A Prototype of a Monitoring Sensor System for Stored Grains in a Real-world Setting

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***Abstract*— This paper presents a further step in the sequence of studies and developments of instrumentation for monitoring grains in Silo bags. The final deliverable of this project will be a monitoring system that includes sensor capsules for detecting the ecosystem conditions within a Silo bag: the electronics, communication protocols, a low Earth orbit satellite, and a central data storage and analysis unit. This document presents partial results from the relevant environment application of a sensor-capsule model. In a bag of approximately 1 cubic meter containing maize, three capsules were installed in positions that were expected to detect different environmental conditions within the bag. Probe 63 was installed near the upper surface of the bag, more exposed to solar radiation. Probe 64 was installed near the center of the bag; and Probe 65 was installed near the base of the bag, where it received less solar radiation but was more exposed to heat transfer by conduction. The experiment served as a proof of concept for the terrestrial component of the monitoring system, and with it, the requirements for its classification at Technology Readiness Level (TRL) 7 were finalized. The experiment also allowed for the identification of the effect of sensor position within the Silo and the correlation between the variables (temperature, humidity, and CO2 concentration).**

Keywords – Silo; Silo-bolsa; grain; soy; corn.

I. Introduction

The National Supply Company (Companhia Nacional de Abastecimento - Conab) [1] estimates that the 2024/2025 harvest will yield 322.3 million tons of grains, comprising 166.33 million tons of soybeans and 119.6 million tons of maize. In the first half of 2024, the storage capacity in Brazil reached 222.3 million tons, equivalent to 69% of the harvest.

The deficit in storage capacity impacts the country's ability to stockpile food, compels producers to sell their product at market price during the harvest period, and tends to reduce grain quality, and consequently its value, when harvesting is not performed under ideal moisture conditions.

Grain storage, for regulatory stock or waiting for more favorable pricing, can be carried out in some types of storage units: Conventional warehouse, Bulk Storage Warehouse, Silo, and Silo bag. The primary difference between these storage facilities lies in the form in which the products are stored (bulk or packaged) and the warehouse structure.

The Conventional Warehouse is intended for the storage of packaged goods (bags, boxes, bales, etc.). It features a flat floor and a single compartment. The Bulk Storage Warehouse is an adaptation of a conventional warehouse for storing grains in bulk. It has a flat floor, which can complicate grain unloading, but it is a more economical alternative for bulk handling.

The Silo is a structure specifically designed for the preservation of large volumes of grains. They are typically constructed in a vertical cylindrical shape. Modern Silos often include temperature monitoring and ventilation systems to prevent grain overheating. These Silos may also feature conveyor systems, screw conveyors, and elevators to facilitate grain loading and unloading.

Silo bags are large, flexible plastic bags made of high-resistance polyethylene, occasionally doped with a substance that reduces the deleterious effects of UV radiation on the plastic. The Silo bag should be installed in an area with low slope (up to 5%, for example) and good drainage. Compared to the previous options, it presents a significantly lower cost. For filling the Silo bag, the use of an implement called a grain bagger is advisable, and for grain extraction, an implement called a Silo bag unloader is used. The load capacity of the Silo bag depends on its length, which is generally 30m to 90m, where it is possible to store hundreds of tons of grains.

Storage units are designed or adapted to provide temperature and humidity conditions suitable for grain preservation. However, controlling these variables within such a large volume is very challenging. Furthermore, storage units exhibit varying levels of airtightness, consequently allowing for gas exchange and potentially the entry of insects and rodents. Additionally, it is not always possible to choose the initial storage conditions, notably the grain moisture content.

Silo bags exhibit good airtightness due to being made of a flexible yet resistant plastic (Low-Density Polyethylene; LDPE). This type of polyethylene allows for the fabrication of bags that conform to the volume of the stored grains. It also possesses good tensile strength and impact resistance, essential characteristics for withstanding the weight of the grains and climatic conditions. Additives, such as UV stabilizers, protect the material from degradation caused by solar exposure. Other additives can be incorporated to enhance tear and puncture resistance, as well as to reduce gas permeability. The polyethylene forming the body of the Silo bag can also be multi-layered to improve its mechanical and permeability properties.

