvantages of fences

Type	Advantages	Disadvantages
Stimulus	Easy implementation	Sometimes immobile
IoT	Remote control: flexible management	Need for Internet
GPS	No physical barrier	Animal must wear an electronic device
Mobility	Adaptable to the landscape	Animal must wear an electronic device
WSN	Remote control: flexible management	Internet required

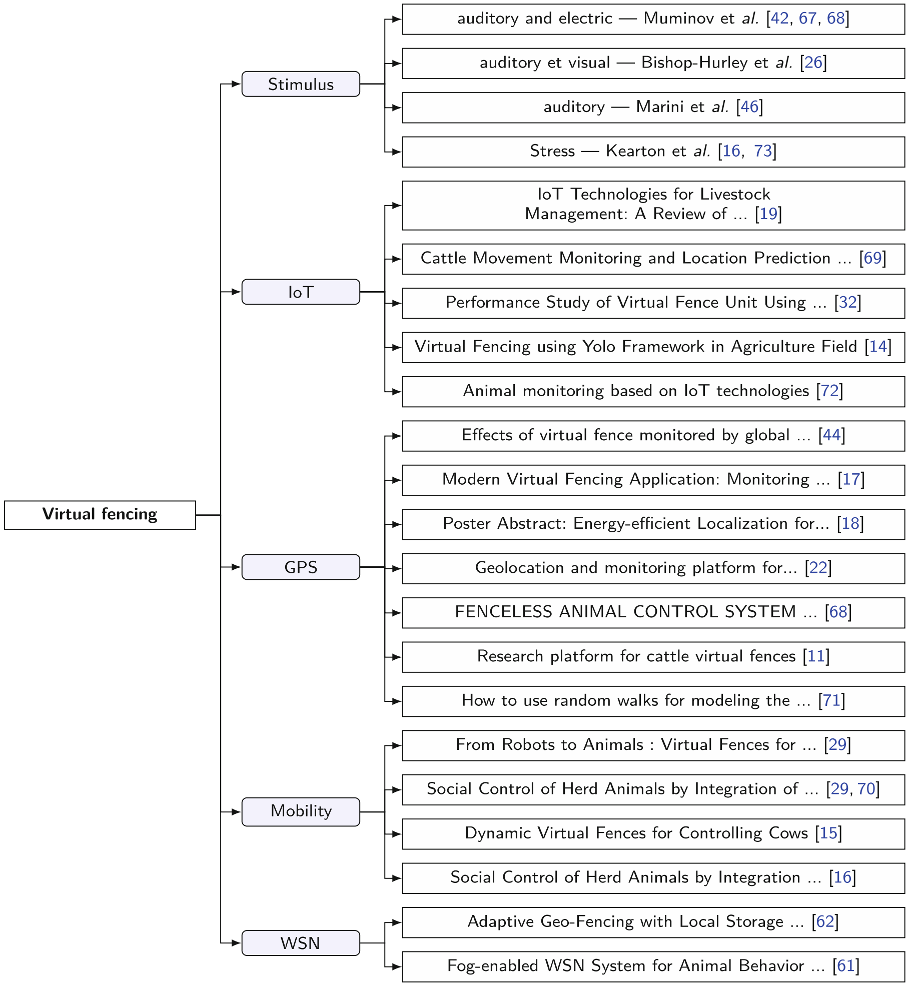

Fig. 4. Taxonomy of virtual fences

3 Location of Livestock

Locating livestock using sensor nodes is an essential process for tracking and monitoring animals. It should be noted that there are several techniques and technologies used in livestock tracking, especially in pasture management. However, we focus on those that are major and most cited in the literature.

The Fig. 5 represents the taxonomy of the concepts and technologies used in the localization of animals or mobile objects.

