Computers and Electronics in Agriculture 170 (2020) 105250

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

High precision real-time location estimates in a real-life barn environment using a commercial ultra wideband chip

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ARTICLE INFO

Keywords:
Large groups
Precision farming
Realtime location systems (RTLS)
Time difference of arrival (TDOA)
Ultra-wide band (UWB)

ABSTRACT

Structural changes lead to an increase in the number of dairy cows and dry sows kept per group. This has consequences in how easily a farmer can supervise his herd and may be detrimental to animal welfare, specifically regarding social relations, time budget and area of residence. An automated tracking system can support the farmer in his management activities and can provide the foundation for a scientific assessment of the welfare consequences of large groups. In this study, a relatively simple and inexpensive real time location system (RTLS) was developed with the aim of achieving precise localization of several tags (animals) in real time and in a real barn environment. The RTLS was based on the ultra-wideband (UWB) technology provided by DecaWave and was adapted for a time difference of arrival (TDoA) procedure to estimate the tags' positions. The RTLS can handle up to a hundred tags simultaneously using a Pure ALOHA random access method at 1-second intervals. The localization of the tags was estimated in 2D on a given fixed height using a constrained Gauss-Newton algorithm to increase accuracy and stability. The performance of the overall system was evaluated in two different dairy barns. To determine the precision of the system, static and dynamic positions measured at withers height of a cow (1.5 m) and closer to the ground mimicking a lying cow were compared with a reference system (theodolite). The 2D deviations between the systems were used as a measure of precision. In addition, the scalability in respect to the number of tags and the size of the observed area was examined in situations with ten tags and the situation with 100 tags was simulated with a ten-fold increase in sampling rate.

According to the field test, the system as developed can be used for the individual localization of animals. At withers height, most of the measured locations deviated less than 0.5 m from the localizations as measured by the theodolite. At lower heights, and closer to the corners of the observed area, some localization estimates were somewhat larger. This was also the case close to large metal barn infrastructure. The measured collision rate of 11% for 100 tags was low. In spite of its low price, the system as a whole is therefore promising and ready for a next step, which should include the observation of large groups of real animals on working farms.

1. Introduction

Economic pressure in the agricultural sector leads to optimization in efficiency in respect to work and machine resources. As part of this structural change, the number of animals kept per farm has increased (Rodenburg and Koene, 2007). In parallel, group sizes in which these animals are kept also increased. The interest in the effect of housing large groups was also reflected in two of the main subjects of the 2010 conference of the International Society of Applied Ethology addressing "Behavioral expressions of physiological coping in large groups" and "Social adaptations to large groups". Even though these subjects were raised several years ago, progress in this research area has remained limited. This limitation is caused largely by the difficulty of collecting detailed data on individuals in large groups of animals.

Social interactions and social relationships heavily influence welfare of livestock animals. The sheer number of animals in a group may challenge the development of individual relationships (Croney and Newberry, 2007; Estevez et al., 2007). Given the evolutionary past of

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https://doi.org/10.1016/j.compag.2020.105250
Received 11 March 2019; Received in revised form 5 December 2019; Accepted 26 January 2020

cattle and pigs, a clear difference in their ability to deal with large groups can be expected (Rodenburg and Koene, 2007). Whereas pigs reintroduced into the wild form relatively small sounders, cattle and closely related ungulates form also large herds. Therefore, pigs may be more specialized to keep up few and personalized relationships in small groups compared with cattle that may more easily deal with larger and possibly anonymous herds. Moreover, the time animals of livestock species spend e.g. feeding, lying and drinking (to satisfy their basic needs) is closely related to where the animals are (their area of residence). Inversely, this means that the knowledge of where the animals spend their time can be used to infer their behavioral budget. In addition, the location where animals spend their time depends on the structure of the barns with different functional areas such as lying, feeding and activity areas that may or may not be separated physically by e.g. walls. The size of the groups and the according size of the barns is likely to influence the time budget due to the longer distances between the functional areas, and the social structure in itself may impair e.g. low ranking-animals' access to certain areas and resources. In addition, in larger groups some of the resources may be provided only on a limited basis (animal-to-resource ratio > 1).

The logistic and technical challenges to follow individuals in large groups has hampered the research on the effects of such large groups on farm animal behavior and welfare. There are a few commercially available systems such as the LPM (inmotiotec GmbH, local position measurement, Regau, Austria), ubisense (Ubisense Limited, Chesterton Cambridge, UK), and the more recent Smartbow (Smartbow GmbH, Weibern, Austria). The systems are expensive at several tens to hundred thousand Euros order cost. In addition, the work effort needed to set up the system in different barns can be huge with up to around 10 man days per barn (for RFID systems that are similar in this respect, see Siegford et al., 2016), specifically if delicate cables such as glass fiber are needed. Yet, the cost due to setting up the system may depend more on the specific setting in a given barn rather than the specific system such that the system price is more relevant for deciding on a system.

The utility of these systems was restricted in the past due to limited accuracy or the necessary intensive post-processing of the data needed to increase accuracy (lpm: e.g. Gygax et al., 2007, 2010; ubisense: Rose, Langbein, personal communications; Smartbow: Wolfger et al., 2017). The accuracy may have reached 0.5 m in optimal locations but only an accuracy of up to a few meters was possible e.g. in the corners of the barns. This kind of imprecision has been too large generally to e.g. study social relationships based on distances between animals. In addition, it has been too variable in different zones of a barn due to interference with local metal structures common in barns (Porto et al., 2014) making the prediction about the precision of a localization estimate difficult. Other technical approaches have not left the state of "proof of concept" (e.g., Huhtala et al., 2007; Ahrendt et al., 2011; Nadimi et al., 2012) or are too novel to have been evaluated in depth in real barn environments (e.g. uRTLS, tracktio, Barcelona, Spain or RTLS, BioControl, Rakkestad, Norway).