The Silo bag remains stationed in the field, subject to climatic conditions and the surrounding ecosystem. The

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primary challenges are the initial conditions and attacks by animals that can rupture the Silo. Generally, rodents cause small breaches. In Brazil, legislation has complicated the hunting of feral pigs (crossbreed of wild boar and domestic pig), which, being of medium to big size, can cause significant damage to crops and the Silo. All of these variables can deteriorate the cargo, or a portion thereof, if countermeasures are not implemented to prevent or mitigate the damage.

Controlling the internal ecosystem of the Silo bag is not feasible. However, automated monitoring of the Silo bag is also challenging, as it relies on a power source, a robust and reliable data transmission system, and the encapsulation of electronics with adequate Ingress Protection (IP) rating. In the agricultural environment, encapsulations with IP65, IP67, and IP69K ratings are more common [2].

Subsequently, following a brief review in Section II, we will describe the prototype utilized in this work in Section III and the experimental setup in Section IV. In Section V, we will present a graphical analysis, and in Section VI, a correlation analysis of the data, prior to the conclusions in Section VII.

II. A Short Review

The state of the art for maintaining the quality of grains stored in Silo bags includes an updated review of topics such as storage techniques [3], modified atmosphere effects, pest control methods [4], and microorganism control methods, property security, sensors and monitoring methods [5], data analysis and mining methods [6], and specific experimental results. As a comprehensive topic, it can be summarized that the objective of this technical-economic area is to reduce post-harvest grain losses. The approach has been to identify relevant variables and their respective sensors, data transmission methods, and data analysis and mining.

Temperature and humidity sensors enable the continuous monitoring of internal conditions within the Silo bag. Carbon dioxide (CO_2) sensors are beginning to be used, but their cost impacts adoption by farmers. The equivalent to these measurements would be oxygen (O_2) concentration measurement. Both monitor the modified atmosphere inside the Silo bag, indicating the effectiveness of the sealing and biological activity (respiration of grains, insects, and fungi).

Vibration and movement sensors can detect damage to the Silo bag structure or unauthorized movements, aiding in property security and pest control. However, the adoption of this type of sensor requires the development of signal conditioners to filter out common interference in the field.

Other aspects of monitoring for loss reduction during storage, such as the complex system of data transmission in the field and anomaly warning algorithms, are usually handled within companies.

Despite advances, field-scale monitoring still demands answers to questions: How does sensor position affect the time series, and; How does position affect the correlation between variables. This work explores these two questions.

III. The Prototype

Temperature, humidity, and CO_2 sensors were utilized in each measurement unit: Probe 63, Probe 64, and Probe 65. The probes have a cylindrical format divided into two parts: the lance and the capsule. The lance is inserted into the Silo, and the capsule remains outside the Silo.

Figure 1 illustrates a probe that encapsulates three sensor elements with their respective electronics, one electronic circuit for signal pre-processing, and another responsible for the sensor's communication with a receiving base.

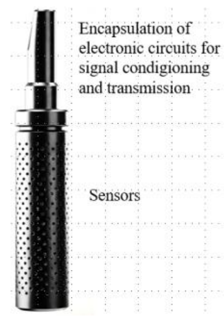

Figure 1. Probe prototype. The probe is composed of sensors, conditioning electronics, and antenna.

Commercial sensor elements were utilized, but all signal conditioning electronics were developed in the CRIAR laboratories. The CO_2 sensor is based on the two-beam Non-Dispersive Infrared (NDIR) technology and detects within a range of 0 - 40%, with a resolution of 0.01% Vol. The operating temperature range is between -25ºC and 55ºC.

The relative humidity of the air inside the Silo bag was measured with a resolution of 0.05 to 0.4 %RH and a typical accuracy of +/-3.0 %RH.

In this work, a version of the telemetry system for Silo bags (e-SILOBAG) [7] was utilized, which included sensors, data transmission protocol, data reception and storage infrastructure, and analysis, as shown in Figure 2.

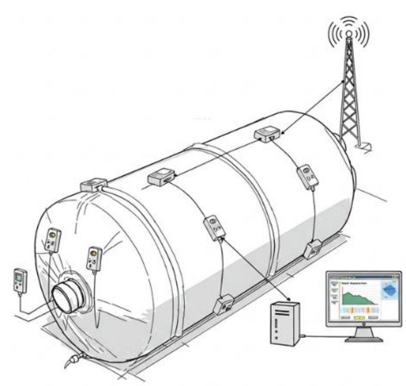

Figure 2. Ground communication network is formed by probes installed in the Silo, a hub (data concentrator) coupled to a ground station that transmits the signal to a database in the processing unit.

