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On the use of 3D camera to accurately measure volume and weight of dairy cow feed

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ABSTRACT
The paper discusses the challenges facing the dairy industry due to increased farm sizes and reduced staff-to-animal ratios, which are impacting animal welfare. The development of precision livestock farming (PLF) technologies has gained momentum to address these challenges. PLF technologies can assess animal welfare and health status by monitoring animal behavior and biological changes, and alerting farmers of any issues. However, the applicability of PLF tools in other productive phases of the dairy cattle is still limited. The article focuses on the challenges of managing unweaned dairy calves, particularly the variability in relation to when calves start consuming solid feed, and how PLF technologies can be used to monitor individual calf intake and manage weaning at the individual level. The attention is mainly focused on the advantages of using automated feeders for unweaned dairy calves, including labor savings, greater precision in measurement and control of individual intake of liquid and solid feed, and higher preweaning growth rates. In particular, a method is proposed, involving a 3D depth camera and a proper algorithm to measure the volume and weight of eaten feed. The method is preliminarily assessed in tests conducted in laboratory, which highlight a remarkable concurrence (differences as low as 2 %) with respect to nominal values.

Section: RESEARCH PAPER

Keywords: Dairy cow feed; 3D camera; volume measurements; distance measurements

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1. INTRODUCTION

Nowadays, the dairy industry is facing an accelerated trend towards larger farm sizes and higher-yielding animals [1]. Consequently, the husbandry staff to animal ratio is decreasing [2] and the implications of mass-production systems on the welfare of dairy animals are troubling the consumers [3]. In response to these challenges, the development of new technologies has gained momentum.

Precision livestock farming technologies have been developed to assess the welfare and health status of dairy animals by reducing labour demands [4]. A variety of systems using technologies (i.e., sensors, cameras, or microphones) are currently available and several countries are already investing in their development to be part of strategies to move toward sustainable agriculture [5].

Through this system, the farmer can monitor the animals' everyday lives irrespective of the size of the herd [6]. Particularly, they monitor the animal behaviours, the behavioural and biological changes that influence the animals' health and welfare status [7]. The detection of such behavioural changes triggers a warning signal, suggesting an immediate action, and leading to an early problem diagnosis or an immediate housing practices assessment [8].

Currently, the most common devices used in cattle are accelerometers to detect calving, estrus and lameness (based on activity data); cameras to determine standing heat (combined with machine learning), body condition scores (BCS), and estimate weight; reticulum boluses to monitor estrus, calving and physiological factors (i.e., body temperature or pH); and ear sensors to monitor the temperature [5].

However, there is still a lack of knowledge on the applicability of precision livestock farming tools in other productive phases of the dairy cattle.

2. PROBLEM STATEMENT

The current calf management practices need profound changes to improve dairy calf health and survival, enhance the long-time performance of dairy heifers and satisfy consumer interests in farm animal welfare [9]. The development of calves depends on prenatal and postnatal conditions. At birth, calves are defined as functional monogastric, relying on nutrients from milk or milk replacer [10].

Therefore, the pre-weaning stage represents a biological critical window that may affect the performance and overall well-being of calves for their entire life [11]. Early weaning is adopted to accelerate the early intake of solid feed and the development of the forestomach system [12]. Nevertheless, a later weaning regimen allows a smooth transition of physiological functions from the pseudomonogastric status to full ruminant status avoiding potential consequences for later health and metabolic performance [12]. In later weaning method, body maturation of calves is supported not only by milk/milk replacer but also by solid feed (concentrate and hay).

Nowadays, dairy calves are typically weaned from milk to solids according to a gradual weaning method (step-down technique) based on age [13]. It consists of gradually reducing the milk allowance, from four weeks of age until weaning. Still, even with the use of a step-down weaning program, a variability is observed in starter intakes of intensively managed calves, suggesting that the calves begin to consume starter based on their individual ability cope with early weaning [14].

Heinrichs and Heinrichs [15] reported a 27 % coefficient of variance in the age to consume 0.91 kg of starter; de Passillé and Rushen [16] reported ranges of 59 days of age for calves to first consume 0.2 kg/day of starter and of 36 days to first consume 1.4 kg/day of starter throughout the milk-feeding period (12 L/day). Similar results were reported for different levels of milk allowances ([17]-[18]).

This variability in relation to when calves begin to consume starter suggests that individuals will vary in how well they cope with early weaning. Hence, moving toward individual-based and data-driven farm management, there is growing interest in monitoring the solid intake of unweaned dairy calves and managing weaning at the individual level [16].

3. RELATED WORKS

In the last few years, there has been a growing interest in the use of automated feeders for unweaned dairy calves. The advantages of automated feeders include labor savings [19]; greater precision in the measurement and in the control of individual intakes of liquid and solid feed [16], [17]; simpler feeding of unweaned dairy calves more milk/milk replacer; and higher preweaning growth rates [10], [20].

