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Review

Mapping Welfare: Location Determining Techniques and Their Potential for Managing Cattle Welfare—A Review

Gerben Hofstra [1,*], Judith Roelofs [2], Steven Mark Rutter [3], Elaine van Erp-van der Kooij [2] and Jakob de Vlieg [4]

1 Applied Biology Department, HAS University of Applied Sciences, Onderwijsboulevard 221, 5223 DE 's-Hertogenbosch, The Netherlands
2 Animal Husbandry Department, HAS University of Applied Sciences, Onderwijsboulevard 221, 5223 DE 's-Hertogenbosch, The Netherlands
3 Department of Animal Health, Behaviour and Welfare, Harper Adams University, Edgmond, Newport TF10 8NB, UK
4 Department of Mathematics and Computer Science, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
* Correspondence: g.hofstra@has.nl

Abstract: Several studies have suggested that precision livestock farming (PLF) is a useful tool for animal welfare management and assessment. Location, posture and movement of an individual are key elements in identifying the animal and recording its behaviour. Currently, multiple technologies are available for automated monitoring of the location of individual animals, ranging from Global Navigation Satellite Systems (GNSS) to ultra-wideband (UWB), RFID, wireless sensor networks (WSN) and even computer vision. These techniques and developments all yield potential to manage and assess animal welfare, but also have their constraints, such as range and accuracy. Combining sensors such as accelerometers with any location determining technique into a sensor fusion system can give more detailed information on the individual cow, achieving an even more reliable and accurate indication of animal welfare. We conclude that location systems are a promising approach to determining animal welfare, especially when applied in conjunction with additional sensors, but additional research focused on the use of technology in animal welfare monitoring is needed.

Keywords: PLF; dairy cows; cattle; location; animal welfare; GNSS; UWB; RFID; WSN; computer vision; data science; multi-sensing

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1. Introduction

Since the beginning of this century, the general public has become more concerned with animal welfare and a growing number of European consumers now believe that welfare standards in livestock production should be improved [1,2]. This concern also translates to consumer purchase decisions and consumers are willing to pay a premium for credence attributes of animal welfare in beef and dairy products of up to 19 and 31%, respectively [3].

Animal welfare can be defined in several ways. The Five Freedoms, as first suggested by the Brambell Committee [4] and further developed by the British Farm Animal Welfare Council (FAWC), have been regarded as a standard for animal welfare for over half a century. Animals should have freedom from hunger and thirst, discomfort, pain, injuries or disease, freedom to express normal behaviour, and freedom from fear and distress [5]. In a large EU-funded research project animal welfare was later redefined as the four principles of Welfare Quality®: good housing, good health, good nutrition, and appropriate behaviour [6]. More recently, the Five Domains Model for animal welfare assessment, which was originally formulated in 1994 by Mellor [7] to facilitate structured, systematic, comprehensive, and coherent animal welfare assessments, is also often used. This model has already been updated several times to embrace scientific progress in ideas on animal welfare [8]. The Five Domains Model has a significant focus on subjective experiences, known as affects, which collectively contribute to an animal's overall welfare state [9]. Based on these animal welfare frameworks, protocols have been developed to measure, for instance, cattle welfare [10]. However, these extensive assessment protocols have proven to be time-consuming and therefore costly, which limits their potential for practical application [11–13].

In recent years, several researchers have pointed out the potential of precision livestock farming (PLF) for animal welfare management and assessment [14–22]. However, no system exists yet that can provide the broad, multidimensional integration that is required to give a complete assessment of the welfare of any species, including cattle [17]. The automated monitoring of cattle welfare through technology has the potential to reduce the labour requirements and make the assessment more reliable by utilising continuous, real-time monitoring. These systems provide the farmer with more information on their animals, possibly resulting in higher production efficiency and improved animal welfare [14,17].