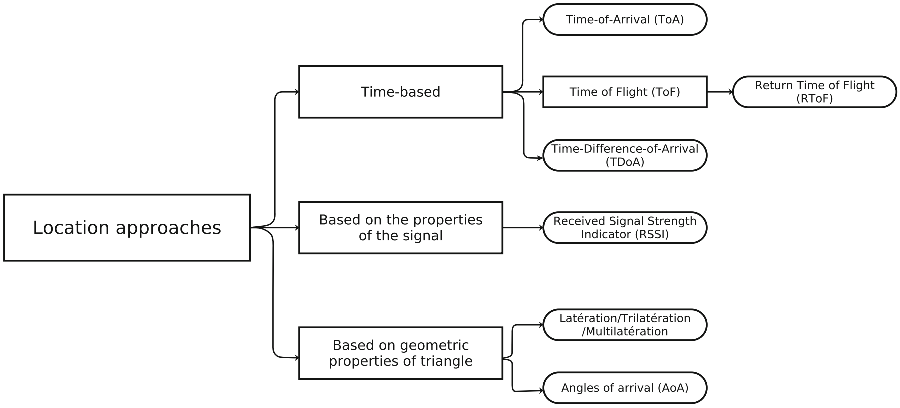

Fig. 5. Taxonomy of approaches for locating animals and/or mobile objects

3.1 Conceptual Approaches to Locating Livestock

Localization techniques have made rapid progress. Several localization systems have indeed been developed for various needs. One of the best known systems is GPS. GPS is an extremely efficient technology that has been continuously evolving for years.

(a) **Time-of-Arrival (ToA)**
SEBASTIAN SADOWSKI *et al.* [74–78] have used the so-called "Time-of-Arrival (ToA)" localization technique which consists of calculating the distance between the transmitter and the receiver based on a clock synchronized between the signals transmitted and the signals received. They point out that *ToA* is one of the most accurate techniques available that can provide localization with high [76] accuracy.

$$\sqrt{(x_2 - x)^2 (y_2 - y)^2} = v(t_2 - t_0) \quad (5)$$

$$\sqrt{(x_3 - x)^2 (y_3 - y)^2} = v(t_3 - t_0) \quad (6)$$

$$\sqrt{(x_4 - x)^2 (y_4 - y)^2} = v(t_4 - t_0) \quad (7)$$

The sender broadcasts a time-stamped message whose header indicates the time and date the message was received. They illustrate the ToA technique by the Fig. 6.

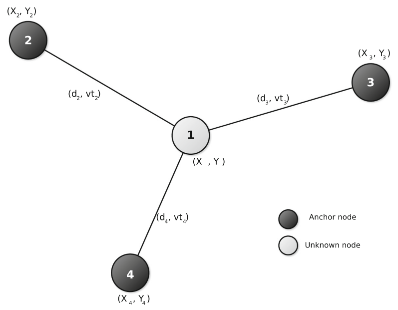

Fig. 6. Illustration of the ToA scheme

(b) **Time-Difference-of-Arrival**
In the articles [53,79], the authors state the so-called Time-Difference-of-Arrival (TDoA) concept based on the differences in arrival times between anchor nodes.

$$\sqrt{(x_2 - x)^2(y_2 - y)^2} - \sqrt{(x_3 - x)^2(y_3 - y)^2} = v(t_2 - t_3) \tag{8}$$

$$\sqrt{(x_2 - x)^2(y_2 - y)^2} - \sqrt{(x_4 - x)^2(y_4 - y)^2} = v(t_2 - t_4) \tag{9}$$

In Fig. 7, the distances are calculated as a function of the propagation times. The efficiency of this approach can be impacted by the delay that the transmitted signal can have.

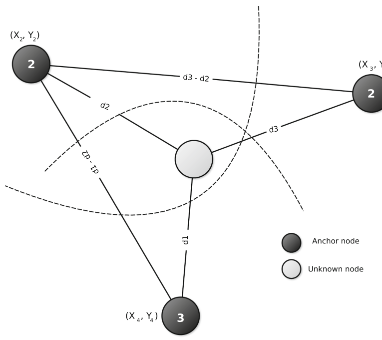

Fig. 7. Time-Difference-of-Arrival (TDoA)

(c) **Received Signal Strength Indicator (RSSI)**
Rajika Kumarasiri*et al.* [75,80] propose a localization technique based on the Received Signal Strength Indicator (RSSI) concept. This concept has received a lot of attention in recent years. The concept of RSSI is commonly used for target detection, but also for locating and tracking animals [81]. However, it must be specified that the measurement of the intensity of the

received signal is very sensitive to interference and can therefore undergo significant deviations from one measurement to another.
To relate RSSI values to distance the following, equation is used :

$$RSSI = -10n\log_{10}(d) + C \tag{10}$$

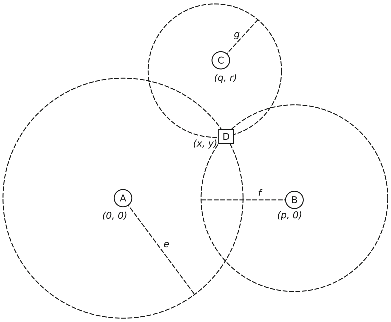

Fig. 8. RSSI - Received Signal Strength Indicator

In the paper [74], the authors presented a schematic of a trilateration experiment shown in Fig. 8.

