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Non-Invasive Sensor Technology for the Development of a Dairy Cattle Health Monitoring System

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Abstract: The intention of this research is to establish a relationship between dairy cattle diseases with various non-invasive sensors for the development of a health monitoring system. This paper expands on the conference paper titled "Sensor technology for animal health monitoring" published in the International Journal on Smart Sensing and Intelligent Systems (s2is) for the proceedings of International Conference on Sensing Technology (ICST) 2014. This paper studies and explores particular characteristics of dairy cattle's health and behavioural symptoms. The aim is to consider the nature of the diseases a cow may have and relate it with one or many sensors that are suitable for accurate measurement of the behavioural changes. The research uses ontological relationship mapping or ontology matching to integrate heterogeneous databases of diseases and sensors and explains it in detail. This study identifies the sensors needed to determine illnesses in a dairy cow and how they would be beneficial for the development of non-invasive, wearable, smart, dairy cattle health monitoring system to be placed on the cows' neck. It also explains how the primary sensors identified by this research can be used to forecast cattle health in a simple, basic manner. The scope of this paper is limited to the discussion about the non-invasive, wearable sensors that are needed to determine the cattle diseases. We focused only on non-invasive sensors because they are easy to install on cows and no training is required for them to be installed as compared to invasive sensors. Development of such a system and its evaluation is not in the scope of this paper and is left for our next paper.

Keywords: wearable sensors; sensor technology; embedded system; precision dairy farming; dairy cattle health; ontological relation study; intelligent systems; design and development; non-invasive wearable sensors

1. Introduction

This paper expands on the conference paper titled "Sensor technology for animal health monitoring" published in the International Journal on Smart Sensing and Intelligent Systems (s2is) for the proceedings of International Conference on Sensing Technology (ICST) 2014 [1].

The agriculture industry, including livestock/dairy farming, is crucial to the European economy. The extent of dairy farming throughout the world and Europe has significantly grown in the past few years. The dairy farms have grown larger (>200 cows) and become largely profit-driven ventures. The main reason for this development is the competition, market pressure, and a significant reduction in the cost of liquid milk. This turnaround has stipulated a major upgrade of technology and equipment to reduce expense, labour costs and simultaneously boost profits [2].

At present, there are 13.7 million farms in the European Union, out of which 2.5 million are dairy farms. Of those farms, 5% or 126,000, have a herd size greater than 50 cows, 93,000 farms between 50 to 100 cows and 33,000 greater than 100 cows (<200 cows), with over 2 million farms with less than 50 cows [3,4].

Of all these dairy farms, about 3%–4% speculate in new milking parlours each year, which catalyses a considerable market for dairy cattle health monitoring system sales [2,3,5,6].

The overall objective of this paper is to research and identify the principal dairy cow diseases and to determine the non-invasive, wearable sensor types required to aid in the monitoring of disease symptoms. This, in turn, will lead to the research and development of automated solutions for animal health monitoring for application within the livestock industry, focussing on the dairy industry. The resulting system will continuously monitor the dairy cattle's health in order to maintain high milk quality, predict the presence of abnormal health issue to prevent its spread and have a significant bearing on farm profitability. To observe an animal's health, it is important to develop a per-animal unit that will collect bio-medical data from sensors and wirelessly transmit this data to a base station. The sensors will be chosen through the assessment of which sensors are necessary for the detection of the presence of any abnormal behaviour in the cattle. This paper presents the methodology used to determine the relevant sensor that may be used to develop a dairy cattle health monitor.

This research provides an in-depth study of specific diseases that are common in dairy animals and develops an ontological relationship mapping specific animal behaviours to these illnesses. The ontological model is further extended to include sensors that can be used to detect these symptoms and their related diseases. The designated sensors are vital to the development of the next generation of a health monitoring system prototype for dairy animals. This paper will only include non-invasive sensors that can be fitted into an embedded hardware device for placement on the cows' neck. Invasive and implantable sensors are out of the scope of this project.