Automated monitoring and managing of individual cows start with recognizing the animal and its behaviour. Location, posture, and movement of the cow are key elements in this process. Multiple technologies are now available for the automated monitoring of the location of individual animals. These techniques, ranging from global positioning systems (GPS) to ultra-wideband (UWB), Bluetooth and even computer vision, yield the potential to manage and assess animal welfare. The location of a cow in a functional area, for instance, is closely related to the activity of the animal, e.g., feeding, lying, and drinking (basic needs) and thus location can be used to infer its behavioural budget [23,24]. Deviations from predetermined behavioural patterns in turn might be an indicator of disease or compromised welfare [25–27]. In addition, social relations can be inferred when comparing locations of group members in relation to each other [28,29]. However, each location determining technology has its constraints, such as range and accuracy, and might not have the same potential for determining animal welfare in every situation, e.g., indoor vs. outdoor. This review aims to provide an overview of the location determining techniques used for cattle and their potential for managing and assessing animal welfare. The different techniques and approaches currently applied for determining animal location will be discussed and the potential of these techniques for animal welfare management and assessment will be reviewed.

2. Location Determining Techniques

2.1. Global Navigation Satellite Systems (GNSS)

The Global Navigation Satellite Systems (GNSS) rely on radio signals from specialized satellites available at the given time of positioning. GNSS, such as the global positioning system (GPS), have been used for over 30 years to track domestic animals [30]. They have been used by ecologists to track and monitor the behavioural ecology of free-ranging animals [31,32], but also for monitoring cattle movement in the field [33,34]. GNSS works well outdoors when there is an unobstructed line of sight, although radio signal attenuation from walls causes standard GNSS receivers to perform poorly in indoor environments [35]. However, new technologies that enhance and/or repeat the GNSS signal indoors might have the potential to enhance indoor GNSS performance [36,37]. One of the concerns with poor signal strength is the inherent GNSS error when cows are inactive, which may overestimate daily travel by cattle by as much as 15% [38].

In general, when GNSS collars are used in cattle [39] they appear to have little to no effect on their behaviour [30]. Schleppe et al. [40] experimented with a GNSS ear tag; due to weight restrictions and consequently battery size, run-time was insufficient for practical applications. When using GNSS, the sampling frequency, which is often a trade-off with battery life, should be considered carefully since longer intervals may propagate flawed spatial interpretations [41]. When automatically classifying cattle behaviour, the data are commonly segmented using a fixed window size for feature extraction. However, a fixed window size might not always represent one single behaviour; thus, variable window sizes for feature extraction may lead to enhanced behaviour recognition [42].

For the management of animals in extensive grazing systems, it is suggested that monitoring grazing distribution via livestock GNSS trackers can, in some cases, improve stocking rate adjustment calculations [43]. Furthermore, GNSS data can give more insight into the relationship between cattle behaviours and pasture characteristics [44–48], which could, in turn, inform the development of management strategies to modify cattle distribution in the field, such as the strategic placement of water, shade and mineral points to decrease overgrazing and nutrient accumulation at resting sites [47]. In addition, social associations as monitored by GNSS data among individual cows may provide some insight into cattle grazing patterns, forage utilization and availability [49].

The detection of potential health issues such as lameness is possible when considering the modified exploratory dynamics of lame cows based on GNSS data in combination with accelerometers [50]. In combination with a birthing sensor, GNSS information can provide useful information about the location of calving events in the field, allowing the farmer to reduce potential injury to the calf caused by the mother or by environmental factors [51]. The spatial behaviour of cows and their calves can also help understand their behaviour in extensive grazing systems with potential applications to improve calf survival and performance [52]. Herd social structure based on GNSS data can provide cattle contact patterns that potentially have major implications for infection transmission within the herd [53] or between domestic cattle and wildlife species [54].

GNSS data offer the possibility to monitor animal behaviour, such as foraging, walking and resting, with an accuracy ranging from 57 to 87.5% depending on the circumstances [55–62]. However, the potential of GNSS for behavioural monitoring might benefit from combination with other sensors such as accelerometers [63–72]. GNSS data can also be utilized to understand and monitor cattle herd spatiotemporal behaviour [57] and consequently changes in herd dispersion–aggregation patterns [73,74]. The monitoring of this spatiotemporal behaviour of cows makes it possible to determine the social structure [63,73] and identify dominant animals in herd situations [73].

