SPECIAL INTEREST SECTION

Electronic instrumentation of a swingletree for equid pull load monitoring: a contribution for the welfare and performance of working donkeys

JOÃO PAULO COELHO,[1,2] JOÃO BRANDÃO RODRIGUES,[3] LUÍS QUEIJO,[1] HIGOR VENDRAMINI ROSSE,[1] FRANCISCO ALBUQUERQUE,[1] ANDREW JUDGE,[3] FIONA COOKE[3] and CHRIS GARRETT[3]

[1] Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

[2] Research Centre in Digitalization and Intelligent Robotics (CeDRI), Campus de Santa Apolónia, 5300-253 Bragança, Portugal

[3] The Donkey Sanctuary, Devon EX10 0NU, Sidmouth, UK

Correspondence: jpcoelho@ipb.pt

Abstract

Equids play a fundamental role in supporting livelihoods in many parts of the world. Being able to access the animal's welfare, especially while performing tasks that involve high levels of physical effort such as those found in agroforestry activities, is of utmost importance. The Donkey Sanctuary, a UK-based international charitable institution, has designed a project that aims to develop a set of tools to evaluate the working conditions of donkeys and mules worldwide. This requires the measurement of several different parameters, including the force exerted by an animal to pull a load during work. This article presents the stages of design, development and implementation of a device capable of carrying out these measurements with minimal human intervention and with negligible impact on the task operating conditions. Data obtained from real field conditions validates the devised measurement method.

Keywords: working equids, Animal Welfare, embedded systems, electronic instrumentation, data acquisition, force measurement

Introduction

Equids are still kept for working purposes and relied upon as a major resource in many parts of the world and are essential to agricultural and industrial activities, both as pack and traction animals.[1,2] They also play a key role in strengthening human livelihoods through their contribution to economic, environmental and social capital, particularly in low and middle-income countries, where animal energy represents a vast and extremely important sustainable power resource.[3] Equids also make a wider, systemic contribution to the sustainability of agroforestry-based economies, through the amelioration of soil degradation and near optimal transfer of consumed biomass into workforce and natural fertiliser.[4] This, in turn, supports food security and economic self-reliance through a reduction in the consumption of external resources.[5] These reasons have, over recent years, contributed towards an emerging trend for the use of animal traction, as an alternative or complementary option to motorised traction, in small and medium sized farms in developed countries. The use of animal traction has also proved to be economically viable in other activities such as forest or urban surrounding management.[6]

Although there is very little doubt about their importance as a working force, the use of equids should always respect their appropriate physical limits, dignity and ensuring their health and welfare. The correct and efficient use of working equids clearly depends on how they are attached to the implement they are pulling, the weight distribution of the materials they are carrying, the quality of equipment used and also how well the animals have been trained and managed throughout their lives.[7] The way an animal is harnessed and hitched to a plough, cart, wagon or saddle can affect their overall health, welfare and ability to execute the required tasks efficiently. A poorly designed or ill-fitted, harness will cause inefficient transfer of power from the animal to the equipment, leading to decreased working efficiency and output, discomfort, fatigue and in many cases cutaneous and musculoskeletal injuries.[8]

The gathering of evidence based scientific knowledge regarding working equids, is considered a powerful tool in improving the health and welfare of working equids in developing countries, as well as for animals used in modern animal traction work.

The Donkey Sanctuary, a UK based, international charity working with donkeys and mules worldwide, designed a research project focussed on the analysis and characterisation of different harness models. The aim of this project was to better understand the interactions between working equids and different equipment while performing a set of distinct load pulling tasks. A central aspect of this project was the monitoring of the force exerted by the animals and this paper aims to describe the methodology used to obtain such data resorting to the instrumentation of a custom-made swingletree.

In the context of animal traction processes, a swingletree is a device used to balance the load during the pull and allows the harness to move freely with the equid without causing abrasions. By embedding the load cell and related electronics into the swingletree, it enables the measurement of pulling forces without disrupting the task carried out by the equid. In this frame of reference, this paper describes a novel solution devised to continuously and, with minimal human intervention, monitor the force exerted by an animal during work.

Related work

Strain gauges are transducers that can directly translate deformation variation into changes in electrical resistance. Despite their simplicity, these types of devices are ubiquitous and can be found in a myriad of different industrial, technical and scientific state-of-the-art applications. For example Huang and Ying (2017) resort to three-axis strain gauges to measure printed circuit board warping due to reflow based soldering processes.[9] In Anaf *et al* (2020), the same type of sensors are used to monitor the wood behaviour in real-time measurements.[10] Biomedics is also an area where those types of sensors are frequently employed.[11]

The use of strain gauges can also be found in the context of health monitoring and animal behaviour evaluation. For example, Chien and Chen (2018),[12] uses those type of transducers to detect the number of eggs in hens' nests and Sturges *et al* (2019)[13] resort to those types of sensors to measure the intracranial pressure in dogs.

In the equid context, a very expressive number of the scientific articles found in the literature focussed on the analysis and influence of several distinct variables on the pressure exerted by the saddle over the sport horses' backs, in response to the demands of the equine industry. The variation in pressure over the animal skin, when subjected to different types of loads is traditionally measured using commercially available saddle pressure measuring system composed of an array of piezoelectric sensors.[14-17] When compared to strain gauges, piezoelectric sensors have a high-pass frequency behaviour which makes them unsuited to steady-state or low frequency load measurements as is the case of the current work. Moreover, since the majority of the available studies are conducted regarding the influence of riding saddles and validation of rehabilitation exercises,[18] little has been explored about the injury caused by the misuse of equipment used by working equids.[19] This fact adds an increased value to this work since it focusses on the development of a measuring device that can be used to explore those lines of research.

It is worth noticing that commercial dynamometers are unable to be used in the actual framework due to several reasons: first, the measurement system must be able to withstand harsh environmental conditions that are found under real working conditions. Standard solutions found for measuring static forces are typically built to be used within laboratory conditions and not in dusty environments, subject to collisions and high variations of temperature and humidity. Second, the measurement device must not interfere with the task to be monitored. The typical shape of a dynamometer involves a load cell connected to a measurement unit through an electrical cable. This arrangement is not suited for the required application since the cables would make the measurement process difficult to manage and may even interfere with the working capacity of the equids or the normal execution of the task under real conditions. Moreover, being able to provide the type of power supply required by some of the commercial solutions, can present several logistic and technical challenges since the measurements must be carried out in remote rural locations. Finally, other factors that prevented the choice of a commercial solution are related to economic cost and ease of use. Regarding the latter, it is worth noting that equid owners themselves may need to carry out the measurement. Hence, the measurement system cannot introduce additional obstacles to the operating conditions of everyday tasks. Furthermore, the device must be simple to operate and should not rely on the existence of smartphone terminals or third-party communication infrastructures.

Due to all these design constraints, a custom made swingletree, with an integrated dynamometer, was designed, implemented and tested in real-life operating conditions.

Material and methods

The study took place in the Animal Traction Interpretation Centre (CITRAN), in Galiza, Spain, during June 2019. Three healthy adult Zamorano-Leones donkeys (10, 13 and 13 years old), living under similar management and working conditions, were used in the experimental field trials. At the commencement of the study, individual bodyweights were accurately obtained (354, 345 and 340 kg). All donkeys presented an ideal body condition.