Ideally, a system for animal localization would not only allow to estimate the animals' position in 2D but also the height of the tag above ground level. This would allow knowing about the animals' general posture (lying versus standing) in addition to their whereabouts. To achieve reasonable results for vertical triangulation, the fixed infrastructure of the system (anchors) would need to be positioned at clearly different heights. This is difficult in practice because barns have a fixed and rather low height and all positions close to the ground are problematic to start with because they never provide a direct line of sight due to barn infrastructure. Due to these physical constraints, we decided that we did not attempt to estimate the vertical part of the position estimate at all and would use an assumed fixed height of our 2D position estimates to increase speed and accuracy of the system. For the time being it seems reasonable to use simpler and more specific additional systems to infer standing or lying in barn-kept animals such as 3D-accelerometers attached to their legs (e.g. Weigele et al., 2018).

Table 1
Abbreviations used in the text in alphabetical order.

Abbreviation	*Description/definition*
2D	*two dimensions, two-dimensional*
3D	*three dimensions, three-dimensional*
ALOHA	*stochastic channel access method in which any tag can send a data packet at any time*
CDB	*clock distribution box*
CLE	*central location engine*
FP	*first path signal power*
FPNR	*first path to noise ratio*
LOS	*line of sight (path)*
NL	*noise level*
NLOS	*non-line of sight (path)*
PRF	*pulse repetition frequency*
Qi	*standard protocol for wireless charging systems*
RxP	*received signal power*
RTLS	*real time location system*
SFD	*start of frame delimiters*
SN	*sequence number*
TDoA	*time difference of arrival*
ToF	*time of flight*
UID	*unique identification number*
UWB	*ultra-wideband*

The distance or, as an equivalent, the time of flight (ToF, see Table 1 for all abbreviations used in this text) between an animal's tag and a fixed infrastructure can be measured at possibly high precision using UWB technology. Such a system can be realized today on the basis of commercially available UWB transceiver chips. Such an approach has several main advantages over commercially available systems. First, recent UWB chips feature high precision (Jiménez and Seco, 2017) at a much lower cost. Second, the chips can be adapted with regard to important system requirements, such as scalability for a large number of tags or position update rates. Moreover, transparent and flexible data processing is guaranteed due to direct chip access. This means that systems can be tailored with reasonable effort exactly to the needs of researchers and independently of commercial production and interests. Finally, the small size of the chip allows the development of tags with an adequate shape for attachment on the animals and a reasonable battery autonomy more easily. In this study, an RTLS was implemented based on a commercially available UWB chip and evaluated for accuracy of localization estimates in real barn environments.

2. Methods and material

2.1. Real time location system

Our RTLS (Graf and Twardawa, 2015; Nüesch, 2017) was developed based on DecaWave's UWB technology (DW1000; DecaWave, Dublin, Ireland). A TDoA procedure was used for localization. The system consisted of mobile tags and fixed anchors. Both of them used the same transceiver chips. The tags broadcasted UWB packets at an interval of 1 s. The packet payload included a unique identification number (UID), a sequence number (SN) (which was incremented after each broadcast) and the current battery voltage of the respective tag. Though, in principle, the 2D-position of a tag can be estimated by using three anchors (receivers), a stable localization estimate depends on at least four synchronized anchors with a known fixed location. This arrangement was used in the current approach. The anchors were complemented by a clock distribution box (CDB) and a central localization engine (CLE) running a software developed in C#. The CDB provided the time-synchronization of and the power for the anchors (see below).

The position of a tag was determined in the CLE by evaluating the individual reception times of a single UWB packet received by the four anchors. For this purpose, a TDoA report was transmitted to the CLE each time an UWB packet was received by an anchor. A TDoA report contained the received UWB packet, the reception time stamp and the diagnostic values regarding the signal quality of the received UWB packet. The signal quality analysis included an estimate of whether the UWB packet was received via the line of sight (LOS) path or a non-line of sight (NLOS) path as well as an estimate of the timestamp quality. The receive path was estimated by comparing the received signal power (RxP) and the first path signal power (FP; see manual of the DW1000; DecaWave, Dublin, Ireland). The more similar the two values the higher the probability for an LOS path. The timestamp quality was estimated based on the First Path to Noise Ratio (FPNR), which was calculated from the ratio of the FP and the noise level (NL). Both these measures are among the standard outputs of the DecaWave chip. A high value indicated a good timestamp quality. The TDoA reports were first transmitted to the CDB via the twisted pair cables and then forwarded to the CLE using a USB cable. In the CLE, the TDoA reports were grouped by their UID and by their SN. The tag position was estimated for all groups of packets with identical UID and SN with four TDoA reports. Those packets that had only three or less TDoA reports were omitted.

The tag positions and the diagnostic data were visualized and recorded in real time in the central localization engine, i.e. the movement of the tags were immediately visible on screen. The visualization showed the current 3D coordinates of each tag in a list and its position in a 3D visualization of a room. In addition, the current battery voltages of the tags were displayed. To check the signal quality of the tags, the current diagnostic values RxP, FP and FPNR were displayed in a table, taking into account every tag-anchor combination. The following log files were created for offline evaluation. For statistical evaluations, all localizations were stored in the standard log file. This included the estimated tag 2D-position, the TDoA reports, the anchor coordinates, and the corresponding log time. For debugging purposes, all TDoA reports were stored in a separate binary stream log file, including the corresponding log time.