A virtual fence (VF) can be defined as a structure serving as an enclosure, a barrier, or a boundary without a physical barrier [75]. Some virtual fencing technologies use GNSS collars that deliver an audio cue when the animal approaches a GNSS-defined virtual boundary (e.g., [76,77]). An aversive electric stimulus is delivered by the device if, following the audio cue, the animal walks beyond the virtual boundary, but not if it stops walking or turns back. The animal learns to associate the audio cue with the pending electrical stimulus unless it changes its behaviour, and increasingly responds to the audio cue alone [78]. The general public has shown some concern about animal welfare when it comes to implementing virtual fencing technology [79]. Acosta et al. [80] have thus suggested replacing the electrical stimuli with tactile stimuli. However, several authors have confirmed that the VF does not impact welfare any greater than traditional physical electric fencing [81–85]. When the use of a VF promotes the use of, for instance, strip grazing instead of keeping animals indoors, it can improve animal welfare [86].

2.2. Ultra-Wideband (UWB)

The technique of ultra-wideband (UWB) has been around since the 19th century, but has only recently been used for the tracking of animals [87,88]. UWB is a wireless technology developed to transfer data at high rates over very short distances at very low power densities [89] and is one of the most reliable and accurate technologies available in the field of indoor positioning [90]. The UWB techniques used to track animals are spatially and temporally more accurate than GNSS technology [91]. The tracking of animals is mainly performed indoors but has also recently been successfully applied in field settings [92,93].

In many environments, the data from a UWB tracking system can contain unwanted noise due to the signal being masked or interfered with by the animals or by equipment in the barn [94]. Missing data from UWB devices might hinder reliable continuous monitoring and analysis of animal movement and social behaviour [95]. However, the quality of the data can be enhanced using filters [23,96,97] or with automated image analysis on density maps based on animals locations [94]. In this respect, the precise calibration and validation of a UWB tracking system is of the utmost importance [98].

Tracking cow activity with UWB and monitoring circadian rhythms might help detect health issues such as lameness and mastitis [99]. UWB data can provide information on, for instance, walking distance and lying time, which can be used for lameness detection [100]. It is also possible to monitor the proximity interaction network of a herd, which in the future might be used to detect individual differences in social associations; in turn, this could be used to identify health issues [29,101]. Data from UWB positioning systems can be used to measure animal behaviours [23,102,103] such as feeding behaviour [26,96,104] and oestrus behaviour [99,105–108]. However, Shane et al. [109] showed that one should be careful when inferring the behaviour based solely on the location data of the animal. Additional sensor data might be complimentary to UWB data. For instance, Ren et al. [28] were able to detect affiliative and agonistic social interactions with high accuracy when combining UWB with computer vision technology.

2.3. Radio Frequency Identification (RFID)

Radio frequency identification (RFID) was originally developed for identification purposes, but it can also be applied for the positioning and tracking of animals. RFID systems consist of a tag or transponder and a reader or transceiver that reads and writes data to a transponder [110,111]. RFID tags can be active, passive, or semi-passive. Passive and semi-passive RFID send their data by reflection or modulation of the electromagnetic field that was emitted by the reader, which limits the reading range to between 10 cm and 3 m. The battery of a semi-passive RFID is only used to power the sensor and data processing circuitry. An active RFID has a battery that enables higher signal strength and an extended communication range of up to 100 m, but is larger due to the presence of that battery and more electronic components [112,113]. The speed of travel of the animal [114,115] and body tissue near the transponders [116,117] have a strong influence on the reading performance of the system so the optimal position of the tag and reader should be considered [117]. Curran et al. [112] experimented with RFID-Radar where the reader calculates the location of transponders while interfacing with the reader instead of just recording its presence. In this capacity, it could be used as an indoor RFID-based location determination system, but Curran et al. deemed it impractical due to too many inaccurate readings.