The objective was to understand if working donkeys exerted different force for the same task, depending on the type of collar used. For that, three different collars were used (a complete adjustable full collar, a breast collar and a new prototype collar developed by the harness makers involved in the project) while pulling a modern light plough along a flat transect, comprised of two segments of 75 metres each.

Pulling forces exerted by the animals were recorded using a custom-made dynamometer whose design, implementation and metrological characterisation is the main objective of this article.

During the process, a team of welfare professionals and veterinarians continually monitored the health and welfare of the animals. The workload effort was evaluated through the heart rate, measured using an Equine Polar System® attached to the donkey's harness.

UK Animal Welfare legislation was followed during this study.[20] Non-invasive techniques were used to assess the equids involved. The study was conducted in accordance with the Declaration of Helsinki[21] and the protocol approved by the executive board of The Donkey Sanctuary, UK.

Instrumented swingletree: architecture and implementation

The objective of this study was to perform the instrumentation of a swingletree to measure the mechanical stress exerted by donkeys or other equids, during their normal work while pulling different load types.

The use of a measurement system in real operating conditions poses several challenges that must be considered. In the current case, one of these challenges is related to the extreme conditions to which the device will be subjected during the measurement process. In particular, vibrations caused by collisions, high thermal amplitude, dust and debris as well as high levels of humidity.

In addition to the harsh environmental conditions, it is necessary to ensure that the deployment in the field of the measurement system does not conflict with the normal operating conditions. That is, the complexity of using the dynamometer should not cause additional difficulties or even increase the animal's rigging time when compared to the use of conventional equipment.

It is also an important design condition that Animal Welfare is not disturbed. Furthermore, the measurement device must be able to cope with technical conditions such as being able to be battery operated, withstand at least 8 hours of continuous activity and be easy to be managed by regular workers in the field.

For the system to be wear-resistant and able to withstand extreme operating conditions and not increase the burden associated with the execution of normal tasks performed by working equids, any external electrical wiring must be avoided or kept to a minimum.

The use of wireless technology in order to avoid the use of connecting cables between the load cell and the data logging system was initially considered. Indeed, wireless data transmission methods have already been presented in the literature as a way to keep the transducer away from the data acquisition and recording system. For example, DiGampaola *et al* (2017) present a wireless strain gauge measurement system resorting to near-field communication using RFID techniques.[22] Harnett *et al* (2011) describes a strain gauge based wireless sensor network applied to stream flow measurement in environmental research.[23] Wireless measurement of Computer Numerically Controlled (CNC) tools cutting forces using strain gauges has been reported by de Oliveria *et al* (2020) and Chakavarthi *et al* (2018) resort to an RFID based technology to keep track of the strain in metals.[24,25] Also, in the domain of civil engineering, Kumar and Hossain (2018) and Furkan *et al* (2020) report the development of wireless sensing systems for monitoring the health of civil structures.[26,27.]

However, none of those solutions were suited to be included in the current study. On one hand, all those methods require a two-part solution: the emitter, which includes the load cell and the receiver which must be handled or operated by the worker during the task. On the other hand, due to mechanical constraints, the swingletree steel structure prevents radio frequency

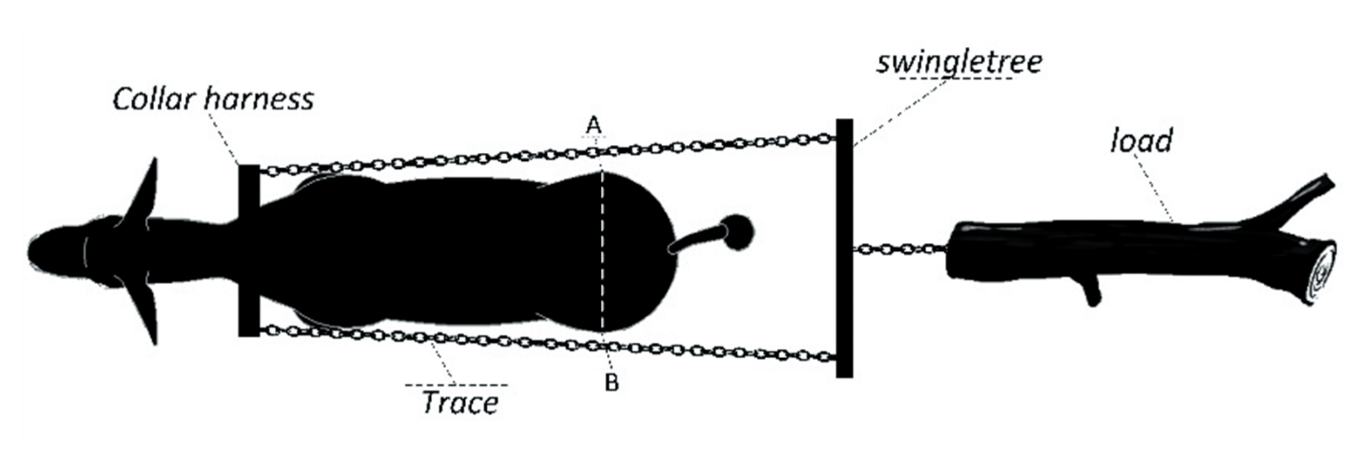

Figure 1. Diagram of a single animal hitched to a load where the main components of the harnessing structure can be viewed. The distance between points A and B, drawn over the croup's hips, is used to define the length of the swingletree.

(RF) data transmission. At the same time, the current solution must be self- contained in the sense that it should not require the user to have access to any type of third-party technology, such as hand-held devices or information network infrastructures. This is due to the fact that it is expected to use this dynamometer in some developing countries where those technologies are not readily available.

In this frame of reference, a custom-made measurement system was designed and developed where a load cell, together with the data acquisition and recording electronics, was completely integrated into a regular-sized swingletree. This compact approach leads to a robust plug-and-play measurement solution that can be easily deployed in the field, even by non-technical staff, under real operating conditions.

Overall system design

Conceptually, a swingletree consists of a rod or bar made of wood or metal to guarantee the traction balance produced by a draught animal when pulling a load. In the current framework, an additional technological layer must be added to this simple device to enable the measurement and recording of the pulling forces occurring during a typical donkey's working day. The traditional swingletree was completely redesigned to integrate the embedded electronics. For this reason, this section presents a thorough description of the mechatronic project component. Specifically, the details associated with the swingletree structure will be presented within subsection Mechanical Structure with further subsections to describe the features concerning the electronic instrumentation, the embedded system and its firmware. Finally, the subsection Integration and Casing reports the solution devised to integrate both the mechanical and electronic components.

Mechanical structure

Figure 1 represents the typical way of hitching a donkey to a load using a collar harness. When pulling a load the animal's legs and shoulders displace forwards and backwards leading to movement, in opposite directions of both traces. The swingletree enables the independent movement of the traces whilst ensuring that the draft on both sides of the harness remains balanced. That is, it turns the cyclically moving motion of the donkey into a steadier source of pulling power, by negating the movement around its shoulders.

The size of the swingletree is related to the size of the equid that it will be used for. The minimum size should correspond to the distance between points A and B of the hips in the equid's croup. This will allow the traces to move freely around the equid's body and will avoid friction. Considering the average size of working equids worldwide, it was decided to design the swingletree with 60 cm as a standard measure for this study.

The swingletree will be connected to the collar via the traces and to a light plough weighing around 40 kg.