The high potential precision of the tested RTLS required that the exact coordinates of the anchors were set in the CLE. Accordingly, the anchor's coordinates were measured with the help of a theodolite (Trimble Tachymeter 3305 DR, Trimble Inc., Sunnyvale, CA, USA). The precision of the coordinate estimates also depended on a common time base of the anchors, i.e. that they were exactly synchronized. A common crystal-stabilized (rectangular) synchronization clock of 38.4 MHz for all anchors was therefore provided by the CDB. Clock propagation delay differences, e.g. caused by different cable lengths, were determined with the aid of a static reference tag with known coordinates and were used to adjust the time stamps of the TDoA reports (Fig. 1, top). The clock propagation delay differences could be calculated because the distance, or equivalent the ToF between the reference tag and the anchors, were known.

Tags: The tag hardware was designed to be attached to a neck collar and comes in a robust casing (Itin and Hoch, Liestal, Switzerland; Fig. 1, bottom left) at a total weight of 92 g. The tags operated continuously for a period of 6 months when UWB packets were sent at 1 Hz. The integrated 1200 mAh battery was rechargeable via contactless Qi. The tag hardware (Fig. 1, bottom right) contained the UWB module DWM1000 (A), 8 LEDs (B, disabled in the current application), an acceleration sensor, a gyroscope and a pressure sensor (C, not used in the current approach), as well as a microcontroller (D, used for controlling A, B and C).

Anchor: The anchors of the tested system were realized with DecaWave's evaluation kit EVK1000 (DecaWave, Dublin, Ireland). Each evaluation kit was extended with an electronic circuit, providing a twisted pair-based interface to the CDB. The interface was used to supply and clock the anchors as well as the transmission of messages, such as the TDoA reports.

2.1.1. *System access*

For the tags, a temporal scheme for their broadcasting had to be chosen ("system access"). This scheme should ensure that concurrent broadcasting ("collisions") occurs as seldom as possible. Here, we implemented a so-called pure-ALOHA protocol (Table 1, Abramson, 1970). The broadcast interval of the tags consisted of a fixed delay of 950 ms and a random delay which was equally distributed between 0 ms and 100 ms. The resulting average transmission interval of 1000 ms guaranteed a certain deterministic behavior between two localizations. The randomly generated delay prevented permanent packet loss in case multiple tags were running synchronously.

The tested RTLS was configured with a center frequency of 6.5 GHz (UWB channel 5) and a bandwidth of 500 MHz. The data rate equaled 6.8 Mbit/s and the pulse repetition frequency (PRF) 16 MHz. The length of the preamble was 128 symbols and the length of the start of frame delimiters (SFD) 64 symbols. The transmitted payload was 18 bytes. The resulting transmission duration was 184.6 us, which allowed the transmission power to be increased by 6 dB to −8.3 dBm/500 MHz (Decawave, 2015).

2.1.2. *Tag scalability*

The number of tags that can be deployed in the developed RTLS was directly related to the acceptable probability of localization failures caused by UWB packet collisions (Nüesch, 2017). The probability of a collision in a Pure-ALOHA system is determined stochastically and depends on the transmission interval and the vulnerability interval. The vulnerability interval itself consists of twice the transmission time plus the signal processing time in the anchor, during which no further packets can be received. The measured signal processing time in the developed RTLS was 800 ± 0 μs. In a conservative approach, it is assumed that in case of a collision all UWB packets involved are lost and that the vulnerable period is the processing time plus twice the blink duration (180 us each) totaling in approximately 1200 us. With a pure aloha process, it can be assumed that the number of blinks in an interval follows a Poisson distribution. Therefore, the probability of a collision can be estimated by $P_{coll} = 1 - P_{succ} = 1 - e^{-\lambda(1200\ \mu s)}$, with λ the number of packages sent per s. The collision rate was accordingly estimated at 11.3% for 100 tags. A more accurate prediction considered the reception of at least one UWB packet in case an interval violation occurred during signal processing. The simulated collision rate for this scenario was 10.7% for 100 tags (Fig. 2, tested system). In the future, the collision rate can potentially be optimized further by reducing the signal processing time in the anchors. The simulated lower limit for this was 3.9% for 100 tags (Fig. 2, optimized system).

2.1.3. *Observable area*

The tested RTLS had a range of approximately 30 m. Since the packets had to be received by all four anchors, it was possible to observe a maximum square with a side length of 21 m (and a diagonal of about 30 m), where the anchors were installed in the corners at a height of 3 m. This corresponded to a typical setup in a barn, where the required LOS area for each anchor was maximized by installing it in a high position. The limiting factors for the range were the LOS connection (30 m) and the sensitivity of the system to multipath (Decawave, 2014). In barns larger than this area, additional anchors are needed. The length of the barn can be covered with adding anchors at roughly every 20 m. The same is true for wider barns. In the latter case, there are often different barn compartments on both sides of a central barn corridor. In that case, the pens on each side could be equipped each with their own set of anchors.

2.1.4. *Localization algorithm*

A tag position was estimated in 3D in the CLE on the basis of four UWB reports with identical UID and SN. For this, a TDoA procedure with an iterative Gauss Newton algorithm (also called Taylor Series Estimation, TSE; Foy 1976) was used. The search region of the algorithm included the area spanned by the four anchors with a margin of 1 m and was fixed at approximate withers height (1.5 m). The fixed