$$e^2 = x^2 + y^2 \tag{11}$$

$$f^2 = (x-p)^2 + y^2 \tag{12}$$

$$g^2 = (x-q)^2 + (y-r)^2 \tag{13}$$

By solving the system of equations, we get:

$$x = \frac{e^2 - f^2 + p^2}{2p} \tag{14}$$

$$y = \frac{e^2 - g^2 + q^2 + r^2}{2r} - \frac{q}{r}x \tag{15}$$

(d) **Angle-of-Arrival (AoA)**
In the articles [79,82], the authors introduced the Angle-of-Arrival (AoA) technique based on the triangulation method and requires the use of two anchor nodes. The distance between the two anchor nodes is known (d) as shown in Fig. 9. Each anchor node calculates the angle of arrival of the received signal. The height h of the received signal is calculated using the following equation:

$$h = \frac{d\ \sin(\varnothing 1)\sin(\varnothing 2)}{\sin(\varnothing 1 + \varnothing 2)} \tag{16}$$

The distances between the target and the reference points are determined as follows:

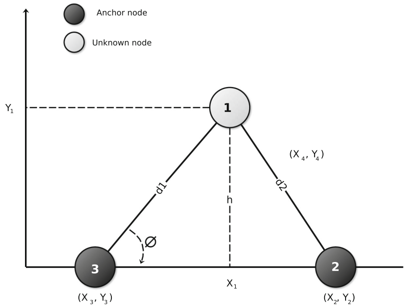

Fig. 9. Angles of arrival (AoA)

$$d1 = \frac{h}{\sin(\varnothing 1)} \tag{17}$$

$$d2 = \frac{h}{\sin(\varnothing 2)} \tag{18}$$

The authors conclude that the position estimation is made by the intersection of these distances in the direction of the two calculated angles, i.e. a triangulation is performed in order to determine the position of the receiver.

(e) **Return Time of Flight (RToF)**
Faheem Zafari *et al.* [78] presented the Return Time of Flight (RToF) localization technique. It is used to measure the propagation time of the round trip signal (transmitter-receiver) to estimate the distance between T_x and R_x. Upon receiving a signal from the transmitter, the receiver responds and calculates the total ToA of the round trip. The main advantage of $RToF$ over ToA is that clock synchronization between T_x and R_x is required.
The important problem of $RToF$ based systems is the response delay at the receiver, which strongly depends on the technical aspects of the receiver. This factor can be neglected if the propagation delay between transmitter and receiver is large compared to the response time, but the delay cannot be ignored in short range systems (Fig. 10).

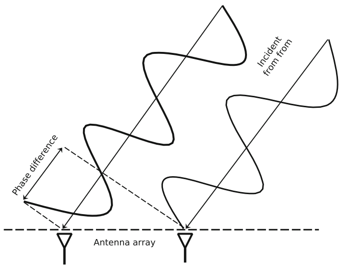

Fig. 10. Localization based on RToF

Let t_1 be the time T_{x_i} sends a message to R_{x_j} which receives it at t_2 where $t_2 = t_1 + t_p$. j, at time $t3$, transmits a signal back to i which receives it at t_4 Thus, the distance between i and j can be calculated using the Eq. (19).

$$D_{ij} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} \times v \tag{19}$$

(f) **Triangulation**

Song Chai *et al.* [83] proposed a positioning algorithm implemented in Java using the Android SDK and executable on a mobile phone. They used the [84] "Kalman filtering" method and the RSSI to determine the distance between the target and the reference point.

Once the mobile device connects to the three remote beacons, triangulation is performed to determine its coordinates. Three circles, centered on each beacon as shown in Fig. 11. The location of the triangulation is the centroid of the triangle ABC, which consists of chords of intersection of three circles.

