GluCAT: A Feline Biofluids IoT Hub for Electrochemical Glucose Biosensing

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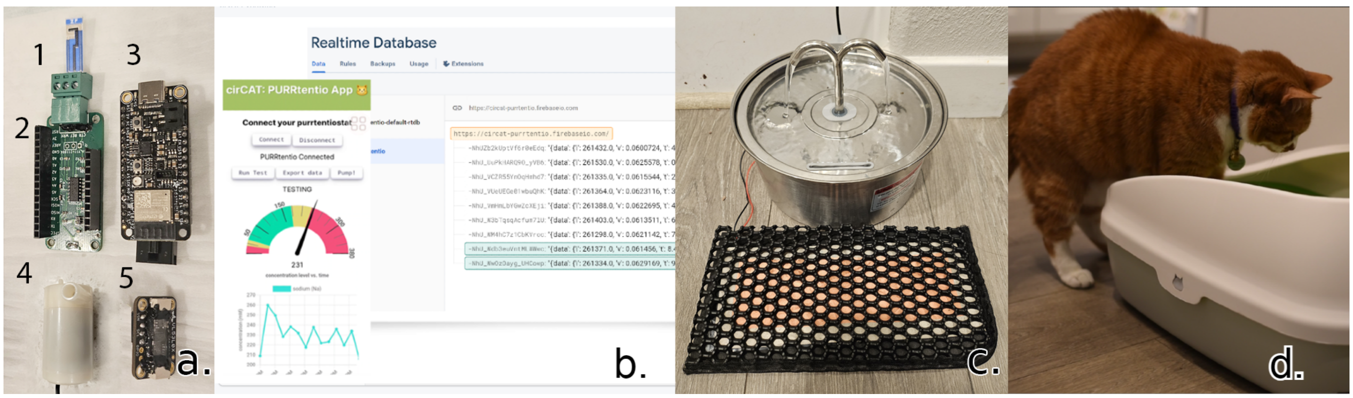

Figure 1: a) Hardware Components in the litter box: 1. electrochemical biosensor, 2. potentiostat, 3. microcontroller, 4. pump, 5. distance sensor b) Software: App and database receiving data c) Activity sensing mat in front of water fountain d) In-the-wild case study

ABSTRACT

Feline urine provides valuable insights into an animal's well-being. However, professional veterinary urine analysis can be invasive, costly, and infrequent. Electrochemical biosensors, widely used in medical diagnosis, environmental monitoring, food quality control, and drug discovery, offer a promising solution for sensing analytes in feline urine. This paper introduces the "Feline Biofluids IoT Hub" concept that aims at making previously inaccessible biological data in pets' fluids visible and integrates biofluid sensing with an Internet of Things (IoT) system to enhace comprehensive animal health monitoring. To implement that concept, our project GluCAT includes a biosensing litter box and an activity sensing mat to facilitate the care of diabetic cats. Chronoamperometic data is capture from the electrochemical biosensor using a potentiostat and send to a database via Wi-Fi, providing data visualization through a mobile application. We present electrochemical biosensor tests across five glucose levels. We compare results from feline urine samples with laboratory-grade tests. Furthermore, we share insights from a real-world user study involving a cat interacting with GluCAT for over 50 hours. We envision our project enabling the monitoring of various illnesses by detecting analytes like pH, sodium, and glucose in feline urine using electrochemical biosensors, complemented by data from pet-oriented IoT devices measuring water intake, activity, weight, and food consumption.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing systems and tools**; *Personal digital assistants*; • **Hardware** → *Sensors and actuators*; *Sensor devices and platforms*; • **Applied computing** → Health informatics.