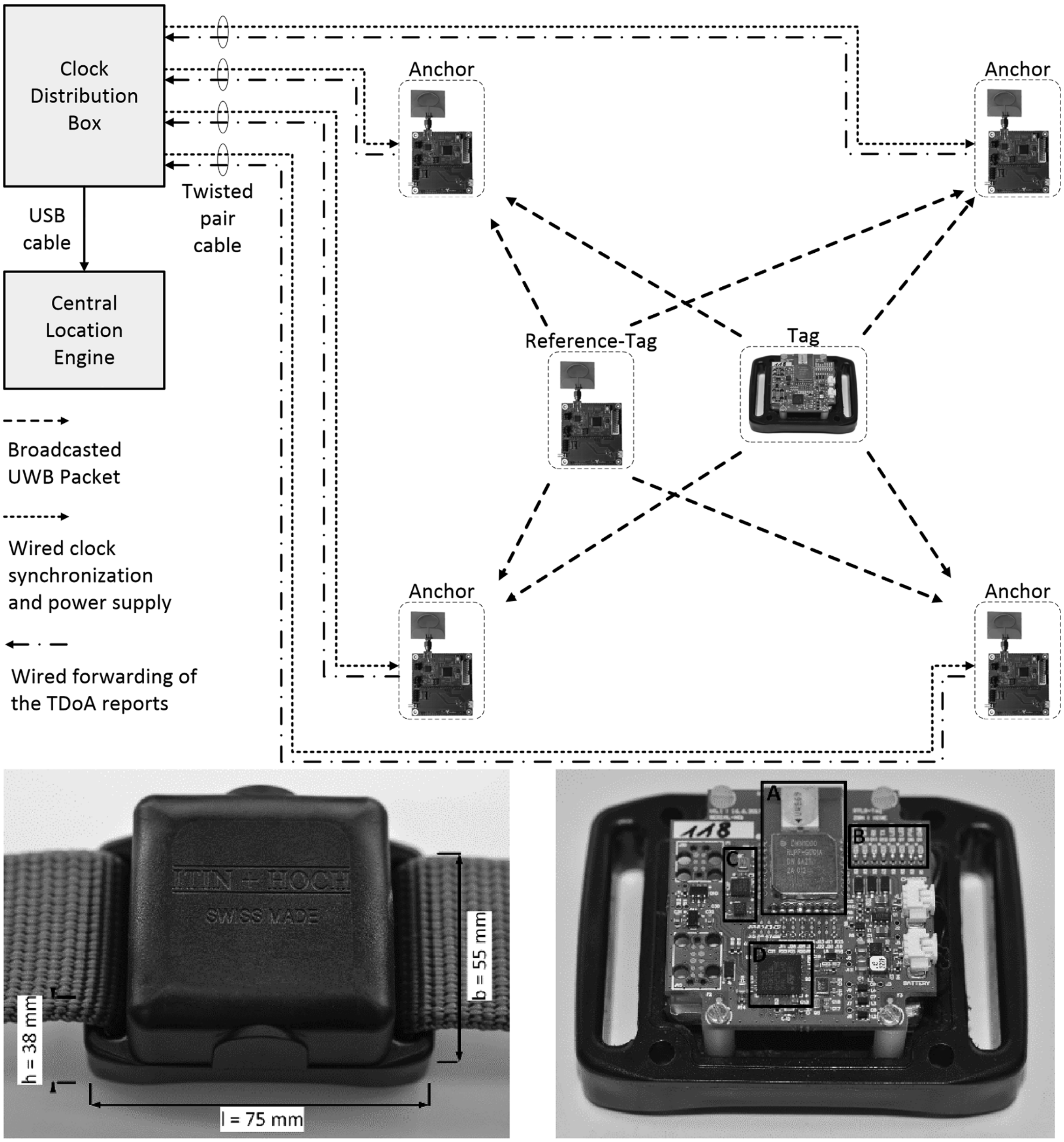

Fig. 1. Components of the TDoA-based RTLS. Example with four receiving anchors and one tag (top), tag as attached to a neck collar (weight: 90 g; bottom, left), tag hardware (bottom, right) with UWB module DWM1000 (A), 8 LEDs (B), acceleration sensor, gyroscope and pressure sensor (C), and microcontroller (D).

height stabilized the estimation algorithm by preventing ambiguities that often (but not exclusively) occurred in the Z-axis due to the preferred anchor arrangement in barns (see above; Nüesch, 2017). An incorrectly estimated height resulted in a horizontal localization error, which was accepted in favor of the more stable estimation algorithm. For the setup described above, the localization error was simulated in two scenarios. The estimated height in both simulations was 1.5 m, while the actual height was 1.0 m in the first scenario and 2.0 m in the second scenario. The simulation clearly showed that the deviation in the center was negligible. Larger deviations only occurred near the anchors, where the absolute horizontal deviation did not exceed 0.3 m at a distance of 1 m from the anchor (Fig. 3), which was reasonable due to the expected measurement accuracy of the entire system. This behavior also applies to many other configurations and can be checked with a simulation first. Therefore, fixating the z-value at the approximate wither height (1.5 m) should not lead to large deviations in somewhat smaller or larger cows. This may need to be adjusted for lying cows, though.

2.2. Measurements

2.2.1. Collision rate verification

The verification of the collision rate was carried out with long-term measurements (at least 60 min). In the test scenario, the collision rate of a complete RTLS with 4 anchors spanning an area of 5 m × 9 m was analyzed. For this measurement, the tags were positioned in the middle of the room with line of sight to each anchor (Nüesch, 2017). The measurement was performed with 10 tags, for which the broadcast interval was set to 1 s in a first scenario (for a duration of 3711 s). In the second scenario, the system behavior of 100 tags was emulated using the same 10 tags. For this purpose, the broadcast interval of the tags was reduced to 0.1 s (for a duration of 4073 s). The loss rate due to collision was determined on the basis of the number of blinks received over the known time period. Some blinks were not received by all four anchors, but were received by at least three remaining anchors. It was unlikely that collisions would occur at a single anchor only given the geometrical set-up. Therefore, all blinks that were received by at least