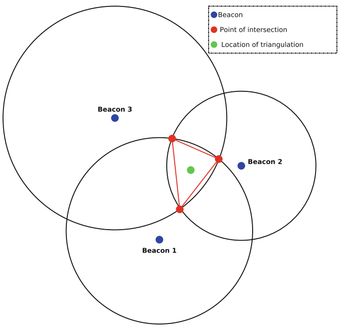

Fig. 11. Triangulation using three beacons

The positioning algorithm based on Kalman filtering is as follows:

Algorithm 5: Kalman filtering

```
Initial A , H , r , p , q and d ;
while true do
    Input dist ;
    d = A × d ;
    p = A × A × p + q ;
    gain = (p×H) / (p×H×+r) ;
    p = (1 − gain × H) × p ;
    d = d + gain × (dist − H × d) ;
    Output d ;
```

In the article [85], Thurmond *et al.* state that localization techniques have evolved over time. However, they have advantages and disadvantages which are presented in the table.

(g) **Multilateration**

Asif Iqbal Baba *et al.* [86] have shown the importance of the multilateration technique. They explain that localization is a process of obtaining information about the location (of an object or animal) using nodes that already have the information.

To measure distances between nodes, the authors use the time-of-flight (ToF) ranging technique [78]. These distance measurements are then used by the multilateration technique which requires distance measurements between three or more nodes to estimate the location.

Multilateration consists of calculating a position according to the distances relative to reference positions. They illustrated this basic idea multilateration using Fig. 12.

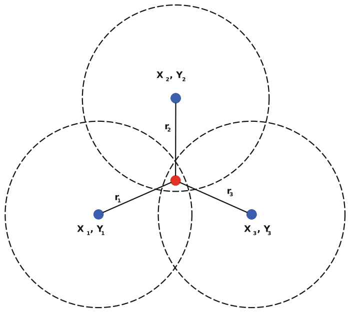

Fig. 12. Illustration of multilateration

$$position = \left(A_T \times A\right)^{-1} A^T \times b \tag{20}$$

The authors specify that the position is determined by the Eq. (20). If $A_T A$ is a singular matrix, that means the starting point nodes are placed on a line, then the equation becomes invalid. The lower the number of starting points used, the greater the difference [87].

3.2 Localization Algorithms

Davide Cannizzaro *et al.* [75,88–92] examined in their work a distance-based algorithm and three (3) algorithms that rely on fingerprints. Consistent with their writings, the authors studied these algorithms as those that provide the most consistent results in different types of environments.

The algorithms represented in this subsection are among the most used methods in the process of locating animals and moving objects.

A) **Trilateration algorithm**

The trilateration algorithm shown in Fig. 13 is a sophisticated version of triangulation that directly calculates the distance from the target object, rather than indirectly through the angles. Still in Fig. 13, U is the known distance between beacon B_1 and B_2, while V_x and V_y are the coordinates of beacon B_3 with respect to B_1 . The radii of the three circles, obtained from the RSSI measurements are r_1, r_2 and r_3. With this notation, the coordinates of the object P in a space $2D$ are calculated using the following equations:

$$V^2 = V_x^2 + V_y^2 \tag{21}$$

$$x = \frac{r_1^2 - r_2^2 - U^2}{2U} \tag{22}$$

$$y = \frac{r_1^2 - r_3^2 + V^2 - 2V_x x}{2V_y} \tag{23}$$

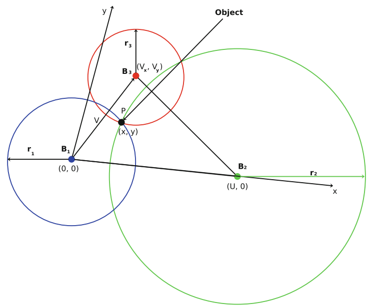

Fig. 13. Trilateration algorithm for locating objects using three tags $B1$, $B2$ and $B3$

In the same vein on the concept of trilateration, Xiantao Zeng *et al.* [93] have proposed an algorithm (Algorithm 6) for trilateral localization. The trilateral location algorithm is the most common distance-based method, while having simple and efficient characteristics, while the distance measurement error between nodes is smaller. They achieve higher location accuracy. The trilateral localization algorithm proposed by the authors is as follows:

Algorithm 6: Trilateral location

Input: neighbor_anchor_list (alias as node) ;
Initialize: $index = 0$, $count = size(node)$;
for $i = 1$ *to count* $- 2$ **do**
    for $j = i + 1$ *to count* $- 1$ **do**
        for $k = j + 1$ *to count* **do**
            $candidat_liste(index++) =$
            $triposition(node(i), node(j), node(k))$;

B) **Herd tracking algorithm based on the peak method**
In the articles [94,95], the authors proposed an algorithm based on the **point method** and considered it as a dynamic model. They conclude that the algorithm has been tested on confined herds and those in freedom as well.