RFID systems have been used to detect feeding behaviour [118–120], drinking behaviour [121,122] and supplement intake [123] based on proximity to the feed bunk, water point and mineral lick block, respectively. Toaf et al. [124] found that an RFID-based ear tag recording of brush proximity was not yet a reliable representation of grooming behaviour as some animals spent a relatively large portion of time standing idle close to the brush, resulting in false positives.

2.4. Wireless Sensor Networks

Wireless sensor networks (WSNs) use small, low-cost, low-power sensor nodes that communicate untethered over short distances [125,126]. WSNs have attracted more research efforts in the past few years and several standards in communications protocols such as Bluetooth and Zigbee have already been established [113]. These offer great opportunities for cattle monitoring [127–129] and localization [130–132]. There are several wireless communication technologies available for WSN, such as Bluetooth, Zigbee, BLE, LTE, WiFi and LoRa, each with its advantages and disadvantages [133,134]. For a wireless technology such as Zigbee, the network range is mostly between 10 and 30 m [135], which would be impractical for tracking purposes in large, outdoor environments; however, according to Feng et al. [136], it is preferable for indoor situations owing to its low power consumption. For long-range communication (>5 km), LPWAN technologies such as LoRa are preferable [136,137]. The system and the number of nodes needed for accurate communication depend on the environment [138]. Maroto-Malino et al. [139] developed a promising fusion system for a field setting with a few animals in the herd being fitted with a GPS collar for location determining and the rest of the animals being fitted with low-cost BLE tags to determine their relative location to the animals with the GPS collars. Nodes are becoming increasingly smaller and energy-efficient [140,141]. WSNs are often bioinspired, meaning that the network mechanisms are based on animal behaviour [142] and data collection may be real-time or more opportunistic [143].

Nadimi et al. [144] used a Zigbee WSN to determine the total number of animals roaming in a certain area of the field when using strip grazing and their total pasture time to use the presence of the animals as an indicator of the grass quality and quantity, which may help determine the right time to provide access to a new strip. WSN can be used to determine the position of animals and, in combination with a three-axis activity sensor, movement and activity status can be observed. This implies that it can be used for analysing animal behaviour at specific locations in the barn [135]. By detecting abnormally long walking distances, oestrus might be detected using a WSN [145], or by detecting if an animal is being mounted, standing oestrus might be detected [146].

2.5. Computer Vision Technology

Computer vision is a simulation of biological vision and is part of the field of artificial intelligence. In the field of animal science, computer vision is about deriving useful information from videos and translating the videos into new insights on e.g., animal behaviour through data science. A computer vision system extracts certain features from images while performing other subtasks, e.g., edge detection, corner detection, image segmentation and pattern recognition [147]. Although not primarily a location-determining technique, by mimicking the human eye, computer vision can identify individuals and thus identify an animal's location. Biometric identification of animals through computer vision is possible [148–150] and also the tracking and counting of animals [151–155]. The use of a thermal sensor might even improve the tracking capabilities since it will make it easier to detect animals against the background and distinguish between overlapping individuals [156]. Computer vision relies on visual information only and thus is entirely non-invasive and non-intrusive [157]. Outdoors, cameras could be mounted on drones for locating and counting animals in the field [111].

The individual feed intake of dairy cows is an important variable in dairy farming which vision technology has the potential to measure [158–160]. Using low-cost RGB-D cameras, vision has the potential to measure the individual feed intake of dairy cows in a cowshed [161] but the deep learning models used do need to be tuned to different types of feed [162]. Computer vision can also be applied to determine behaviours such as lying [163,164] or feeding and standing behaviour [165]. Being able to monitor animal behaviour makes it possible to detect abnormal activities in case of disease [166,167].