2. Background Study

The conference paper titled "Sensor technology for animal health monitoring" published in the International Journal on Smart Sensing and Intelligent Systems (s2is) for the proceedings of ICST 2014 describes the diseases of dairy cattle in brief. It also defines what sensors are and why to use sensing on animals, their categories and types [1]. Hence, it will not be repeated in this research paper.

This paper will look at the impact of these diseases to the farmer and the measurable indicators of the diseases will be considered to further form the basis of the sensor study. All the important diseases of the dairy cow have been studied and are shown below in Table 1.

Table 1. Dairy cattle diseases.

Health Events	
1.	Mastitis
2.	Lameness
3.	Cystic Ovarian Disease (COD)
4.	Displaced Abomasum
5.	Ketosis (Acetonaemia)
6.	Milk fever
7.	Retained Placenta
8.	Bovine Viral Diarrhoea (BVD)
9.	Heifer Pneumonia or Bovine Respiratory Disease (BRD)

All the animal illnesses have the capability to affect the human population directly or indirectly. This can happen by either reducing the quality of the food or the quantity of the food or by a decrease in other livestock products such as dairy and may also be by a reduction in animal power (such as in transport). Anyhow, it affects the production and hence causes financial and livestock loss to human, decreasing their assets [7].

A brief summary given by Bill Woodley at Shur-Gain on the data obtained from the United States on the culling rates of illnesses indicates that the top 3 health issues are mastitis, infertility and lameness in dairy cattle and that these problems are on the rise continuously. Table 2 provides an overview of the main health problems in cattle [8].

Table 2. Percent of cows by health problems [8].

Percentage of Cows by Health Problems			
Problem	**NHAMS Dairy 1996**	**NHAMS Dairy**	**Trend**
Mastitis	13.40%	16.50%	↑
Lameness	10.50%	14.00%	↑
Infertility problems	11.60%	12.90%	↑
Retained Placenta	7.80%	7.80%	↔
Milk fever	5.90%	4.60%	↓
Displaced abomasum	2.80%	3.50%	↑
Respiratory	2.50%	3.30%	↑

These diseases form the basis of this study and will enable estimation of the sensors required to detect these illnesses, helping to avoid the adverse impact on the cow health and welfare. The health status of the cow has a significant effect on the farm profitability by increasing the calving-to-conception intervals and increasing or reducing milk yield components. The greater longevity of the cow is directly proportional to the profit per cow for the farmer as there is more milk produced and a smaller investment in breeding for replacements. The health issues that directly impact the production cause an increase in treatment costs and reduced output and can be instantly noticed by the farmers [4].

The health problems of cattle considered herein can have a different impact on the cows and their productivity. Some illnesses can cause a high impact on production while some can cause a significant risk of the longevity of the cow. Some can influence the complete herd health, and some can cause international trade concerns. Some diseases can cause widespread zoonotic risks that can be a great concern for trade and human health as well [4].

Table 2 shows that mastitis and lameness are most occurring diseases in the dairy cattle. Other prevalent conditions are reproductive disorders and metabolic diseases such as cystic ovarian disease (COD), displaced abomasum, retained placenta, ketosis, milk fever. These diseases reduce the profitability of the farm severely by affecting the investment and by the lack of available health and welfare monitoring systems.

The cows are more commonly housed in groups rather than individually nowadays considering their health and well-being, but this makes the spread of disease easier and faster within the herd. Hence, use of sensors can be a helpful tool to determine the cow that may fall sick and predict the risk of the transition health diseases of the cattle and the herd in advance to save the losses that may be incurred due to the spread of these diseases [9]. This leads to the development of a sensor box prototype to monitor dairy cattle health.

The summary of diseases with respect to their economic impact on the farmer and the key measurable indicators is developed as a Table 3 shown below.

Table 3. Economic impact and measurable indicators of cattle diseases.