Algorithm 7: Calculation of $\phi(\delta T)$

Input: $f(\delta T)$, $f((\delta - 1)T)$
Output: $\phi(\delta T)$
if $f(\delta T) - f((\delta - 1)T) < 0$ **then**
  $\phi(\delta T) \leftarrow \phi((\delta - 1)T) + \phi_0$
else
  $\phi(\delta T) \leftarrow \phi((\delta - 1)T) - \phi_0$

C) **Algorithm DBSCAN**
Xiaohui Li and Li Xing [96] deployed drones to minimize the average distance *drone-animal* based on the information obtained on the location of the targeted animals. Their objective is to cover a maximum number of targeted animals. For this, they adopted a density-based clustering algorithm *DBSCAN* to achieve this goal. The DBSCAN algorithm presented by the authors is the 8 algorithm. They apply this algorithm by taking into account the locations of all target animals as initial points of an input data set. The output is a set of targeted animal clusters.

Algorithm 8: DBSCAN

Input:
$U^0 = \{U_1^0, U_2^0, ...U_N^0\}, \epsilon, \rho_{th}$
Output:
A set of density-based targeted animal clusters mark all data points in U^0 as unvisited ;
repeat
randomly select an unvisited point U_i^0 mark U_i^0 0 as visited
if *the* $\epsilon - neighbor$ *density of* U_i^0 *is larger than* ρ_{th} **then**
  create a new cluster C_n , and add U_i^0 to C_n let N_p be the set of $\epsilon - neighbor$ of U_i^0;
  for *each point* $p\prime$ *in* N_p **do**
    if $p\prime$ *is unvisited* **then**
    if $p\prime$ *is not yet a member of any cluster* **then**
      add $p\prime$ to C_n ;
    output C_n ;
else
  mark U_i^0 as noise ;
until no point in U^0 is unvisited.

D) **Real time livestock tracking system**
Nthetsoa Alinah M. *et al.* [97] implemented a real-time livestock tracking system. For this system, they perform a location function based on estimating the distance between two nodes. The distance d is therefore calculated using the following equation:

$$d = \frac{c \times (T_{total} - T_{process})}{2} \tag{24}$$

where c represents the speed of the signal transmitted between beacon nodes, T_{total} represents the time during which the sender sends a packet and the receiver receives a response, and $T_{process}$ is the time it takes the receiver to process a response (Cf. 14). To estimate the position of a node, the authors used the trilateration method [93]. They point out that two conditions must be met: $P1$ must be on the y-axis and $P2$ on the x-axis. x and y of $P4$ are determined using Eqs. (25) and (26).

$$P_4x = \frac{r_1^2 - r_2^2 + e^2}{2e} \tag{25}$$

$$P_4y = \frac{r_1^2 - r_3^2 + f^2 + g^2}{2g} = \frac{f \times P_4x}{g} \tag{26}$$

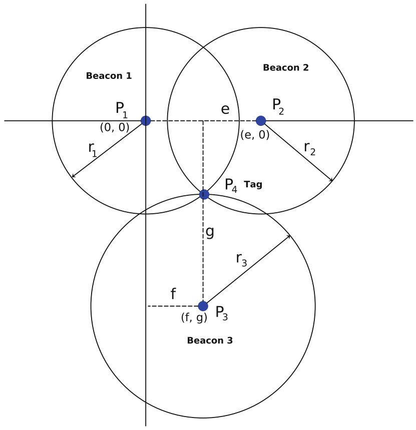

Fig. 14. Trilateration method with 3 beacon nodes

Algorithm 9: Localization with activation of beacon nodes

```
Input: accelerometer
Output: animal and position
Initialisation nrf24L01 + as a primary transmitter
for i ← 0  to  3 do
    beacon[i] ← payload
    start timer
    while (response = 0) do
        restart timer
        beacon[i] ← payload
    stop timer
    tag ← accelerometer  data
    if accelerometer  data ≠ previous  accelerometer  data then
        change[i] ← 1
    else
        change[i] ← 0
if (change[0] = 1||change[1] = 1||change[2] = 1) then
    animal ← active
    else
        animal ← inactive
calculate position of node
basestation ← position
basestation ← animal
```

3.2.1 Analysis of Localization Algorithms

There has been a lot of research done on localization in WSNs over the past few years. The process of locating a node can be explained as determining the position of a node relative to several landmarks using the specific computational methods and location technologies. Guangjie Han *et al.* [98–100] explained that today in WSNs, it is possible that an unknown node can itself calculate its own position based on on connectivity information between nodes and landmarks.