During the proof of concept of this system version, limitations in power supply were detected, which were quickly resolved, allowing for the continuation of the experiment.

IV. Experimental Setup

A small storage Silo, constructed from the plastic used in Silo bags and with an approximate volume of 1m³, was positioned on a concrete surface, adjacent to a masonry wall. The Silo was filled with maize grains.

Probes 63, 64, and 65 were installed (these labels were arbitrarily assigned), as depicted in Figure 3. Probes 63 and 65 were positioned 20cm from the Silo surface, and probe 64 was positioned 40cm from the surface, near the center of the Silo.

The probes were installed in non-equivalent positions. Probe 63 received more direct solar radiation, as did probe 64. Probe 65 received less direct solar radiation but was closer to the lower surface of the Silo, which received more heat via conduction.

All three probes are equipped with 2 sensor sets: one internal to the Silo and the other external to the Silo. The internal set measures internal Temperature, internal Humidity, and CO2. The external set measures external Temperature and external Humidity.

Measurements were taken every 60 minutes, and the data were transmitted to a concentrator and from there to a database. The measurements were conducted over a period of 133 days.

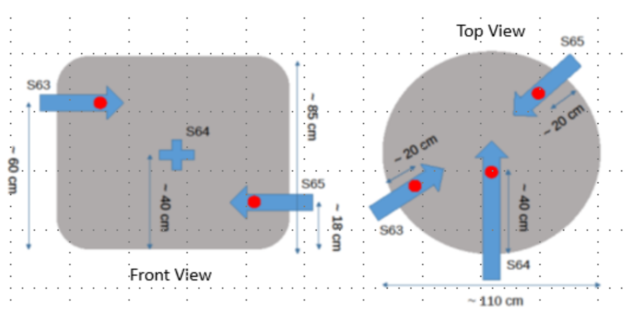

Figure 3. Position of probes and sensors within the Silo bag. Probes 63 and 65 measured at 20 cm from the surface, and probe 64 at 40 cm. Probe 63 received more direct solar radiation.

V. Graphical Analysis

Figure 4 presents the behavior of CO2 concentration (%) measured by the three probes. The data were normalized (Z-score normalization), and 12-period moving averages were calculated.

Throughout the experiment, the CO2 (Figure 4) concentration was practically the same across the three probes, indicating that this variable tends to be independent of the position within the Silo.

The graphs suggest that the behavior of the concentration went through at least three phases: up to day 27, when the first increase in concentration occurs; between days 45 and 95, when the second increase occurs; and after day 105, when the concentration stabilizes and tends to decrease.

Upon opening the bag, we identified the presence of a small population of maize weevils (*Sitophilus zeamais*). The first phase of the CO2 curves may be associated with the increased respiration of the grains, the second phase with the development of the weevil population, and the third phase with the equilibrium state and degradation of the ecosystem.

Figure 5 presents the time series of the internal temperatures measured by the three probes. It is observed that the three probes exhibit the same general behavior; that is, the trend of increase or decrease is followed by all three probes.

Probe 63 shows greater temperature variations; that is, over some days, the amplitude of the diurnal variations is larger than that of probe 65, which indicates the relative position of the probes with respect to the sun.

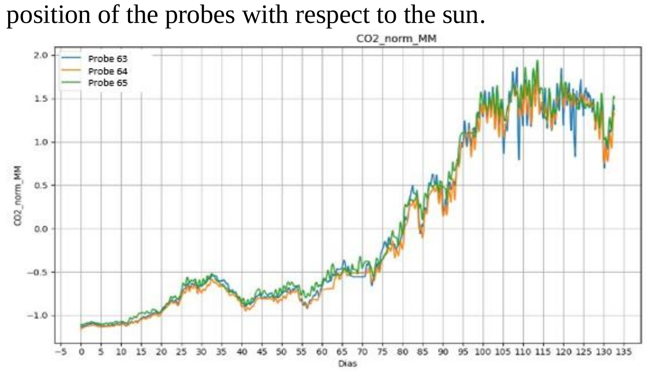

Figure 4. Behavior of CO2 concentration, measured by the three probes.

Probe 65, located in a more shaded area, measures the effects of the surface on which the Silo rests, which is made of concrete. Concrete has high thermal diffusivity, rapidly transmitting heat absorbed from solar radiation.