There is mounting evidence that high preweaning growth is associated, in some way, with increased first-lactation milk yield [21], [22]. Previous research demonstrated that the same automated feeder used for milk can be used to supply starter and record both milk and starter intake independently [16], [23], [24]. They gave calves access to automated feeders supplying milk and starter, controlled by a single computer (CF 1000 CS Combi, DeLaval Inc., Tumba, Sweden). This computer recognized individual calves from their radio frequency ID (RFID) tags and independently controlled and recorded milk and starter intake for each calf. Hay and water were available ad libitum from automated feeders that weighed the intake of each calf at each meal (RIC, Insentec B.V., Marknesse, the Netherlands).

Rosenberger et al. (2017) [24] tested a step-down procedure, where milk allowance was initially reduced at 42 days of life and then again at weaning (50–54 days), providing social housing and access to forage, and observed a lack of difference in total starter intake throughout the experimental period. Still, in their conclusions, they stated that further research was needed to compare weaning protocols and identify which features are required to set up weaning protocols tailored to meet the needs of different individuals [16].

In the present study, we used a 3D camera to accurately measure the volume and weight of dairy calves during the pre-weaning period.

4. PROPOSED METHOD

The key idea underlying the proposed method is the exploitation of a 3D depth camera in order to digitize the distance with respect to the surface of the solid feed thus making it possible to estimate its volume and, knowing the density, the associated weight ([25]-[29]). In particular, the 3D camera is capable of reconstructing a suitable map of the distance of each pixel in its frame and, by means of straightforward calculations, the volume of the regions of interest. For the sake of clarity, the operating steps of the proposed method will be discussed in detail in the following with respect to an application example.

1. The first step accounts for the digitization of the framed scene. To this aim, the camera subdivides its field of view into a defined number of pixels (let us suppose, for example, $M \times N$ pixels in the whole image) ([30]-[33]). The measured values are arranged according to an $M \times N$ matrix, whose entries are the distance of the specified pixel with respect to the camera. It is possible to provide an image in fake colours, where each colour corresponds to a specific distance with respect to the camera (Figure 1).
2. The region of interest (i.e., the one whose volume we are interested in) is then determined by selecting the coordinates (i.e., row and column indexes) of two points

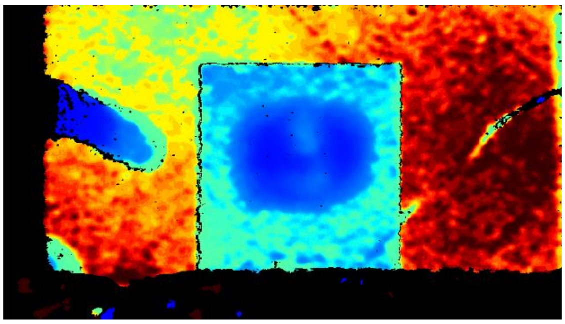

Figure 1. Example of 3D distance map represented in false colours.

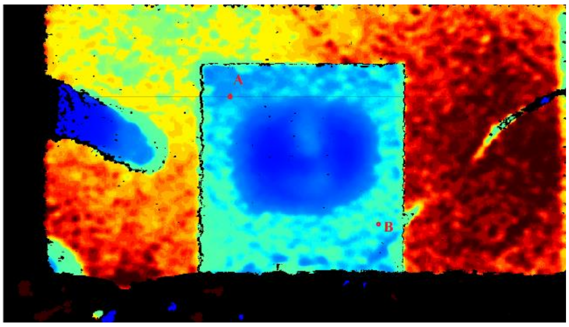

Figure 2. Determination of the region of interest by selecting two opposite points A and B.

in the acquired 3D image (as an example, the points A and B in Figure 2).

3. The coordinates of two further points are singled out (as an example, the points C and D in Figure 3) in order to define the distance of each point of the manger with respect to the camera. To this aim, the distance *d* of a generic point of the bottom of the trough (whose coordinates are referred to as *x* and *y*) is obtained according to a bi-linear approximated model:

$$d_b(x,y) = \frac{d_1\,(x_D - x)\,(y_D - y)}{(x_D - x_C)\,(y_D - y_C)} + \\ + \frac{d_2\,(x - x_C)\,(y_D - y)}{(x_D - x_C)\,(y_D - y_C)} + \\ + \frac{d_3\,(x_D - x)(y - y_C) + d_4(x - x_C)\,(y - y_C)}{(x_D - x_C)\,(y_D - y_C)} \quad (1)$$

where (x_C, y_C), (x_D, y_D), d_1 and d_4 are the coordinates of the pixel C and D, respectively; while, d_2 and d_3 represent the distances of the points whose coordinates are equal to (x_C, y_D) and (x_D, y_C), respectively.