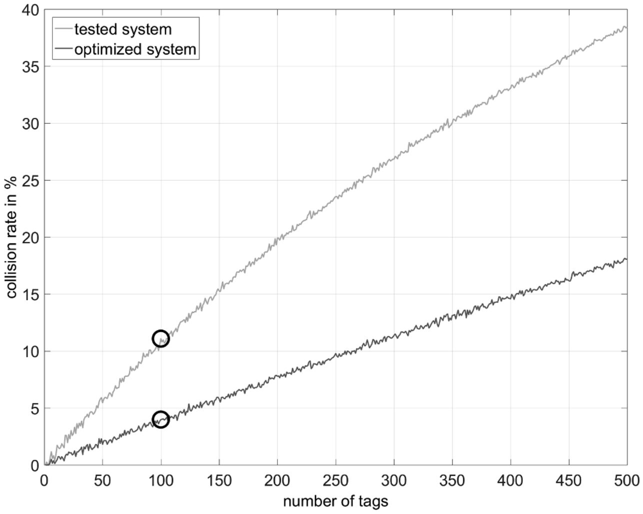

Fig. 2. Estimated and simulated collision probabilities of RTLS.

three anchors were considered as non-collisions.

2.2.2. *Static performance of the RTLS 1*

A first series of measurements were collected in a barn compartment that measured approximately 16 × 16 m (Fig. 4, top). The anchors were attached at a height of 3.5 m and with a distance of 0.3 m to each wall to minimize multipath. Positions at the feed rack, in the walking areas as well as in the lying cubicles were chosen (Fig. 4, top) and two different tags were positioned at three different heights of approximately 0.5, 1.5 and 2.2 m above ground at each position. These heights corresponded approximately to a lying and a standing cow. As described above, we did not attempt to estimate this height using the RTLS system but we wanted to check how much the precision of the system depended on the height of the tags above ground level. The 2.2 m were chosen additionally outside the range of cow sizes because at that height interference of barn equipment was thought to be minimal. In each location (position × height combination), at least 100 localization estimates were collected. The deviation of the localization estimate from the true position was taken as a measure of the precision of the measurements.

Statistical analysis: The data collected were evaluated using linear mixed-effects models based on the functions lmer (package lme4, Bates et al., 2015) in R 3.4.0 (R Core Team, 2017). We used the log-transformed distance between the location estimates of our RTLS and the location as measured by a theodolite (Trimble Tachymeter 3305 DR, Trimble Inc., Sunnyvale, CA, USA) as the outcome variable of a statistical model. We checked assumptions on the errors and random effects using a graphical analysis (package DHARMa, Hartig, 2017).

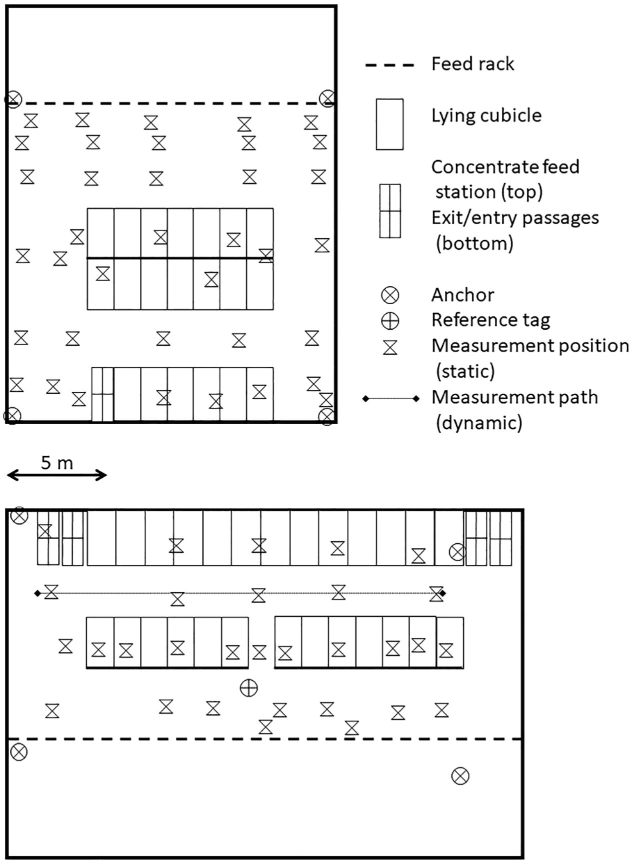

Fig. 4. Barn lay-out for the first static measurement (top) and for the second static measurement as well as the dynamic measurement (bottom).

We included the distances from the barn center in the X and Y direction (continuous), the halves of the barn in the two directions (two level factors: left-right and front-back, respectively), and height (three-level factor: low, middle, high corresponding to approximately 0.5, 1.5 and 2.2 m above ground) as fixed effects. We allowed for up to the three-way interaction between the distance in the X-direction, left-right, and height on the one hand as well as between the distance in the Y-direction, front-back, and height on the other.

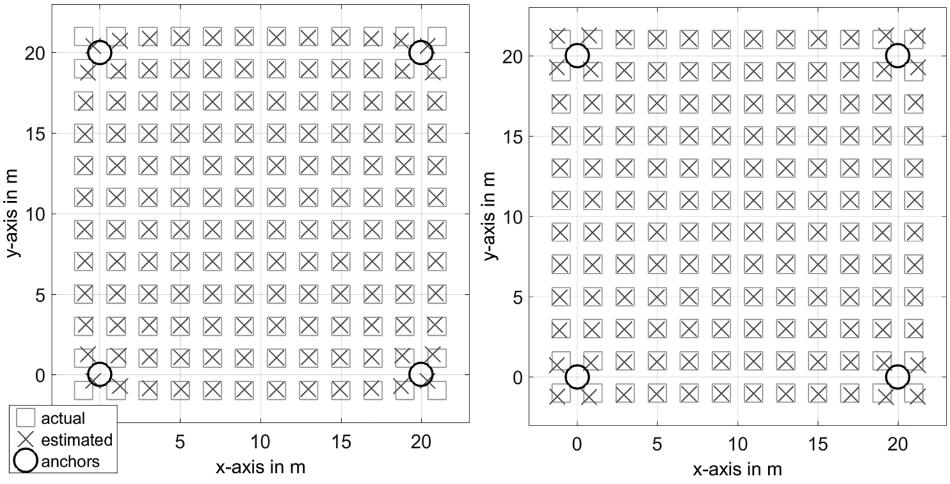

Fig. 3. Influence of height estimated too high (+0.5 m; left) or too low (−0.5 m; right) for 3D localization in RTLS based on TDoA.