	Impact to Farmer	**Measurable Indicators**
Mastitis	€37.6 million (Nationally 2013) Total farm costs (€): 61,085–177,343 [5]	High temperature Reduced mobility Swelling, reddening and hardness of udder Irregularities in milk Diarrhoea, dehydration [5]
Lameness	The cost to a typical 100-cow herd are: No. Cows affected: 20 1.4 episodes of lameness @ €296.61 per cow [10] €200/lameness case [11]	Digital or hoof lameness (white line disease, solar haemorrhage, laminitis, slurry heel) Inter-digital infections (digital dermatitis, foul-in-the-foot, inter-digital dermatitis); and Solar ulcers [10]

Table 3. *Cont.*

	Impact to Farmer	Measurable Indicators
Cystic Ovarian Disease (COD)	Each episode of COD costs the producer $137 per lactation [12]	Appearance of raised tailhead Formation of cyst(s) in the ovary/ovaries Bullying behavior Excessive mounting, standing and bawling with the noticeably deeper tone Inconsistent milk yielding General metabolic changes Rough, dry hair coat Nervous tension Disturbed feeding and rumination [12]
Displaced Abomasum	Daily losses of R$17.21 (US$10.12) per sick cow Each animal cost R$417.00 (US$248.00) [13]	Lack of appetite Milk production and rumination reduction are the primarily frequent symptoms Diarrhoea, a distended abdomen and mild colic Twisting (torsion) occurs—a difficulty common in Right Displaced Abomasum Distress Decreased temperature Elevated heart rate Ketones will be present [14]
Ketosis (Acetonaemia)	£23,000 per year for every 100 cows [15]	Reduced milk yield Weight loss Reduced appetite Dull coat Acetone (pear drop) smell of breath/or milk Fever Some develop nervous signs including excess salivation, licking, aggression [16]
Milk Fever	Exceeds $400 (~280 Euros) per cow [17]	Exhilaration or anxiety Muscle trembles in the head and limbs Stumble Lying Down and can't stand Lethargy Low body temperature [18,19]
Retained Placenta	Total £s per affected cow: 274.00 [20] Loss was 2,139 pounds per year [21] Total average financial loss per case is $206, typical loss of $3,090 per 100 calvings per year [22]	Calf's membranes fail to separate from the mother cow [23]
Bovine Viral Diarrhoea (BVD)	Cost per cow per year €63 Total costs €71.7 million Average of naïve herd costs at €57/cow/year and PI herd costs at €69/cow/year [24]	Weakness and thinning Inappetence Lose watery stool with mucus and sometimes blood Loss of milk production Death if not treated at the right time [25]
Heifer Pneumonia or Bovine Respiratory Disease (BRD)	£80 million annually [26] £82 per suckler calf, £43 per dairy bred calf [27,28] Long term cost of disease £243 per animal, £1,008 per annum [28]	Fever Depression Inappetence Serious nasal and eye discharge Purulent nasal discharge Bloody nasal discharge Stiff gait Mild diarrhea Rapid, shallow breathing Soft coughing [26]

As can be observed from the Table 3 above, cattle diseases cost the dairy industry a significant amount. In addition, the impact on the farmer for Irish dairy industry for some of the diseases is not available even after thorough research. The parameters to decide the impact were not consistent for accurate determination of the diseases according to the economic cost specifically in the Irish dairy industry. Hence, wherever not available, the data from other countries was referenced. In addition, there was an immense difference between the consideration parameters assumed in each study for the determination of the costs, such as some studies measured overall country costs, others calculated for individual cow costs, whereas some study calculated the cost according to various heard sizes of 100 or thousand cows and so on. Hence, an accurate estimation of the prioritisation of diseases based on their impact on the Irish dairy industry is currently not feasible.