In practice, the swingletree is a crossbar built around a piece of hard wood or steel metal. There is a ring at the centre of the swingletree where the load, cart or implement can be connected. At the same time, the end of both traces are attached to grooves or rings at the extremities of the swingletree.

As previously stated, the aim of this work is to develop a swingletree able to measure and store data about the donkey's pulling forces during a common workday. To accomplish this, a new swingletree structure had to be designed and built to allow the inclusion of the entire electronic component which will be described under Electronic Instrumentation and Hardware.

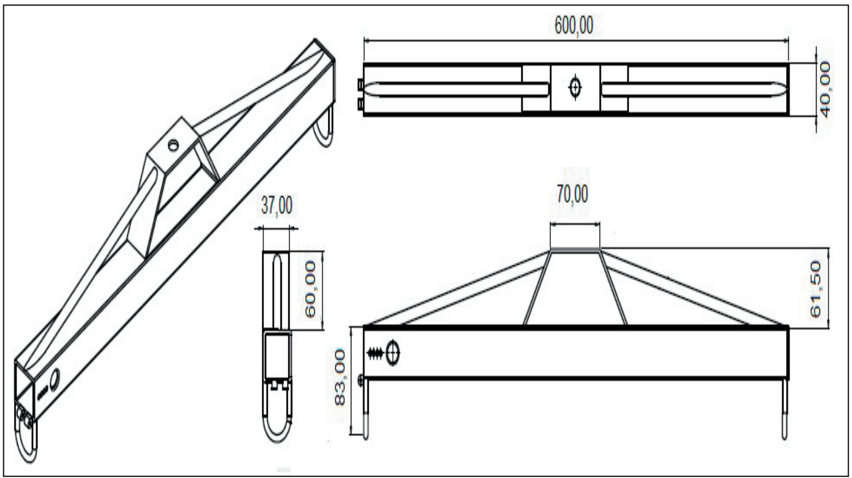

Figure 2. Representation of the most relevant dimensions of the swingletree (expressed in millimeters).

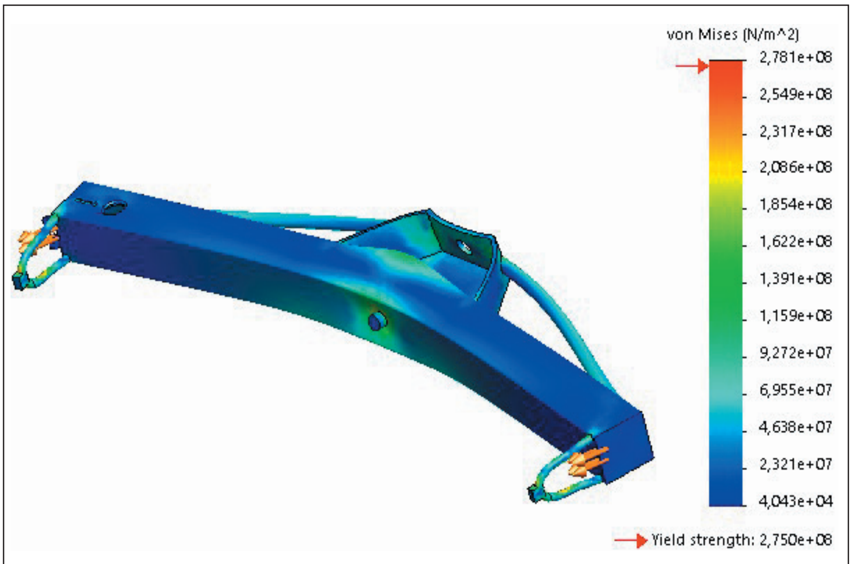

Figure 3. Simulation results where a static force of 4500 N is applied to the two interface rings.

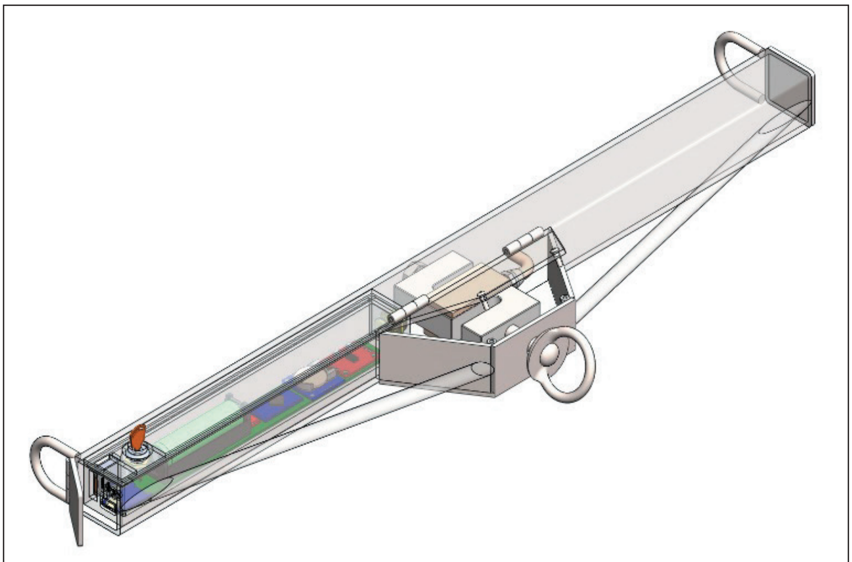

Figure 4. CAD image showing the integration of the load cell into the swingletree. Note the central ring, where the load, cart or implement can be attached.

The overall shape and dimensions devised for this element are presented in Figure 2. The swingletree has an end-to-end length of 60 cm and includes a centred enclosure with a volume of around 240cm^3, where the load cell is fitted.

For the construction of the swingletree main structure, pipes of EN 10219 carbon steel with a 40mm square profile was used. This material exhibits a yield strength of around 275 N/mm^2 and a linear density of 3.3 kg/m. The tube walls have a thickness of 3mm and Figure 3 shows the simulation results where a static force of 4500 N is applied to the two interface rings. The choice of this force value for the simulation is based on the fact that it is the upper limit force of the load cell used.

As seen on the colour map, there are some points where the pressure exerted slightly exceeds the yield strength of the material. However, this is not critical since due to the size of the target donkeys for the current study, we are expecting forces lower than half of this threshold value. It is worth noting that pipes with thicker walls can be used in case one wants to carry out force measurements on stronger animals such as horses.

Having defined the mechanical structure of the swingletree, the following section will describe the electronic instrumentation chain.

Electronic instrumentation and hardware

The load cell is the fundamental component on the electronic instrumentation chain. For this reason, care must be taken to choose an appropriate device to match the application. In this work, the transducer selected is an S-Shape load cell rated to a nominal mechanical load capacity of 500 kilogramme-force (kgf). This device is identified by the company reference CZL-301. The reason for the selection of a 500 kgf load cell was a somewhat conservative decision. First, there is only empirical knowledge on the nominal loads pulled by equids and second, this value has a large dispersion and strongly depends on the breed of the animal as well as the task performed. Moreover, the price is similar to lower range transducers such as those that are in the range of 300 kgf. As it will be shown later, the load measurement resolution achieved with this conservative selection is more than reasonable. Figure 4 shows using a 3D generated Computer-Aided Design (CAD) image, how this load cell will be fitted into the swingletree structure. One of its ends is bolted to the frame and the other has a swivel which will be used to attach the load to be pulled.