Table 2
Measured collision rate of the current system.

Packet interval [s]	Duration [s]	Sent UWB packets	Received UWB packets by all four anchors	Measured collision rate	Simulated collision rate
1	3711.0	37,110	36,606	1.4%	1.1%
0.1	4073.0	407,300	365,285	10.3%	10.7%

Sum-contrasts were used for all factor variables and continuous variables were centered for the statistical model to allow for the interpretation of main effects in the full model even in the presence of interactions (Forstmeier and Schielzeth, 2011). P-values were calculated using parametric bootstrap (Table 4; package pbkrtest, Halekoh and Højsgaard, 2014).

We included the position ID (where three different heights were measured), the measurement ID (a given height at a given position), and tag ID as the random effects to account for dependency in the single measurements.

2.2.3. Static performance of the RTLS 2 with 10 tags

A second series of static measurements was made using 10 tags at the same time. The tags were mounted on two “tables” carrying 6 and 4 tags respectively such that they had fixed offsets in relation to each other. These measurements were taken in a barn compartment measuring approximately 12 × 25 m (Fig. 4, bottom). The loss of data was relatively high because of the metal sides of the passages that led to the exercise yard. Two series of measurements were conducted. In the first series, the tags were always positioned at a height of approximately 1.5 m, in the second at 1.5 and 0.5 m. We report some descriptive statistics in respect to the deviation from the true localization.

2.2.4. Dynamic performance of the RTLS with 6 tags

Using the same arrangement of 6 tags mounted on one table, we also conducted some dynamic measurements. To do so, the table was carried at a height of approximately 1.6 m along the grove for the pulley of the manure scraper between the two rows of lying cubicles (Fig. 4, bottom). Here, we show graphically the deviation perpendicular to the grove when the tags were moved.

2.3. Reference system

A theodolite (Trimble Tachymeter 3305 DR, Trimble Inc., Sunnyvale, CA, USA; angular precision: ± 2″; distance measurement: ± 3 mm) was used as reference system for determining the positions of the system components. During commissioning both the anchors and the reference tag were calibrated with the theodolite. During the measurements the reference positions of the tags were recorded with the theodolite.

2.4. Cost of the RTLS system

An overview of the approximate hardware cost of the system used is given in Table 3. The total cost of the anchors and the tags for 100 cows would therefore be approximately 2800 US$, with a production quantity of 10,000 tags.

Table 3
Approximate estimate of the system cost in US$.

Tag, electronics	$ 19
Tag, casing	$ 1
Total tag, cost per animal (sum of the above)	$ 20
Anchor, electronics	$ 20
Clock Distribution Box (CDB), electronics	$ 100
Clock Distribution Box (CDB), casing	$20
Central Location Engine (CLE, laptop computer)	$ 500
Twisted pair cables	$100
Total fixed installations (incl. 4 anchors; composed of the amounts listed above)	$ 800

3. Results and discussion

3.1. Collision rate verification

The loss rate due to collisions for the situation with 10 tags and with emulated 100 tags was measured at 1.4% and 10.3% respectively (Table 2, Nüesch, 2017). These actual collision rates coincide well with the modelled values. Given the measurement frequency of 1 Hz, a localization estimate is missed once every 6 to 120 sec (depending on the number of animals) on average. Most scientific and practical applications would seem to be able to deal with such misses.

3.2. Measurement of static positions 1

On average, the measurement error of the system as measured by the deviation from the position determined by the theodolite was (1) higher with increasing distance from the barn centre in both, the X and Y direction, (2) higher on the right versus the left-hand side, (3) higher at the back in comparison with the front part of the barn, and (4) decreased with increasing height above ground (Table 4, Fig. 5).

These average patterns were modulated as follows (statistically reflected by interactions; Table 4, Fig. 5). There was a clear increase of measurement error with the distance from the barn center in the X-direction on the right side of the barn but not on the left side where measurement error remained more or less constant with increasing distance. Nevertheless, this increase was stronger, the lower the tag position above ground. Similarly, the increase in measurement error with increasing distance from the barn center in the Y-direction was stronger the lower the position of the tag.

As could be expected, the deviation of the RTLS localization estimate from the true position was larger at the edges of the barn. This effect was more pronounced in the specific setting on the left-hand and back part of the barn, which were tighter and included more metal structures (e.g. the concentrate feeder). At the middle and low height above ground there were several specific locations that had higher measurement errors than on average (the grey dots are above the black lines in Fig. 5). The overall error, specifically in the more open front and left part of the barn was very low at around 0.3 m. This is clearly lower compared with what has been found in other systems (Gygax et al., 2007; Wolfger et al., 2017).