3. Methodology

When any disease affects a cow, her behaviour shows alterations and the quality of her milk depreciates. A farmer or stock person can detect these changes within a few minutes or hours. Nevertheless, keeping an eye on a large herd can be a bit of a challenge and steps for prevention or treatment may be taken a bit too late in some cases. That is where the need for sensors based health monitor arises. New and modern observation technology is required to detect more information, to determine and detect the changes in the behaviour of the individual cow, and to be more observant towards the welfare of the entire herd. Due to the increase in the size of the dairy farms that are completely automated and roboticated; and conventional milking is being transformed into automatic milking systems (AMS), the regular human-cattle interaction has almost vanished. Hence, other methods of observing the behavioural changes have become highly necessary for the well-being of the herd such as advanced sensing and intelligent processing [23]. This section discusses the process of sensor selection by the relation with the disease in the following subsection.

Ontological Relation Study of Diseases and Sensors

The method used for assessing sensor is an ontology. "Ontology is a knowledge tool that enables information manipulation, especially the meaning, by representing knowledge in a domain concept unit and assigning a meaningful relationship between concepts. An ontology model is very friendly for structuring information and can easily represent both mutual relationship and partial situation information." [24].

Changes in the cow's behaviour act as a mirror to changes in the cow's health. For example, if we consider a cow is infected with mastitis, she starts displaying behavioural changes in a few hours, and her milk quality begins to deteriorate quickly. The cow becomes restless within four hours after it is infected with mastitis, and the inflammation starts to spread displaying its signs such as high body temperature, swelling of the udder starts becoming visible [23].

A farmer who milks his cow can detect the onset of mastitis two hours after the cow gets infected. Whereas, in the conventional milking parlours, it may be detected during a milking session and in automated or robotic milking stations it can be detected during milk testing or very late when a cow fails to enter the milking station either once or on several events. Which can be very late for the cow and her welfare and mastitis may be at a higher stage [23].

So, using an ontology for forming a relation between the symptoms of cattle diseases and sensors, diseases have been grouped together according to the similarities cow shows in its health aspect and thus the behavioural changes. It is then correlated to the sensors that can monitor and sense the behavioural change. Diseases with similar symptoms are grouped together for brevity. For example, here, Displaced Abomasum and Ketosis have been grouped together considering the similar impact they have on animal health and the resulting symptoms.

The first stage of building any embedded system is to gather system requirements, the second is hardware development and finally, development of software to run on the system. Hence, in this paper, more consideration is being given to system requirement, majorly which sensors are to be included to develop sensor box capable of detecting dairy cattle diseases. Moreover, distinguishing individual diseases depends totally on the (software) algorithms which will be discussed in detail in next paper as it is out of the scope of the current paper.

Several cow diseases are discussed and how they affect the cows' behaviour through the symptoms and clinical signs of the disease present in the affected cow has been discussed in detail in the research paper [8]. After carefully analyzing the diseases, a table for mapping these conditions to the relevant sensors considering the aspect of animal health and coherent behavioural changes the cow exhibits in that illness, sensors were mapped to it as can be seen in Table 4 below [8].

Here, the information from the cattle health situation is being applied by using the cows' aspect of health and how it is related to the behavioural changes and reflected as a sensor based entity to be able to detect the cows' health.

Table 4. Disease and sensor relation.