Table 9. Technical comparison of localization algorithms

Property	Case under consideration	Algorithm 6	Algorithm 7	Algorithm 8	Algorithm 9
Complexity	**Worst case**	$O(n^3)$	$O(\phi) + O(f)$	$O(n^2)$	$O(n)$
	Best case	$O(n^3)$	$O(\phi) + O(f)$	$O(n^2)$	$O(1)$

Table 9 shows a technical comparison relating to the time complexity of localization algorithms commonly used in the context of animal localization.

4 Discussion

Over the past two centuries, the development of fencing systems has been a revolution in grazing management [2], success in livestock management is directly linked to the ability to retain animals in areas , and exclude them in others or move them from one area to another [4]. Following the historical evolution of virtual fences [7], the words virtual fence are used in various fields. However, they all have in common that the barrier(s) are imperceptible in the landscape to alter animal behavior. The concept of virtual fencing appears more and more in the rehabilitation, whose work involves the management of animals in the wild.

4.1 Strengths and Limitations

In the literature, multiple advantages of virtual fences can be found, especially in the area of free-range animal management. Due to the possibility of gathering livestock at different speeds, time savings can be observed here. However, the disadvantages are related to the fact that the animals must wear a device has some impact on them and, especially in the case of collars sometimes larger [7,16,17,26,101]. In addition, accidents can occur if the animal receives a strong enough stimulus while a person is nearby. On the other hand, progress has been made in the miniaturization of collars worn by animals: [4,11]. Another problem with virtual fencing is the application of electrical stimuli to the animal. This poses animal welfare problems. However, there is work that allows the electrical stimuli to be adapted to the animal's reactions, i.e., the intensity decreases when the animal takes the desired direction [48].

It is important to develop a virtual fence system that allows the animals to learn how the technology works. However, the literature review showed that it is possible to develop a virtual fence to improve animal management and provide opportunities for farmers who could transform the virtual fence.

4.2 Future Challenges and Opportunities

In this subsection, we outline challenges in current work and future possibilities. First, it is true that many works have been devoted to the problem of virtual fences, in particular the question of the battery life of the device carried by the animal, the range of the signal emitted by the devices, etc. Nevertheless, some fundamental questions have not yet been addressed. For example, can we set up a dynamic virtual corridor taking into account the characteristics of different periods of the year, to provide a computer solution to conflicts related to the management of resources between farmers and pastoralists? If the answer is yes, to what extent and how to assess the performance of the different techniques and technologies involved in this innovation? Second, there are many approaches and advances in the development of virtual fences. A direction can be for example, to find an IT solution to the conflicts related to the management of resources between farmers and pastoralists. which could constitute a direction for our future work.

5 Conclusion

Virtual fencing has several advantages, as shown in the literature. Livestock management takes full advantage of virtual fencing technology, which allows access to a large amount of information about animal grazing behavior and activities, without human intervention, for long periods of time, in remote and difficult locations. The ability to monitor animals wherever they are is an invaluable benefit to farmers, who can be immediately alerted to unusual animal behavior and therefore respond quickly. This technology also has the potential to revolutionize pasture management. From this literature review, it is evident that there are many approaches to the development of virtual fencing. In this paper, we reviewed recent research efforts, including tracking techniques and technologies that have contributed enormously to the implementation of virtual fences. We presented a general taxonomy to classify existing virtual fencing improvements according to the specific aspects they aim to optimize good grazing management. Then, we performed a comparative study on the different techniques and technologies of localization. Subsequently, we proposed a taxonomy of the different types of virtual fences and reviewed a number of localization algorithms. Finally, we identified some potential directions for future research that we hope will serve as a useful guide for the development and implementation of virtual fence technologies .

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