Until approximately day 55 of the experiment, the internal temperature of probe 63 tends to follow the troughs of the internal temperature of probe 65. Afterward, it tends to follow the peaks. The explanation for this behavior is not yet clear.

The temperature variations, with greater amplitude, near the Silo surface (probes 63 and 65) indicate an environment more conducive to the development of fungi and bacteria. Probe 64, whose measurements were taken near the center of the Silo, also exhibits significant oscillations, but with lower frequency.

The comparative analysis of these graphs shows that the internal temperature of the Silo is not uniform, and that it depends on the probe's position relative to direct (e.g., Sun) and indirect (e.g., soil) heat sources, and the sensor's depth within the Silo. The explanation for the temperature behavior at the center of the Silo can be attributed to the thermal conductivity, thermal diffusivity, and specific heat of the grain. These properties, however, depend on the grain's moisture content.

For maize grains, according to Andrade et al. [8], the Specific Heat varies by 25%, linearly (r^2=0.9583), for moisture contents (% wb) between 9% and 17%. Within the same grain moisture range, the Thermal Conductivity varies, linearly (r^2=0.9525), by 25%. The authors conducted these measurements in a volume of 0.05 m³.

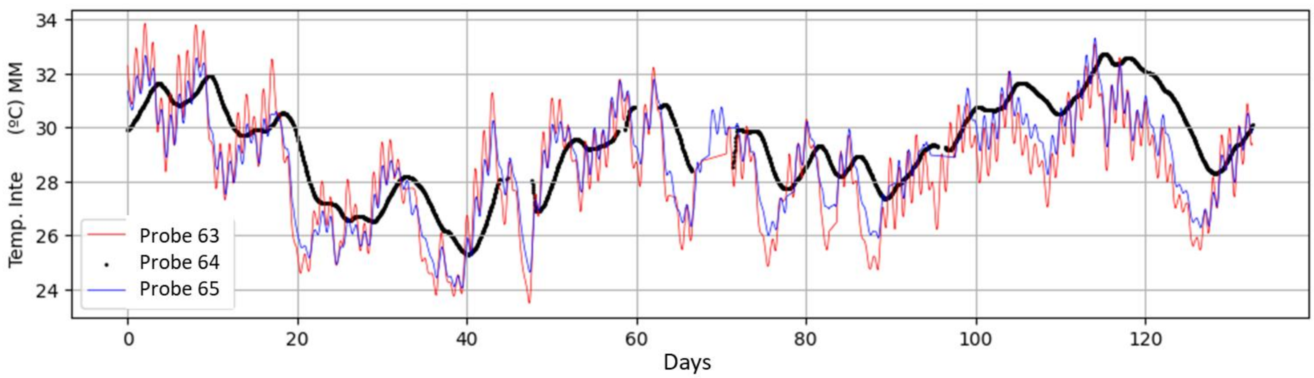

Figure 5. Internal temperature of the Silo, measured by three probes. Two of them (63 and 65) positioned near the surface. Probe 63 received more direct solar radiation.

TABLE 1. CORRELATION MATRIX BETWWEN THE VARIABLES MEASURED BY PROBE 63.

PROBE 63	Temp. Ext (ºC)	Umid Ext (%)	Temp. Int (ºC)	Umid Int (%)	CO2 Int (%)
Temp. Ext (ºC)	1.00	-0.90	0.32	-0.81	0.01
Umid Ext (%)	-0.90	1.00	-0.54	0.82	0.10
Temp. Int (ºC)	0.32	-0.54	1.00	-0.23	0.05
Umid Int (%)	-0.81	0.82	-0.23	1.00	0.19
CO2 Int (%)	0.01	0.10	0.05	0.19	1.00

TABLE 2. CORRELATION MATRIX BETWWEN THE VARIABLES MEASURED BY PROBE 65

PROBE 65	Temp. Ext (ºC)	Umid Ext (%)	Temp. Int (ºC)	Umid Int (%)	CO2 Int (%)
Temp. Ext (ºC)	1.00	-0.67	0.34	-0.49	-0.01
Umid Ext (%)	-0.67	1.00	-0.72	0.28	0.29
Temp. Int (ºC)	0.34	-0.72	1.00	0.30	0.24
Umid Int (%)	-0.49	0.28	0.30	1.00	0.51
CO2 Int (%)	-0.01	0.29	0.24	0.51	1.00

VI. Correlation Analysis

Tables 1 and 2 show the correlation between the variables measured in the experiment, for which the Silo model had a volume of 1m³.