Disease	Aspect of Animal Health	Behavioural Changes	Sensor
Fever	High temperature	-	***Temperature*** *(Neck)*
	Discomfort	Less activity	***Accelerometer*** *(Neck)*
	Bellowing (Distress)	Mooing	***Microphone*** *(Neck)*
Lameness	Motion changes	Standing or sitting	***Accelerometer*** *(Neck, feet, udder)*
	Reduced feed intake	Less grazing	***Accelerometer*** *(Neck)*
	-	Abnormal back arch	Camera (External location)
	-	Non-uniform weight division	Load sensor (Under Feet)
Oestrus	Hormone level (e.g., Estrogen, Progesterone)	Restlessness	***Accelerometer*** (around the neck, feet)
	Yield (Decreased)	Less grazing	***Accelerometer*** (neck, near tail or sacrum)
	Standing to be mounted	Increased activity	***Accelerometer*** (around the neck, feet)
Mastitis	Lying behaviour	Less time lying down	***Accelerometer*** *(Neck)*
	Reactivity during milking	Stepping, lifting and kicking	***Accelerometer*** (around the neck, feet)
	Weight distribution	Weakness/weight shifting	Load sensors (Under Feet)
	Pain, Discomfort, Bellowing	Restlessness	***Accelerometer*** (around the neck, feet), ***Microphone***
	Reduced feed intake	Less grazing	***Accelerometer*** *(Neck)*
Ovarian cysts	Hormone level (e.g., Progesterone)	Restlessness and increased activity	***Accelerometer*** (around the neck, feet)
	Yield	Less/more grazing	***Accelerometer*** (neck, near tail or sacrum)
	Bellowing	Mooing	***Microphone*** *(Neck)*
	Temperature	High/low temp	***Temperature*** *(Neck)*
	Milk quality	Electrical conductivity	Electrical conductivity sensor (Udder)
Displaced Abomasum, Ketosis	Feeding	Grazing	***Accelerometer*** *(Neck, feet)*
	-	Rumination	***Microphone + Accelerometer*** *(Neck)*
	Breathe ketones	-	Gas sensor (Nose)
Milk Fever, Retained Placenta	Movement/motion	Excitement/stiffness	***Accelerometer*** *(Neck)*
	Bellowing	Mooing	***Microphone*** *(Neck)*
	Weight distribution	Weakness/weight shifting	Load sensors (Under Feet)
	-	Temperature	***Temperature sensor*** *(Neck)*
	-	Pulse	Heartbeat sensor (Vein on neck), ECG (Near to the heart)
Diarrhoea, Pneumonia	Fever	High temperature	***Temperature sensor*** *(Neck)*
	Nasal discharge	Running nose	-
	Cough	Coughing sound	***Microphone*** *(Neck)*
	Increased respiratory rate	Sound of breathing	***Microphone*** *(Neck)*
	Decreased appetite	Less grazing/feeding	***Accelerometer*** *(Neck)*

As we can see from the Table 4 above, the temperature sensor appears 4 times, the accelerometer appears 16 times, microphone appears 7 times, load sensor appears 3 times. However, camera, electrical conductivity sensor, gas sensor, ECG and heartbeat sensor only appear once in Table 4.

Other sensors mentioned in Table 4 have been discarded from use in this project due to the following reasons:

1. Camera—can be costly and not very advisable to be placed on the cow as it can be easily damaged due to environmental conditions. Cameras are better to be positioned in the barn area. It is not very necessary as it only occurs once in the table [29,30].
2. Heartbeat sensor—It also occurs only once in the table. It is not feasible as it can be invasive. The pulse can be felt through an artery in the cow's neck, near her jaw [31] and also through the facial artery which passes over the mandible near the angle of the jaw. However, this can be difficult to find and requires the animal to keep still [32]. The device will be moving around the neck and hence is not useful if the device has to be non-invasive.
3. ECG—It also occurs only once in the table. ECG records the electrical activity of the heart including the timing and duration of each electrical phase in your heartbeat. ECG electrodes have to be placed near to the heart of the cow, immediately behind the withers (third to fourth inter-rib space) and the second electrode in the pericardium area [33].

   ECG sensor is not included in the box because:

(a) If we place the accelerometer and microphone near to cow's heart so that we can also include them with ECG sensor in one sensor box, we will not receive good quality activity signal from accelerometer as compared to cow neck as the cow moves her neck more for nearly all activities (e.g., running, grazing etc.) compared to area near cows' heart (its more static), similarly microphone will also receive less signal (mooing, grazing, rumination etc.) as now it has been placed far away as compared to neck, moreover, as in Table 4, ECG signals appears only once hence it is chosen to keep the sensor box location at neck to receive maximum activity signals.