The most relevant metrological features of the load cell can be read from the manufacturer's calibration certificate which is delivered with the product. In particular, the sensitivity is equal to 2.0044 mV/V and it exhibits an accuracy and repeatability, relative to the full-scale value, equal to 0.02% and 0.0017% respectively. The temperature is a very important disturbance factor in any load cell and, in this case, the manufacturer defines the effect of temperature on both zero and range to be equal to 0.0019% of the full-scale for each 10°C of increment in temperature. The input and output impedance are within ± 5 Ω around the nominal value of 350 Ω. Bandwidth is not provided but it is expected to depend heavily on the mechanical inertia of the primary element to which the strain gauge bridge is attached. However, its value is expected to be higher than the dynamic behaviour of the current process which will be below the range of one hertz.

The full instrumentation and data acquisition system developed for the current work is presented in Figure 5. The load cell signal conditioning is mainly performed by the HX711 integrated circuit. A regulated voltage of 2.6 V is supplied to load cell strain gauge bridge and the unbalance voltage generated due to the mechanical deformation is delivered to an analogue amplifier with a gain of 128 V/V. In this context, and taking into consideration the transducer characteristics enumerated above, the maximum unbalanced voltage at the amplifier input will be equal to 2.0044 × 1.8 ≈ 5.2 mV and the full-scale voltage at the amplifier output will be 128 × 5.2 which leads to a value near 667 mV.

This signal will be input to a differential input 24-bit Σ-Δ analogue-to-digital (A/D) converter. According to the HX711 datasheet, the maximum absolute allowable differential voltage at the A/D input is half the bridge voltage AVCC. In the current case, this value is ±1.3 V which means that it is possible to perform measurements over the entire dynamic range of the load cell without attaining saturation.

The data is delivered to the microcontroller unit (MCU) using a synchronous serial communication interface where two wires, one for data and the other for the clock signal, are used. Since we are dealing with a Σ-Δ converter, the use of an anti-aliasing filter is not a fundamental requirement.[28] In fact, this type of A/D converters, oversample the input signal to a rate much higher than that of the *Nyquist* frequency. Moreover, the data is decimated and passed through a digital filter before being available to the output. This also enables the quantisation noise to be moved away from the frequency band of interest. However, in the current setup, a first-order low-pass balanced filter is added. As can be seen from the schematic diagram of Figure 5, this filter is implemented using two 100 Ω resistors and a 0.1 µF ceramic capacitor. Note that the bridge impedance will have a major influence on the corner frequency of the filter which, in this case and with the components used, is near 2 kHz.

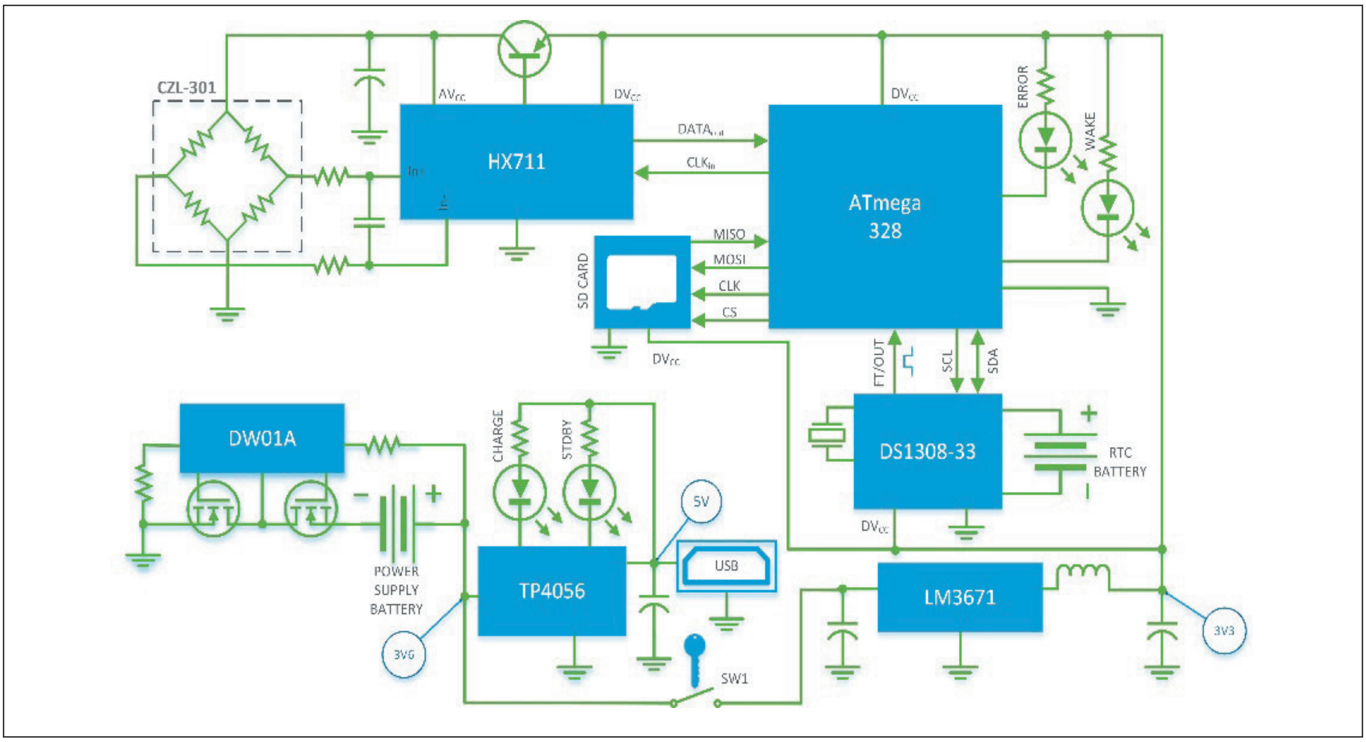

Figure 5. Conceptual diagram of the hardware instrumentation and data acquisition system.

Removal of unwanted signal artifacts and spurious noise is carried out at different levels. Initially, the 50 Hz noise induced by the power lines is mitigated by the electromagnetic interference (EMI) shielding promoted by the swingletree metallic casing and by the HX711 integrated notch filter and secondly, using a digital low-pass FIR filter embedded in the MCU firmware. A detailed description about the firmware and its functionality will be provided in Firmware and Signal processing.

The MCU selected for this application is the popular Atmel's ATmega328. This is a general-purpose microcontroller featuring an 8-bit RISC processor with a modified Harvard architecture. In the present design, the MCU will run with a 3.3 V supply voltage using its internal clock defined at 8 MHz. This device will gather data from several peripherals and populate a secure-digital (SD) card with the time-tag provided by a real-time clock (RTC) and the tensile strength reported by the HX711.

There are several reasons that lead to the choice of an SD card for storing the data: on one hand, the metallic structure of the swingletree prevents the use of RF signals. On the other hand, the measurement system is not reliant on the existence of any third-party communication infrastructure or even on the use of smartphones or other handheld devices. The data communication between the MCU and the SD card is carried out using the SPI protocol where the former acts as the master and the latter as the slave.