4. The volume associated with the generic pixel (x, y) can thus be evaluated as the parallelepipedon whose height is given by the difference between the distance of the pixel from the camera $d(x, y)$ and the estimated distance of the trough at the same pixel $d_b(x, y)$. As for the area associated with the pixel, it strictly depends on the distance with respect to the camera; in particular, said Δx and Δy the base and height of the pixel and α and β the angle defining the depth field of view, the area of the pixel (*i,j*) can be expressed as

$$A(x,y) = \Delta x\,\Delta y = \\ (d(x,y)\ \tan(\alpha))\,(d(x,y)\tan(\beta)) \quad (2)$$

5. The volume of interest can be finally achieved by adding all the volumes of the pixels involved in the region of interest selected in step #2.

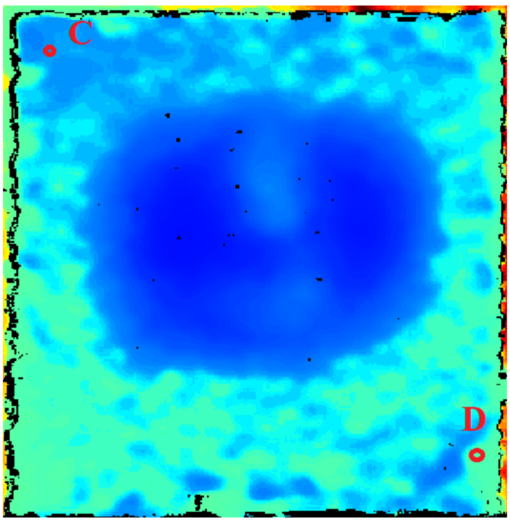

Figure 3. Determination of the trough base by selecting two opposite points C and D.

5. MEASUREMENT SETUP

To preliminarily assess the feasibility of the proposed method, a suitable measurement setup was implemented in laboratory conditions, using a 3D Depth camera, namely Realsense™ D455 by Intel© (Figure 4).

The RealSense D455 is a high-resolution depth camera developed by Intel that utilizes Time-of-Flight (ToF) technology to provide accurate and detailed depth data [34]. It is a compact, lightweight device, measuring 101 mm × 24 mm × 9.5 mm and weighing only 45 g, making it easy to integrate into a wide range of applications.

One of the key features of the RealSense D455 is its depth range, which extends from 10 cm to 10 m. This makes it well-suited for a variety of applications, including robotics, drones, augmented reality, virtual reality, and more. The camera is capable of capturing depth data with a resolution of up to 1024 × 768 pixels, as well as colour data with a resolution of up to 1920 × 1080 pixels. The RealSense D455 can capture data at frame rates of up to 90 frames per second, depending on the resolution and mode selected. It has a wide field of view, with a horizontal field of view of 91.2°, a vertical field of view of 65.5°, and a diagonal field of view of 100.6°. This allows the camera to capture a large area of the scene, making it easier to track objects and navigate through the environment. The main specifications are summarized in Table 1.

The RealSense D455 uses a USB 3.1 Gen 1 Type-C interface for data transfer and power. It is compatible with a wide range of operating systems and development environments, and Intel provides an SDK (Software Development Kit) that allows developers to create their own applications and interfaces for the camera.

In particular, the authors implemented a dedicated MATLAB™ code to control the camera and retrieve the distances measured in the framed scene. The code involves the steps of the method described in Section 4. With specific regard to the identification of both region of interest and trough base, the MATLAB function *ginput*() was exploited to allow the user to graphically determine the extent of the considered regions according to shown distance image.

Figure 4. The 3D depth camera adopted for the preliminary method assessment.

Table 1. Main specifications of the 3D camera Realsense D455 exploited for method feasibility assessment.

Specifications	Value
Depth technology	Time of Flight
Depth Range	10 cm to 10 m
Depth Resolution	Up to 1024 × 768 pixels
RGB resolution	Up to 1920 × 1080 pixels
Frame Rate	Up to 90 fps (@640 × 480)
Field of Views	87° × 58°
Communication Interface	USB 3.1 Gen-1 Type-C
Dimensions	101 mm × 24 mm × 9.5 mm
Weight	45 g