(b) Smartex, Italy has developed a wearable wellness system for humans [34], which was also tested on horses. This unit has two textile ECG sensor and was able to remove 40% of movement artifacts from 7 h of data [35]. Although this data looks very promising but 7 h is very less testing duration for any conclusion, for our application, at least 720 h of testing is required. Additionally, there is still a huge possibility for the sensors to easily get damaged in mud or cow dung as an adult cow tend to sit more than a horse due to the fact that horses "only have to lie down for an hour or two every few days to meet their minimum REM sleep requirements" [33,36].

(c) Even if one could get a continuously accurate signal from ECG electrodes, it would almost certainly be on a customizable basis only, and the wearability would be characterised as "extremely uncomfortable" for continuous donning.

(d) ECG is only used to detect two diseases in Table 4, which can also be detected by Accelerometer, microphone and temperature sensor. Hence, to conclude we can say that it is possible to have an ECG but it can only be added as an add-on sensor for extra measurements. Though its addition will cause an increased cost [37–39].

4. Load sensor—It cannot be included in the sensor box. It has to be installed in the milking parlour as it needs to measure the load from the individual leg of the cow [40,41].
5. Gas sensor—In order to detect any gas, it will have to be placed near to the cows' mouth, or if placed in the sensor box, it will need an opening, which is not a feasible option as the sensor box should be weather proof to avoid any damages to all other electronic components. Moreover, ketosis can also be monitored be feed intake (grazing and rumination) that an accelerometer and microphone can detect [41].
6. Electrical conductivity sensor—It can be invasive in nature. This sensor should be placed at milking parlour and is not necessary to be placed on the cow [42,43].

Also, the addition of these sensors will lead to an extensive increase in current consumption in the device.

4. Results, Discussion and Conclusions

Thus, in conclusion, Figure 1 below displays the major areas of the dairy cow that can be monitored in order to understand the health condition of the cattle. Various sensors can be used to observe these particular areas for health monitoring purposes.

In addition to the areas to monitor in a dairy cow, this research has identified three primary sensors—Temperature, Accelerometer and Microphone (marked as bold and italic in Table 4)—that are primarily required to determine the health quotient of the cattle. The temperature sensor will help to determine if the cow has Hypothermia, Normothermia or Hyperthermy. The accelerometer will contribute to determining the activity or head and neck movement in the cow [1,44]. The microphone is useful in determining if the cow is bellowing in distress, discomfort, pain or if is in heat. The microphone can also pick up the sound of breathing, grazing, rumination or coughing. Thus, these sensors will help in the assessment of cattle's health.

Further work on the system utilising these three sensor types will lead to the development of the next generation, non-invasive, wearable animal health monitoring system to be placed on cows' neck. It will gather relevant sensory information, such as activity, and alterations in head and neck movement and relate the accumulated animal data to predict or identify animal health events [1].