The time-tag is delivered to the MCU, upon request, by a DS1308 RTC integrated circuit. The current date and time are sent to the MCU using the I^2C communication protocol. This device will also produce a regular 1 Hz digital signal that is used to wake up the microcontroller such that a new sample can be registered in the SD card. Data retention is ensured by a coin type manganese lithium battery, CR2032, with a nominal voltage of 3.0 V and a charge capacity of 210 mAh.

The choice of this particular RTC was mainly driven by the requirement of having all the integrated circuits operating with the same supply voltage of 3.3 V. This voltage is provided by a DC-DC buck converter built around the Texas Instruments' LM3671 and three passive external components: one inductor and two capacitors. This voltage regulator can provide up to 600 mA of output current, while also ensuring current overload and thermal shutdown protection.

One of the design requirements was that the system must be battery operated in order to make it portable and self-contained. This aspect was achieved using an 18650 Li-Ion cell with a charge capacity of 2600 mAh. The battery can be charged in situ since the developed electronic circuit board includes a charge regulator, in this case handled by the TP4056 integrated circuit. Overcharge, over discharge and overcurrent protections are provided by the DW01A integrated circuit.

A key design requirement was the capacity to sustain the operation for a period of at least one full working day. The total quiescent current of the measuring system is around 20 mA, raising to near 58 mA during the active state. The current consumption during the active state is slightly above the double of the one observed during the idle state. However, this active state only occurs during less than 10% of the time leading to an average current consumption, during a full operating cycle below 25 mA. That is, an average power consumption of around 83 mW.

Since the battery capacity is rated to 2600 mAh, with a nominal output voltage of 3.6 V, it exhibits an energy content of 9620 mWh which, according to the average circuit consumption, leads to a theoretical autonomy close to 100 hours which is in line with the practical results measured. This result has superseded the initial autonomy design constraint by a factor of ten. The next section will focus on the description of the firmware that runs inside the MCU and the signal processing tasks carried out.

Firmware and signal processing

This system was devised to be used by non-technical persons. For this reason, a plug and play approach was considered and the interface with the user was made as simple as possible. Therefore there is just one switch for controlling the on/off status and a pair of light emitting diodes (LED) to inform the user if the system is active or if an error has occurred.

The firmware that runs continuously on the MCU is presented as a flowchart in Figure 6. It is divided in three different routines: the main routine that deals with the hardware detection and ports instantiation; an interrupt service routine (ISR) that runs whenever a rising edge, generated by the FT/OUT pin of the DS1308, takes place; and an error routine.

The user can activate the system just by turning on the key switch. This will start the firmware that runs a set of hardware interfacing procedures beginning with I/O ports definition, checking the status of the HX711 and RTC and creating a new file in the SD card root. The filename is defined as the concatenation of the current date and an index number. This index is an integer number that is automatically incremented if the storage device already has a file with the same name. Currently, due to using an FAT16 structure, the filename can only have eight characters plus the extension. For this reason, a maximum of 100 files can be created in a single day which, in practice, has been demonstrated to be more than adequate.

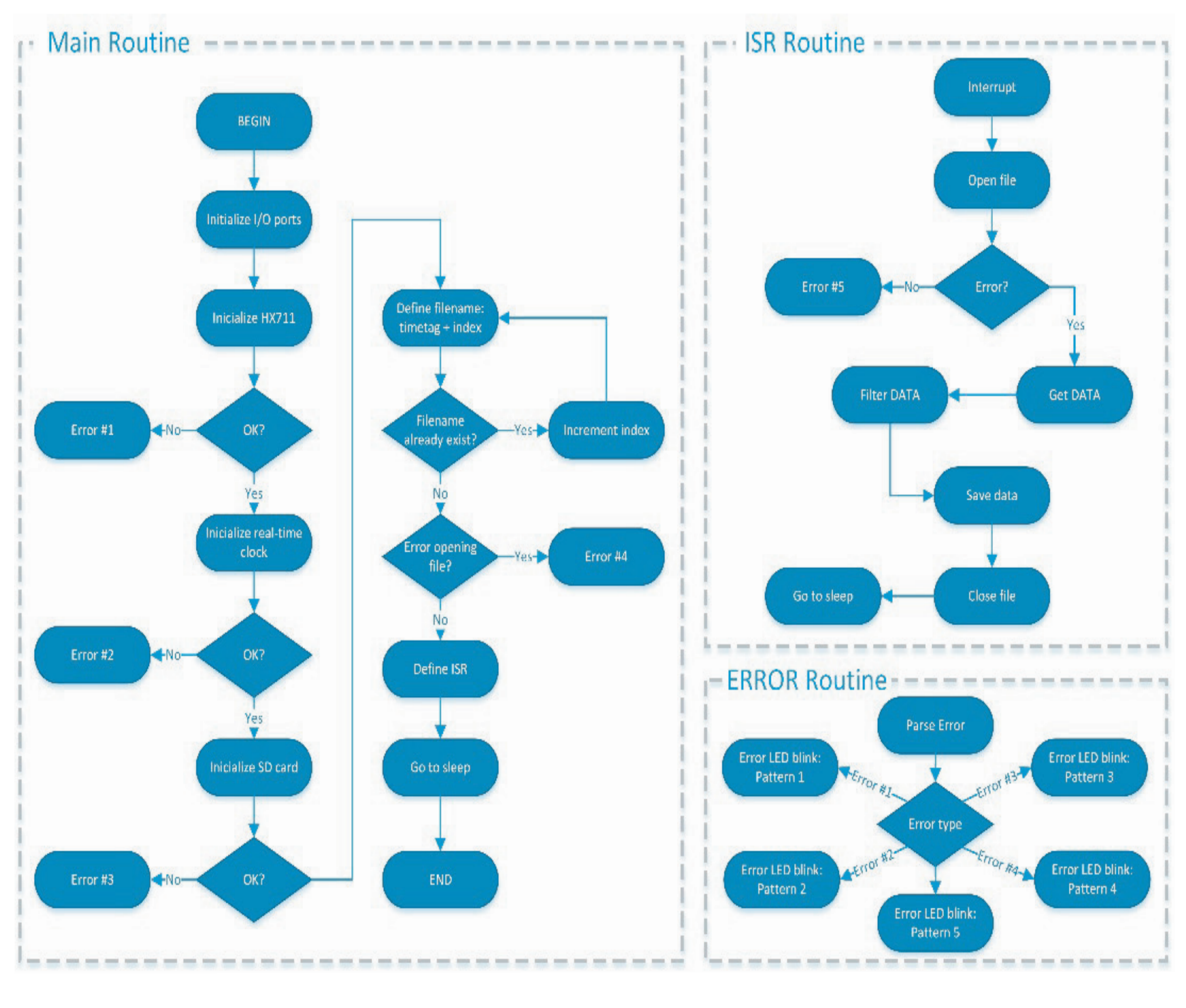

Figure 6. Firmware flowchart running on the MCU.

The last action of the main routine is to turn the MCU into sleep-mode. This feature is used to reduce the overall energy footprint of the device. The microcontroller is awoken, with time rate of one second, by an external interrupt signal generated by the RTC. This triggers the execution of the ISR routine which, in turn, is responsible for acquire, process and record the value of the mechanical tension applied to the load cell.

The actual value of tensile strength is delivered by the HX711 using a two's complement 24-bit format. The update rate of the A/D registry is carried out with a frequency of 10 Hz and the actual mechanical tension data is saved on the SD card and obtained from the average of the last 10 samples.