KEYWORDS

animal computer interaction, ACI, electrochemical biosensors, feline health

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1 INTRODUCTION

Feline urinalysis provides valuable diagnostic information for assessing health conditions[4], but this information is not readily available to general practitioners as it requires clinical lab testing, which can be costly and time-consuming [32]. Repeated tests further add to the inconvenience. Glucose level analysis is essential for routine urinalysis and plays a crucial role in monitoring cats with diagnosed conditions like diabetes, as well as aiding in accurate diagnosis for undiagnosed cats exhibiting relevant symptoms [11, 16, 47]. We develop and evaluate a reusable and continuous biosensing method that uses an electrochemical system to assess glucose in feline urine in an unobtrusive manner.

Furthermore, for diabetic cats, a holistic evaluation of various aspects of health may be required to provide accurate diagnosis. The integration of Internet of Things (IoT) with fluid sensing, with a specific focus on glucose monitoring in a cat's urine, offers a novel approach to feline healthcare. It has the potential to not only enhance the well-being of our feline companions but also shed light on the intricate dynamics between humans and their pets, ultimately strengthening the human-animal bond. For example, we will correlate water intake data with urine analysis data to provide hydration information that is analyzed in accordance with with urine glucose levels, a vital aspect of health upkeep for diabetic cats [11, 25].

Our electrochemistry-enabled litter box aims to access urine information that is not readily accessible without laboratory testing. It is designed to match veterinary metrics so it could complement veterinary care[37, 38]. Integrating other monitoring devices into its network allows us to better provide data for human users by utilizing all capabilities of various technology. We hope to sync multiple aspects of pet life and welfare together to provide a holistic view. This could be used to provide continuous, at home data to veterinary professionals, which were not previously available.

In this project, we presents the following contributions:

- Introducing "Feline Biofluids IoT Hub": electrochemical biosensors integrated with IoT for animal urinalysis.
- Developing a chronoamperometric (CA) system for a litter box to continuously monitor urine glucose levels.
- Evaluating the CA system, including comparison to lab tested feline urine's samples.
- A in-the-wild user study for over 50 hours with a cat participant.

2 RELATED WORKS

2.1 Urinalysis

Feline urine can be used as a diagnostic tool to assess health conditions through urinalysis, used for lower urinary tract issues, hydration, kidney functions, and metabolic disorders [4]. However, this information is often not readily accessible to general practitioners as it only can be obtained from clinical lab, which can be costly in price and time [32]. The inconvenience is compounded when multiple tests are required. We propose GluCAT to serve as a complementary solution to veterinary care, with the aim of promoting awareness among cat owners about pet's health. Having access to information about the chemical status of a cat's body at home can significantly aid in veterinary diagnosis and care. Glucose level analysis is essential for routine urinalysis and plays a crucial role in monitoring cats with diagnosed conditions like diabetes, as well as aiding in accurate diagnosis for yet to be diagnosed cats exhibiting relevant symptoms [11, 16, 47]. Glucose levels in urine can be associated with kidney disease, thyroid issues, diabetes, and other treatments. Glucose measure is considered an integral part of routine urinalysis and even more crucial for cats with diagnosed issues such as diabetes [16, 47]. Routine monitoring of glucose levels is a key component of treatment for diabetics cats [16]. For undiagnosed cats exhibiting diabetes-related symptoms such as polyuria, polydipsia, polyphagia, weight loss, or dehydration, analyzing glucose levels is fundamental for a proper diagnosis [11].

When assessing urinalysis results, glucose is also often examined alongside other markers, such as ketones and bacteria, to be able to diagnosis specific issues that one analyte alone cannot [31]. The intricacies of glucose and diabetic cats underscore the need to consider various factors in a cat's life. Diabetic cats often exhibit distinctive feeding habits, weight changes, and other behavioral patterns, in addition to displaying abnormal urinalysis results[18, 25]. When assessing urinalysis results, it is important to examine glucose alongside other markers, such as ketones and bacteria, for accurate diagnosis [31]. Additionally, diabetic cats exhibit various factors, including different feeding habits and weight changes, in addition to abnormal urinalysis results [18, 25]. To achieve accurate diagnosis, a holistic examination of multiple factors, such as polyuria, weight loss, and dehydration, is necessary [11]. Our project, using Internet of Things, will address these needs by correlating health factors and diagnosing specific illnesses. Specifically, we focus on water intake, correlated with dehydration and glucose intake, as a secondary biomarker to assess alongside urine glucose. By integrating Smart Home devices, we can broaden data analysis capabilities and predict health conditions based on collected data.