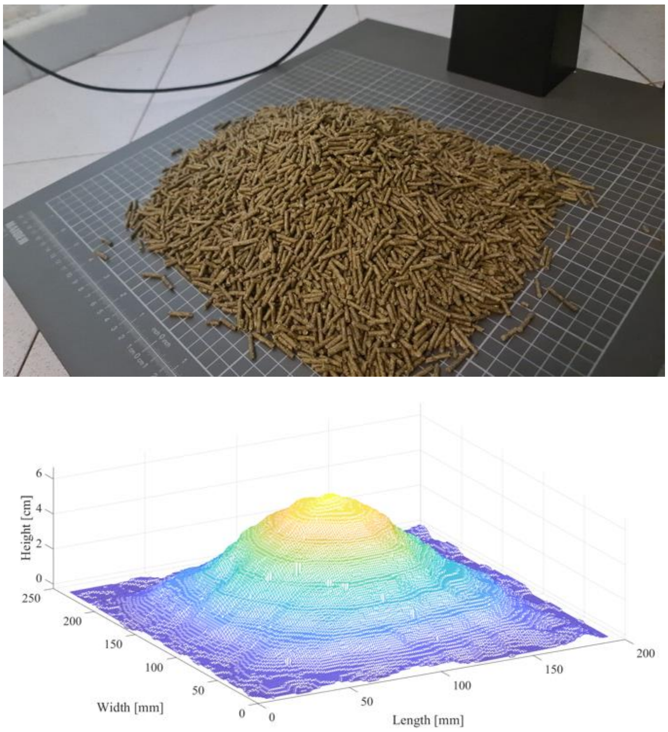

Figure 6. A picture (top) along with the reconstructed surface in the case of 1500 cm^3 of rabbit feed (bottom).

6. PRELIMINARY RESULTS

The 3D camera was installed on a camera holder whose distance from a reference plane could be modified and controlled thanks to a hand crank mechanism. The reference plane acted as the trough, and rabbit feed was exploited to assess the method's feasibility (Figure 5). The 3D camera was positioned at a distance of 65 cm from the reference plane.

A starting volume of 1500 cm^3 of feed was initially placed on the reference plane and the proposed method was applied to the acquired image. Figure 6 shows a picture (*top image*) along with the MATLAB reconstruction (*bottom image*) obtained by means of the proposed method; as for the measured volume, the value of 1490 cm^3 was obtained.

Figure 5. Realized setup for volume measurements of rabbit feed.

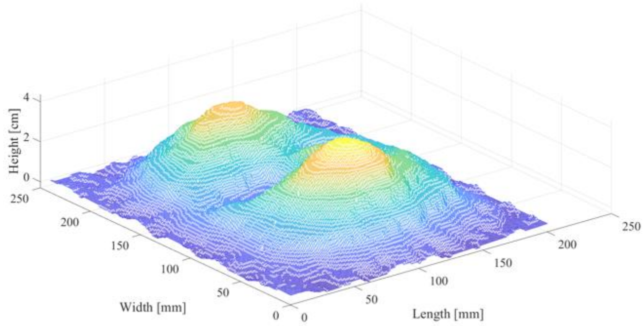

Figure 7. Reconstructed surface in the presence of nominal feed volume equal to 1200 cm^3.

The volume of feed was then reduced in two successive steps, whose value was 300 cm^3 and 200 cm^3, respectively. The associated MATLAB reconstructions are shown in Figure 7 and Figure 8, while the corresponding volume measures were equal to 1220 cm^3 and 1007 cm^3. As it can be appreciated, differences with respect to the nominal values always lower than 2 % were observed ([35]-[46]).

7. CONCLUSIONS

The paper presented a method based on both a 3D depth camera and a suitable digital signal processing algorithm for the measurement of feed volume for precision livestock farm applications.

In particular, the 3D camera provides a distance map of the framed scene, and the algorithm allows extracting measures of both the feed surface and the trough base. Geometrical considerations allow measuring the volume of feed as the sum of

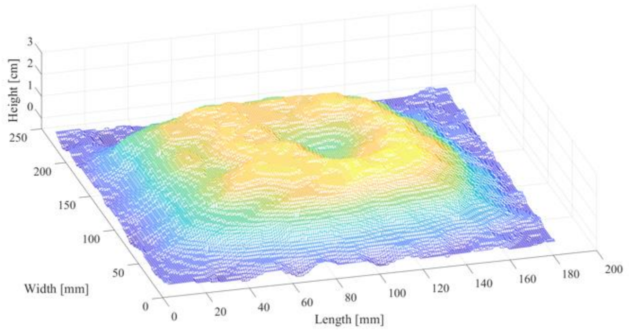

Figure 8. Reconstructed surface in the presence of nominal feed volume equal to 1000 cm³.

the volumes of all the parallelepipedon whose bases are associated with the pixel dimension at the measured distance and whose height is evaluated as the difference between the pixel measured and base-estimated distances.

Preliminary tests to assess the feasibility of the proposed method were carried out in the laboratory, employing a 3D depth camera by Intel. The volume of rabbit feed (nominally decreasing from 1500 cm^3 to 1000 cm^3) was then measured with differences expressed in relative percentage values as low as 2 %.

Ongoing activities are mainly focused on the metrological characterization of the proposed method with respect to possible parameters of the measurement setup, such as the distance and alignment of the camera, scene illumination and geometrical artifacts.

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