On the assumption that a tension force that acts over the load cell has a positive sign while a compression force will have a negative one, and since a 2.6 V voltage is used to supply the strain gauge bridge, the load cell unbalance voltage v_d, expressed in μV, will be equal to:

$$v_d = \pm 0.106 \times F \#(1)$$

where F denotes the force, measured in *newtons* (N), applied to the load cell.

As already referenced, this differential voltage is amplified before being fed to the A/D converter. The gain factor considered in this application was 128 V/V which results in a voltage at the amplifier output being proportional to 13.6 μV for each newton of force applied to the load cell.

Since the A/D converter has a 24-bit resolution which is too high for the current application, a downgrading of the resolution was made by reducing the 24-bit data to half. With 12 bits, the resolution is now equal to 0.635 mV per bit which leads to the ability of detecting load disturbances on the order of magnitude of 40 N.

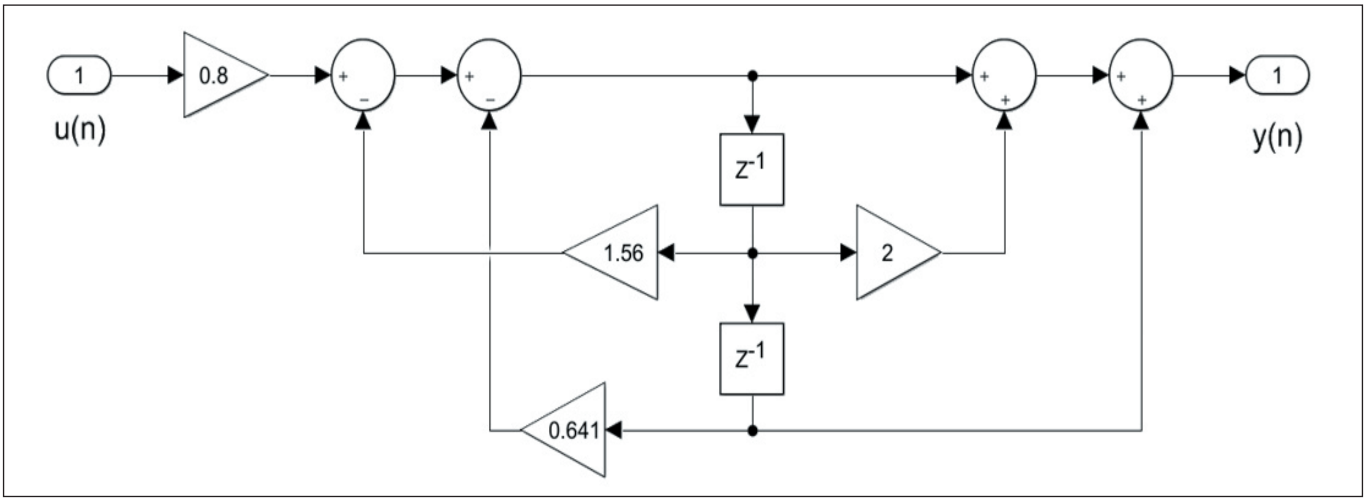

Figure 7. Digital filter structure embedded in the microcontroller firmware.

In order to further reduce high-frequency disturbances, the measured signal is low- pass filtered by a second-order IIR Butterworth filter with a cut-off frequency of 0.45 Hz. The filter was implemented using a direct-form II with one second-order structure as illustrated in Figure 7.

Error parsing is carried out by a third routine that drives the error LED to blink at different rates and patterns according to the type of error found. Five main different types of errors are considered, with each one coded with a different light blinking pattern. This pattern is composed by the concatenation of three bits where each bit is encoded using a line coding scheme where different duty-cycle light pulses are used to represent the two different bit states: 0 or 1. Each bit has a 1000 milliseconds (ms) duration, the bit 0 is defined as having a 20% duty-cycle while the bit 1 is considered to have a duty-cycle of 80%. The three-bit pattern of a give error is repeated cyclically with a period of four seconds. For example, the error regarding the initialisation failure of the HX711 is encoded as “000” which will result in a sequence of three short burst pulses separated by 1000 ms delay. On the other hand, an SD card write failure is defined by “101” which gives rise to two long pulses separated by a short one.

Being able to assemble all the different mechanical components and electronic circuits in one robust solution that could endure the harsh environments found during agroforestry tasks was a particular important condition. The following section will deal with the description of the solutions found to integrate all the components into one final robust solution.

Integration and casing

Having the means of acquiring data with the lowest disruption possible throughout the monitoring process is always a challenging task. This is even more crucial when developing a measurement system targeted to non-technical users and, most importantly, not compromising the normal execution of the equid’s work. It must be stressed that agroforestry processes take place in harsher environmental conditions than those found in many other circumstances such as in common industrial facilities for example. For this reason, robustness and physical integrity are key factors when devising a solution to be used by agroforestry workers in everyday tasks. In the context of the current work, the performance of the electronic instrumentation measurement chain strongly depends on its ability to endure severe environmental and vibration conditions such as large thermal loads, humidity, dust and considerable physical impacts. For this reason, the correct layout of the electronics, in conjunction with an appropriately designed case, will enable the data acquisition equipment to withstand the conditions found in normal operating conditions.

Figure 8 presents a 3D view of the enclosure devised to host the printed circuit-board with all its electronics. As can be seen in Figure 8a, interaction with the user is very simple and composed of only a few LEDs and a turn-key switch. The box slides into the tubular structure of the swingletree as shown in Figure 8b. The status of the LEDs is visible through acrylic lenses embedded in each of the four holes in the metallic structure. Moreover, during operation, the key can be removed from the swingletree switch and a rubber cap can be placed to cover the hole that was left open avoiding the entry of dust, humidity and other debris.

The electronics enclosure box was 3D printed with a ‘Stratasys Eden 260V’ 3D printer, (manufactured by ‘Object Eden’). This machine operation is based on a Poly- Jet technology and the material used in the final solution is identified by the manufacturer using the reference RGD525. According to the product datasheet, this material is able to withstand temperatures up to