The between measurements variance (the error in the model) amounted to 0.047 (on the log scale). The variability that was estimated based on the variance component of the position, that is, the variance between positions in the barn that could not be explained by their coordinates was 0.063. The variance between the measurements, that is between locations in 3D space that could not be explained by the coordinates nor the height above ground was estimated to be 0.098. Finally, the variance between the two tags was estimated as 0. This is a likely indication that a numerical optimization problem occurred. Nevertheless, in a model omitting position ID in the random effect, the variance between the two tags was also estimated at a low value of 0.001. Obviously, an estimated variance component based on only two observations needs to be considered somewhat unstable. Nevertheless, the technical capability of the two tags seemed to be very similar given these results. The variability (measurement error) was similar for the

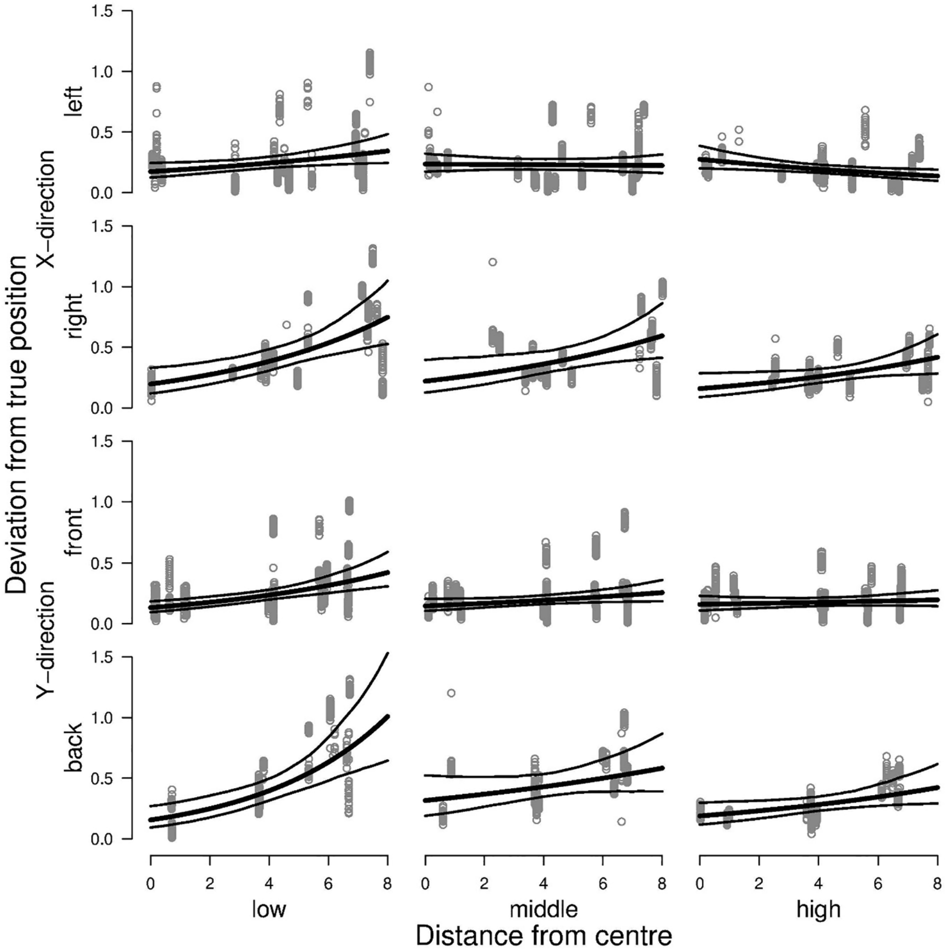

Fig. 5. Deviations from the true position (measurement error) in dependence of the height of the tags (low, middle, high) and their distance from the barn centre in X- and Y-direction for the two halves of the barn in these directions (left-right, back-front). Grey circles indicate single localization estimates.

repeated measurements at a given position, the different heights at the same position and between different positions.

3.3. Measurement of static positions 2

The deviations of the localization estimates from the RTLS were smaller than in the first series of measurements and reached low values of 0.01 to 0.02 m in the median (Table 5). The second series of static measurements could support the results of the first part and showed that the specific barn configuration can influence the precision of the location system to a high degree.

Table 4
P-values for a full model analysis of the different fixed effects included in the analysis of the measurement error. Sum-contrasts were used for factors, the continuous variables were centered. See also section on statistical methods.

Predictor variable		p-value
Global test (all predictor variables)		0.001
Main effects:	Distance from centre in X-direction	0.009
	Side of barn (left-right)	0.004
	Distance from centre in Y-direction	0.002
	Barn-halves (forward-backward)	0.001
	Height of tag (low, middle, high)	0.005
Two-way interactions:	Distance X × side	0.004
	Distance X × height	0.024
	Side × height	0.61
	Distance Y × halves	0.32
	Distance Y × height	0.003
	Halves × height	0.14
Three-way interactions:	Distance X × side × height	0.29
	Distance Y × halves × height	0.54

3.4. Dynamic behavior of tags

When moving the tags in 2D along the activity area at a speed of approximately 0.6 m/s, the RTLS estimation remained within a corridor of approximately 1 m width, that is, with a deviation of at most 0.5 m (Fig. 6). As could be expected, the tags were shifted parallel to each other according to their fixation position on the table. Some consistent and general pattern could be observed in all the tags with a “dip” (lower values on the y-axis) around 7–8 m from the left (Fig. 6). These dynamic localization estimates therefore reached a similar precision as with the static measurements. It is not really clear where the systematic deviation stems from but it is likely that barn equipment is responsible for the shift of the estimates from the actual straight trajectory. Large deviations were rarely observed and may have been due to slanting the table when turning around at the end of the trajectory. It is noteworthy that these extreme deviations were only observed at single localization estimates, which indicates that a smoothing across very few localization estimates could deal with these deviations.

4. Conclusions

In our approach, we reached a precision of 2D position estimates that was at least as good as in commercial systems at the fraction of their price. The system can be tailored also to specific needs with reasonable effort. Therefore, our results seem promising enough to proceed

Table 5
Deviations [m] between the localization as estimated by the RTLS and the localization as measured by the theodolite.