A. *Temperatura*

The measurements from Probe 63, which was more exposed to direct radiation, show that the External Temperature exhibits a strong negative correlation with the Internal Humidity (-0.81) and a weak positive correlation with the Internal Temperature (0.32). The Internal Temperature exhibits a very weak negative correlation with the Internal Humidity (-0.23).

These values may indicate that the independent variable of the system, according to Probe 63, is the External Temperature, with an indirect effect on the other variables. The Internal Temperature, for example, depends on the thermal behavior of the grains and their moisture content. The Silo is a complex system whose behavior depends on multivariate relationships and, in at least some cases, on unidentified variables (such as the unidentified presence of microorganisms).

The measurements from Probe 65 show that the External Temperature exhibits a weak (almost moderate) negative correlation with the Internal Humidity (-0.49) and a weak positive correlation with the Internal Temperature (0.32). The Internal Temperature exhibits a weak (almost very weak) positive correlation with the Internal Humidity (0.30).

This set of values presents the same pattern of behavior as Probe 63, but with the effect of Probe 65's position near the ground. In other words, to better understand the relationship between the External Temperature and the Internal Humidity through a mathematical model, it would be convenient to consider the effect of heat transfer from the ground to the Silo.

B. CO2

The correlations of CO2 concentration with the other variables, according to the measurements from Probe 63, were very weak or negligible.

At the position of Probe 65, which was less exposed to direct solar radiation, the strongest correlation was moderate (0.51), with the Internal Temperature. The CO2 concentration depends on the respiration rate of biotic agents. For maize grains, and constant moisture content, the respiration rate increases with temperature [9], as it does for the maize weevil (*Sitophilus zeamais*) [10]. The effect of temperature on the development of fungi, yeasts, and bacteria requires an analysis of the microbiota, as each species performs its metabolic functions most efficiently within different temperature ranges.

Upon opening the Silo, a significant population of bacteria, fungi, yeasts, and insects was not detected (qualitative observation), suggesting that the correlation between CO2 concentration and Internal Temperature was mainly due to the volume of stored grains. The stronger correlation at the lower position (Probe 65) may indicate a slightly greater presence of microorganisms at the base than at the upper surface of the Silo.

When analyzing the correlations in phase 1 (Figure 4; 0 to 27 days) and phase 2 (Figure 4; 45 to 95 days), the values are different. Regarding Internal Temperature, in phase 1, the correlation was strongly negative for probes 63 (-0.71) and 65 (-0.78), and very strongly negative for probe 64 (-0.93). That is, the increase in temperature reduced the CO2 concentration on the scale of diurnal variations. The negative correlation appears to contradict the expected behavior of respiration in relation to temperature, but the measurements refer to the air temperature inside the Silo, which is not the same as the grain temperature.

Regarding Internal Humidity, the highest value was a moderate negative correlation (-0.66) at probe 65. In this case as well, a positive correlation was expected, but in the same way as for temperature, the sensor measures the air humidity and not the grain moisture content.

VII. CONCLUSIONS AND FUTURE WORK

In a Silo bag model of approximately 1 m³, three probes were installed. Each probe measured temperature, humidity, and internal concentration within the Silo, as well as external temperature and humidity. One probe (63) was installed on the upper lateral side, another on the lower lateral side (65), and both measured near the surface. The third probe (64) was installed on the front side and measured near the Silo's center.

The measurements were enabled and facilitated by the monitoring system developed by CRIAR, where the probes transmit their data to a concentrator, and the concentrator transmits it to a server.

During the 133 days of the experiment, deficiencies in the electronic design were detected that affected power consumption. The problem was resolved, and the new version will feature a solar panel to ensure automatic battery recharging.

The temperature, relative humidity, and CO2 concentration remained within the operational specifications of the sensors (-25ºC to 55ºC; 0 to 95% RH; 0 to 40%). The experiment contributed to understanding the effect of probe position within the Silo and to the development of algorithms for data analysis. Soon, it will be possible to mine information of interest, especially regarding the quality of the stored grains and any damage to the Silo bag structure. The version used is not the latest available but contains the main elements of the system, such as the communication protocols and signal conditioning electronics, which allowed for the proof of concept to be carried out and to indicate some desirable improvements.

The study validated the proof of concept of the measurement and data transmission system in a relevant environment and paved the way for field-scale testing.

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