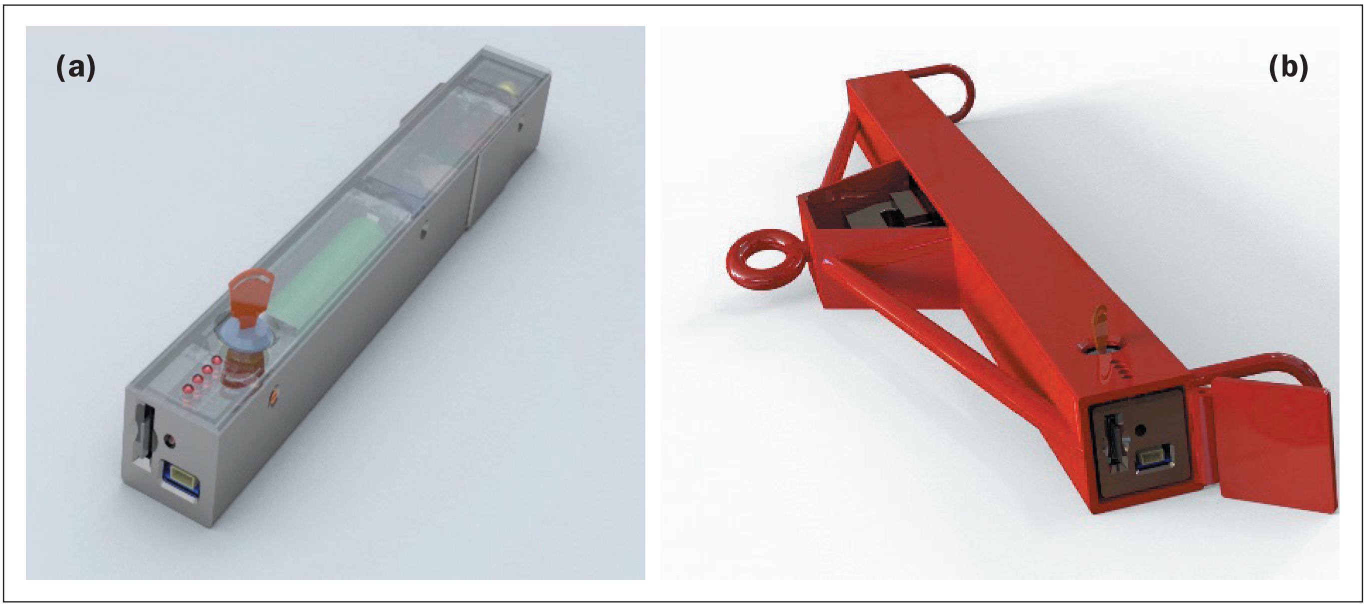

Figure 8. In (a) a 3D view of the solution and in (b) its integration in the swingletree structure.

75°C. For the current prototype, this temperature was considered the upper working limit which is also near the maximum-operating temperature of the enclosed electronics. Figure 9 shows the final version of the swingletree deployed in the field where it has been used to measure the force exerted by the donkey during ploughing.

In the section that follows, details regarding the load cell calibration process will be presented. This process allowed to obtain, in an empirical way, the transducer calibration curve considering the nominal excitation conditions of the strain gauge bridge.

Calibration procedure

In order for the system to be calibrated, the load cell was clamped into a Shimadzu's AGS-X series universal test frames as can be seen in Figure 10. In particular, the trials were conducted using the 10 kN version of this machine. Tensile loads from 0 N up to 4750 N, with a 250 N step resolution, were applied to the measurement system and the raw values delivered by the A/D converter were recorded. It should be noted that, every time a target load was reached, the traction force was kept constant for a time interval of five seconds after which the A/D delivered value was recorded.

Figure 9. The swingletree with all the electronic instrumentation operating in the field.

Figure 10. Calibration setup for the swingletree load cell.

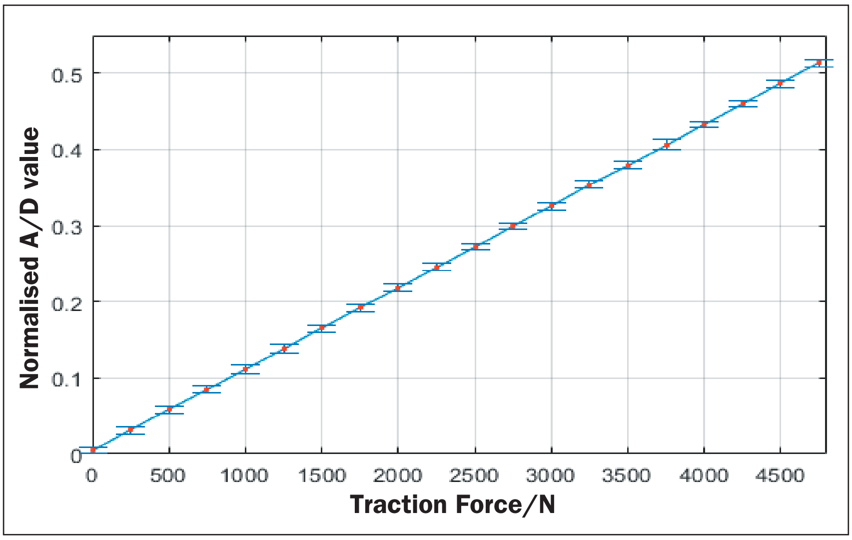

Figure 11. Calibration curve obtained from the set of experimental tests.

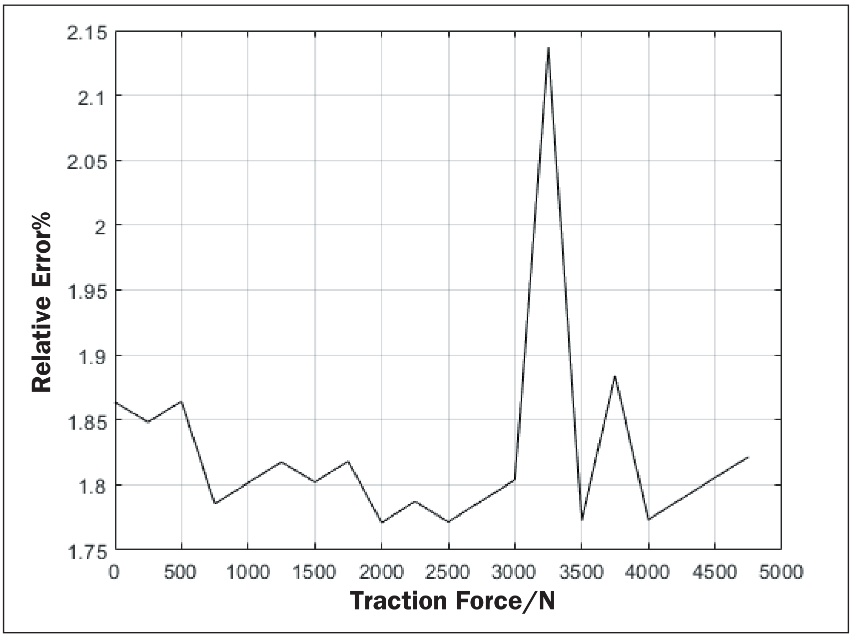

Figure 12. Modelling error, relative to the full-scale value, resulting from the linear approximation described by equation (2).

The interval plot, obtained after a set of trials, is presented in Figure 11. The marking dots identify the measurement average values, which are complemented by the addition of a ±3σ limit bars.

From the calibration curve, there is a clear linear relationship between both the dependent and independent variables. In particular, a least squares approximation of a first-order parametric model to the obtained data, leads to:

$$M_{A/D} = 0.2193 \times F + 9.5952 \#(2)$$

where $M_{A/D}$ is the value provided by the A/D converter and F is the traction force measured in *newtons*.

For this model, the Pearson correlation coefficient is 0.9999966 and, as can be seen from Figure 12, the model error, relative to the full-scale value, is below 2.2%.

This mathematical relation, between the tensile force and the value provided by the A/D converter, is used in the firmware to map the data from the HX711, after being digitally filtered, into traction force.

An initial set of experiments was carried out in order to evaluate the performance of this instrumentation method in the field. The next section describes the methodology adopted in the experimental trials. Samples of the measured data will be provided followed by a discussion of the results obtained.

Results and discussion

Although some data is provided, this section is, by no means, intended to provide an exhaustive analysis of the data gathered during the field assays. Indeed, only a small subset of the experimental data will be used in order to characterise and validate the dynamometer design described in the previous section.