	Min	25% quantile	Median	75% quantile	99% quantile	Max	# localizations	# locations
1st series at 1.5 m, 4–6 tags/location	0.00	0.01	0.02	0.05	0.29	32.09	30′267	35
2nd series at 1.5 m, 1 tag/location	0.00	0.00	0.01	0.01	0.02	0.13	4′666	6
2nd series at 0.5 m, 1 tag/location	0.00	0.01	0.02	0.06	2.13	51.80	12′435	18

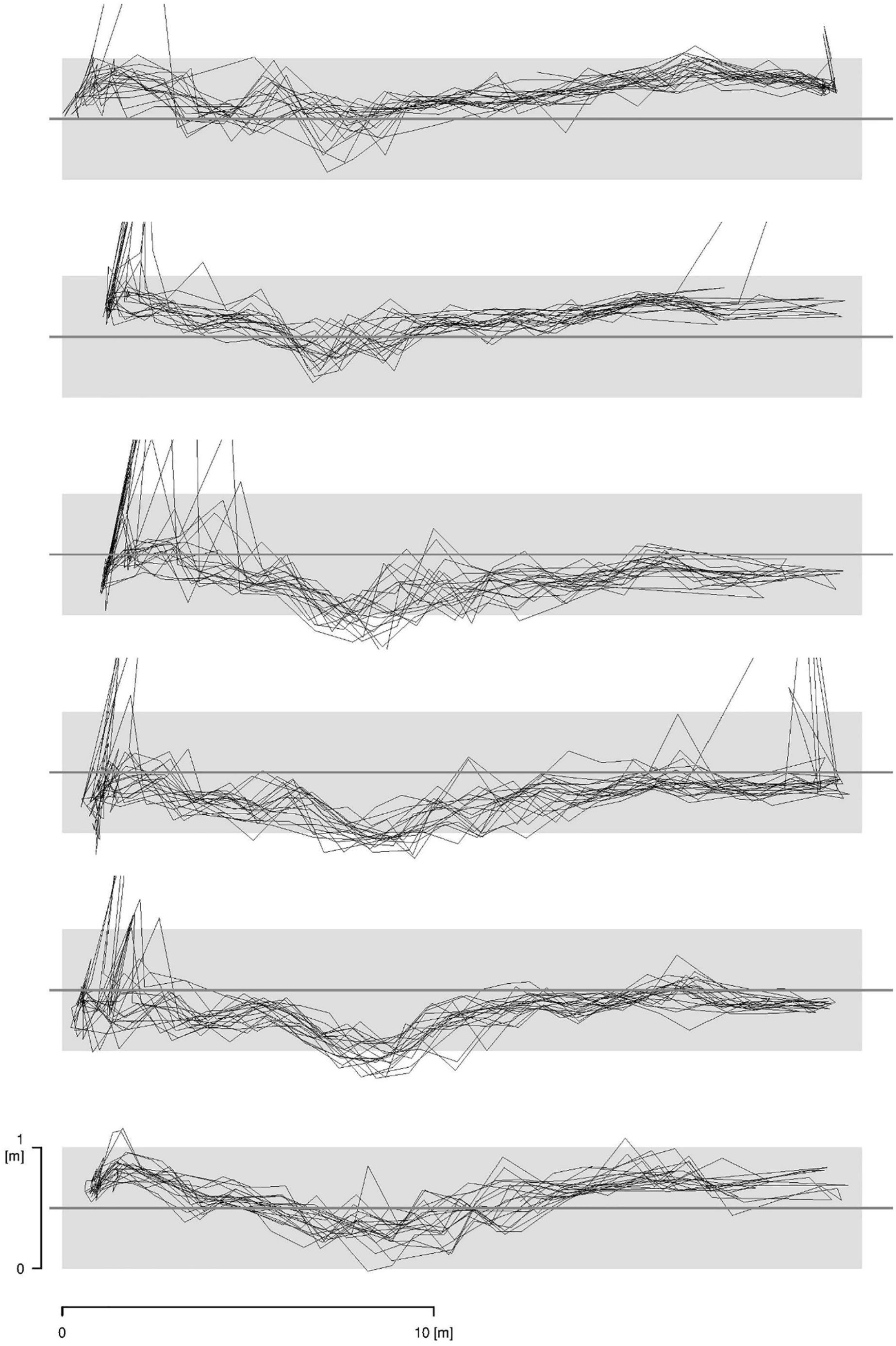

Fig. 6. RTLS localization estimates for the dynamic measurements for each of six tags mounted on the same table. The table was moved on a straight line in the X-direction. The grey line indicates the mean of all measurements in the Y-direction and the grey area a corridor with a total width of 1 m along the mean value.

with the testing the position system based on DecaWave technology using real cattle. It should be possible to track cows precisely enough to infer in what area they reside to supervise how well their basic needs are met, i.e. how long they spend time in e.g. the lying cubicles (lying) or along the feed rack (feeding). The system may even be precise enough to estimate distances between animals and infer their social relationships, i.e. which animals are consistently close to each other. The system is also usable for other livestock species that can carry a neckband such as goats or sheep. In order for the system to become applicable with pigs or smaller livestock such as poultry, the tags would need to be further miniaturized. All in all, the system is likely to empower the researcher interested in spatially locating farm animals and could provide also useful information for the practitioner.

CRediT authorship contribution statement

Philippe Hindermann: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization. **Stefan Nüesch:** Software, Validation, Writing - review & editing. **Daniel Früh:** Methodology, Validation, Investigation, Resources, Writing - review & editing, Supervision, Project administration. **Andreas Rüst:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Lorenz Gygax:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Agroscope, Tänikon, for the opportunity to conduct measurements in their barns and M. Keller for support of the installations in the barn. This project was funded by grant No. 2.17.3 from the Federal Food Safety and Veterinary Office.

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