Vision systems have a much wider scope than just determining location. They can also be utilized for lameness detection [168,169] or to detect facial expressions associated with health issues such as 'pain face' [170]. Using infrared cameras makes it possible to measure animal temperature to detect fever [171] indicating disease. Another possibility would be to detect the warm exhaled air to measure raised respiration rates [172] indicating heat stress or disease.

2.6. Challenges with Location Determining Technologies

There are several promising techniques available for determining location and animal monitoring in cattle, but all of them will have to compromise between performance and system efficiency in terms of battery life, size and cost (Table 1). Besides this compromise, there are issues such as standardization, data security, robustness and scalability, and educational challenges that need to be taken into account [173,174].

Table 1. Comparison of current location determining techniques used for cattle and details of the research conducted to date in relation to the Welfare Quality principles.

	GNSS	UWB	RFID	WSN	Vision
Works inside barn	-	++	+	+	++
Works in the field	++	-	-	+	-
Battery life	-	+	++	+	n/a
Size transponders	+	+	-	+	n/a
Measuring welfare	1,2,3,4	3,4	1	2,4	1,2,3,4

-: poor, +: adequate, ++: good, n/a: not applicable 1: Good Housing, 2: Good Nutrition, 3: Good Health, 4: Appropriate Behaviour.

3. Welfare and Animal Location

According to the Welfare Quality system, welfare can be monitored in four domains: good housing, good nutrition, good health and appropriate behaviour. In the previous paragraphs, we have shown how different location determining techniques can play a role in monitoring welfare in these domains (Table 1). Good housing can be assessed by using location determining techniques to monitor space use, freedom of movement, standing behaviour (as a measure for insufficient or unsuitable lying space) and preference for certain drinkers or feeders. Good nutrition can be monitored by using the location determining technique to monitor the distribution of a herd in the field or to calculate time spent at the feeding rack or drinkers as an indicator of feeding and drinking behaviour. Health can be monitored by using the location determining technique to detect changes in behaviour, walking speed and social associations. Finally, location systems can give an indication of behavioural patterns, social interactions and time budgets for behaviour, which can be a strong factor in determining animal welfare. Several location determining techniques are promising for this purpose but, as discussed, might not function in every situation. GNSS has the longest history in animal tracking and thus has had more attention as to its use; however, it is mostly just suitable for outdoor applications. Systems that function well indoors, such as UWB and WSN, have difficulties in an outdoor setting due to a lack of networking connectivity. Currently, GNSS seems to have the most benefits for welfare monitoring based on location in a field setting. For an indoor setting, vision technology, which has been receiving increased attention in recent years, may hold the most potential for welfare monitoring. This is partly because it is much more than just a location determining technique, it is also a system that can measure and monitor behaviour. A future overall solution for location-based welfare monitoring might very well come from WSNs, which is still in its infancy for this purpose but could potentially work well both indoors and outdoors. Combining sensors (e.g., accelerometers) with any location determining technique in a sensor or data fusion system can give more detailed information on individual cows, and give an even more reliable and accurate indication of animal welfare. For example, an inertial measurement unit (IMU), which uses an accelerometer, gyroscope and magnetometer to accurately determine movement and relative position [175], can be used in a data fusion system with RFID [176] or GNSS [177] to give more precise information on behaviour. Another example is that an accelerometer alone might give information on standing idle but the added information on location helps determine whether this is a possible welfare issue. Idling in the queue in front of the AMS might be considered normal behaviour, whereas idling at the feeding rack or in the cubicle could indicate welfare issues such as disease, insufficient feed or unsuitable cubicles [178]. Still, it is a major challenge to manage and translate the huge amount of heterogeneous data produced by the various sensing technologies into new scientific insights.

4. Conclusions

We conclude that location systems are a promising tool in determining animal welfare, especially when applied in conjunction with additional sensors, but additional research focused on the use in animal welfare monitoring is needed. In a field setting, GNSS have the best potential for welfare monitoring based on location. Vision technology may hold the most potential for welfare monitoring in an indoor setting. In the future, sensor and data fusion systems may lead to objective ways of measuring animal welfare, which could greatly benefit both animals and farmers.

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