Throughout this section, the data obtained from the set of experiments carried out under the conditions described in Materials and Methods will be presented. This data will be used to infer about the measurement's consistency and repeatability of the devised swingletree dynamometer under real operating conditions.

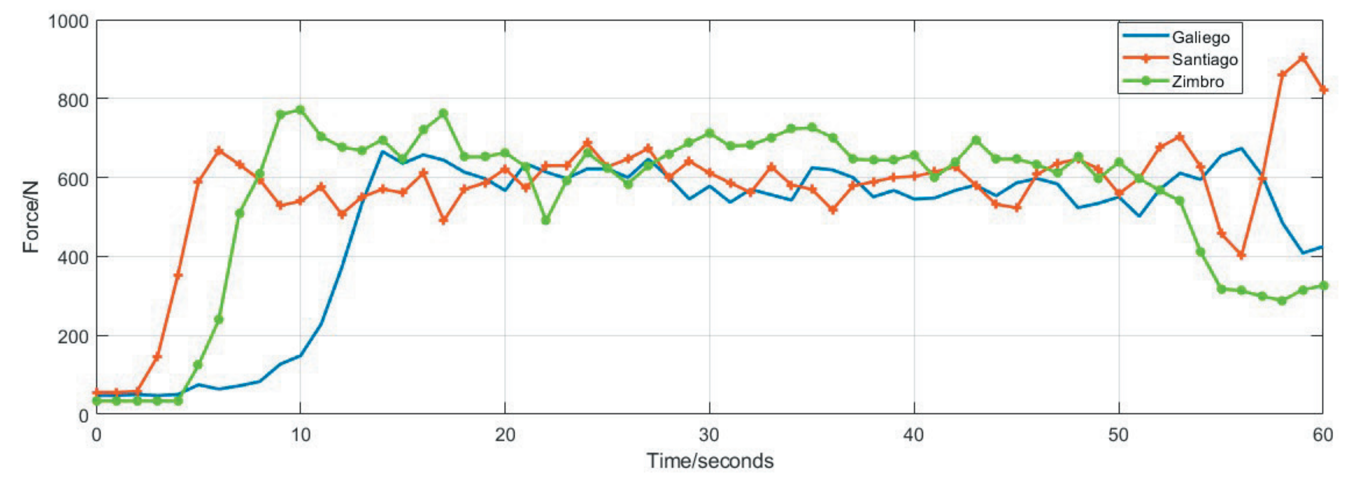

Figure 13. Force delivered by three different donkeys, Zimbro, Santiago and Galiego during a one-minute test period using the same collar.

The plot presented in Figure 13 represents the pulling force delivered by the three different donkeys during the first one-minute timeframe. As highlighted in the beginning of this section, the analysis of the acquired data is outside the scope of this paper. For this reason we will concentrate instead on the metrological results of the dynamometer.

To test for data consistency, a series of trials were carried out and ANOVA tests were used to analyse data. In this case, we will test the null hypothesis that there is no statistical significance between the data acquired from a set of two different trials performed under the same conditions. That is, the same donkey, with the same load, same collar and following the same route. Each trial is composed of sixty samples which concerns a one-minute data registration. It is worth noting that the donkeys were allowed to rest between trials to reduce variability resulting from donkey tiredness. Indeed, a new trial only began when the heart rate was around 44 bpm, which is considered the normal rate at rest.

Table 1 presents the statistics summary regarding the data gathered from two trials conducted with the donkey Zimbro and Table 2 show the respective one-way ANOVA table assuming an α value equal to 0.05.

From Table 2, it is possible to see that the F value is lower than that of Critical Frequency (Fcrit). For this reason, the null hypothesis is accepted which lead to the conclusion that the means of the two datasets are statistically equivalent.

The same procedure was carried out for the remaining two donkeys (Santiago and Galiego). Table 3 and Table 4 show the ANOVA results computed using the dataset of two trials with Santiago. Moreover, Tables 5 and 6 refer to the ANOVA obtained from the Galiego set of trials.

	Count	Sum	Average	Variance
Trial #1	60	32365	599.35	51526.97
Trial #2	60	29222	541.14	35111.41

Table 1. Data summary regarding two trials, under the same operating conditions, performed by the donkey Zimbro.

	Count	Sum	Average	Variance
Trial #1	60	31824	578.61	20710.96
Trial #2	60	30558	555.59	21348.57

Table 3. Summary regarding two trials, under the same operating conditions, performed by the donkey Santiago.

Variation	SS	df	MS	F	p-value	F_{crit}
Between groups	91479.02	1	91479	2.1	0.14913	3.9307
Within groups	4591834	118	43319			
Total	4683313	119				

Table 2. ANOVA table obtained from two trials done with Zimbro.

Source	SS	df	MS	F	p-value	F_{crit}
Between groups	14583.93	1	14584	0.7	0.41	3.93
Within groups	2271214	118	21030			
Total	2285798	119				

Table 4. ANOVA table obtained from two trials carried out with Santiago.

Source	SS	df	MS	F	p-value	F_{crit}
Between groups	156208	1	156208	3.6	0.06	3.93
Within groups	4747753	118	43170			
Total	4904961	119				

Table 5. Data summary regarding two trials, under the same operating conditions, performed by the donkey Galiego.

	Count	Sum	Average	Variance
Trial #1	60	30840	550.72	41563.93
Trial #2	60	26658	476.03	44777.03

Table 6. ANOVA table obtained from two trials completed with Galiego.

The analysis of the Santiago and Galiego ANOVA tables is consistent with the one formulated for Zimbro. That is, there is a 95% confidence that the means of both trials are equal which validates the repeatability of the measuring process under field conditions.

Conclusion

Animal Welfare is directly related to the conditions in which the animal lives. Moreover, in cases where equids are used as a workforce, it is essential to ensure that they are working within their physical capacity while respecting their health and welfare boundaries. For this reason, it is fundamental to be able to quantify and provide insights into the load profile of donkeys within their working environment while carrying out tasks. So far, this information is not available in the literature due to the lack of commercial measuring tools targeting this specific application. To address this problem, a new strategy was devised to measure the forces delivered during draft work and without influencing the tasks performed by the animals. This alternative measuring strategy has been documented within this paper and concerns the development and instrumentation of a swingletree. The developed device can measure the pull forces and record their values as a time-series on an SD card for subsequent offline data analysis.

As the system must be replicated in order to be used in different parts of the world, it is necessary to ensure that the economic cost is low, both in terms of technology and its application. Moreover, the exact conditions that may affect the use of the technology in some countries are unknown, which steer the required solution towards being autonomous and not relying on any third-party technologies or information infrastructures such as smartphones, Wi-Fi or any other wireless communication standard. These constraints have led to the solution documented throughout the Instrumentation section. Besides these requisite design conditions, the system must additionally be able to withstand the extreme conditions found in agricultural environments. Materials and methods presents the results obtained from a set of trials carried out in typical field condition. From the results obtained, it was possible to verify that the designed measurement system is able to provide data consistency.

Several trials have already been conducted and many data points gathered within different work operating conditions, such as different types of loads and distinct collars worn by the donkeys. In future, it is intended to gather the same type of data from other places in the world where donkeys have a major footprint in the economic ecosystem.

Acknowledgement

The authors would like to acknowledge the APTRAN – Portuguese Association of Animal Traction and AGATRAN – Galician Association of Animal Traction, for the support provided during the field work.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship and/or publication of this article.

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