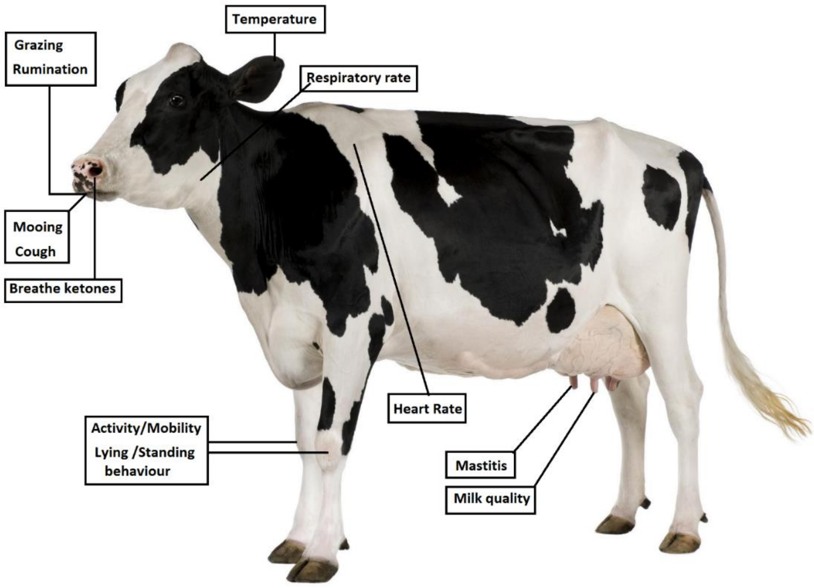

Figure 1. Areas to monitor a dairy cow.

The Table 5 below shows the basic information for forecasting cattle health. The three sensors can provide the data shown on this chart. The measurement of all the sensors will be done on the neck of the cow. These sensors can aid in the diagnosis of diseases in cattle.

Table 5. Basic information for cow health forecasting [23].

Sensor	**Category**	**Value**		
Temperature	Hypothermy	36.5–38.5 °C (Cold)		
	Normothermia	38.5–39.5 °C (Normal)		
	Febricula	39–40 °C (High)		
	Middle fever	40–41 °C (High)		
	Hyperthermy	Over 41 °C (High)		
Posture	Posture Category	Three-Axis Accelerometer		
		x	y	z
	Move freely	Variable	Variable	Variable
	Do not want to move	Constant	Constant	Constant
	Laid down and cannot move	Constant	Constant	Constant
	Keep standing	Constant	-	Constant
	Limp	Variable	-	Variable
	Lift leg up with neck movement	-	-	Variable
	S line posture	-	Variable	-
	Turn in one direction	Variable	-	-
	Stumble	Variable	Variable	-
	Cross legs, do not move	Constant	Constant	Constant
Sound	Mooing	Yes		
		No		

The information is later simplified for the output using fuzzy logic rule-based deduction engine such that it is easily understandable by the user. There is an established need for using sensors and technology to create an intelligent autonomous device to monitor the health of individual cattle and entire herd, to help the farmer provide a safe and productive environment for cattle. Thus, resulting in an increase in milk production.

The research done here is for the development of a sensor system for dairy cattle health monitoring. The sensor systems development may be described in four levels:

1. Sensor technique: Measurement of raw data for a cow (e.g., activity, temperature);
2. Data Interpretation: Interpretation that condenses change in the sensor data (e.g., increased activity) to fabricate information about the status of the cow (e.g., Oestrus);
3. Information Integration: Information can be integrated from other sensors (e.g., data from milking parlour or load cells) as an add-on for decision making; and
4. Decision-making: The decision-making depends on the farmer, or the sensor system may do it autonomously (e.g., to call doctor or farmer depending on the situation) [1,42].

Using this knowledge and the sensors determined in this paper and basic health forecasting information, the design and development of a prototype is deliberated. The said prototype will have three major elements—sensing, data processing and data analysis.

Therefore, this research proves that the diseases of the dairy cattle can be determined using various non-invasive sensors. An ontological relation study described in this paper on this topic advertently affirms this notion. The device developed using this correlation will successfully monitor various parameters of cow health such as its core temperature, head motion and (mooing) sound. Analysing these outputs using an intelligent algorithm can predict if the output values cross the threshold values. These parameters can aid in the diagnosis of the cow health issues and display an alert to inform the farmer.

Author Contributions: Joseph Walsh and Daniel Riordan conceived the idea of this project and supervised the project, Anshul Awasthi contributed towards the idea of ontological mapping; Amruta Awasthi performed background research, analysed the data for the ontological study. All authors have read and approved the final manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

BRD	Bovine Respiratory Disease or Pneumonia
BVD	Bovine Viral Diarrhea
COD	Cystic Ovarian Disease

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