2.2 Electrochemistry

There are research on cats involving the manipulation of cat litter, especially colorimetric sensing litter for pH levels. The use of a litmus agent in the cat litter makes the litter change color with cat pees, which is used to determine the pH level of the urine [12, 19, 46]. Most relevant to our project, one uses cat litter to detect diabetes in cats, the method uses an absorbent substrate manipulated with sugar detecting chemicals [35]. For electrochemical approach, a group created a salivary urea sensor with a diode and photo-conductive cell to detect blood urea nitrogen in chronic kidney disease patients [40]. This research was used then to create a cat litter capable of sensing kidney diseases.

Several projects use electrochemistry for analytes detection in human fluids. Previous works explored adhesive-style wearable sensors [15, 17, 41]. Another developed a ring for detecting biomarkers from saliva [24]. Sweatcessory is a sodium-detecting sweat biosensor [45]. BioSparks is a jewelry-based biosensor for monitoring sweat glucose [36].

For glucose, material requirements are different due to the enzymatic nature of glucose biosensing. The standard electrochemisty methods for glucose is Chronoamperometry (CA), where a voltage is stepped on the working electrode, and the resulting current is measured [2, 10, 14]. The biosensor composes of a three electrodes system. The working electrode reacts with the analyte, glucose. The other two electrodes are reference electrode, which has fixed potential electrode to as reference, and counter electrode, which is an auxiliary electrode [13, 48].

2.3 IOT

Plenty of Internet of Things (IoT) technology exist for pet care, especially for monitoring certain aspects of an animal's life; many touch on the concept of a technological environment for animals and humans[3, 30, 33, 39]. It was stated that through environmental choice and control, human-assisted animal interaction with technology can enhance human-animal relationships, and provide data collection opportunities for research [7]. Using human-animal bond as a motivator, one research designed technology to improve daily activities at home for children [28]. One paper looked into how might the animals and humans in animal-centric robotic spaces engage with the systems and with each other, specifically looking into the role "trust" plays [5]. Environmental audio monitoring systems have been examined for improving the quality of life for patients and caregivers through the recognition of barking patterns [1]. These previous works in the field of ACI provide a framework for possibilities IoT bring [22].

The "Feline BioFluids IoT Hub" concept aims to monitor various illnesses by detecting multiple analytes in feline urine using electrochemical biosensors. These capabilities are complemented by data from other pet-oriented IoT devices, such as those measuring water intake, activity, weight, and consumption. To implement this, GluCat creates a biofluid sensing system with specific focus on glucose monitoring in a cat's urine to support veterinary care at home.

3 IMPLEMENTATION

In this GluCAT project iteration, we implement hardware and software for sensing glucose levels from feline urine using a litter box. To explore the dynamic between water intake and urine glucose levels, we created a pressure sensing mat for tracking water activities. We connect these devices with a database and IoT principles.

3.1 Eletrochemistry Litter Box

3.1.1 Hardware and Software. The base hardware includes an Adafruit Feather HUZZAH V2 board. Cat detection in GluCAT utilize a VL53L0X Distance sensor (ToF). The Rodeostat Featherwing V0.3 R1 potentiostat from IO Rodeo, with modified circuitry and software implementation, is employed. Glucose detection utilizes Chronoamperometry (CA), applying a stepped voltage to the working electrode and measuring the resulting current [2, 10]. We programmed our system to output a constant voltage suitable for the biosensor used, determined by cyclic voltametery for each biosensor. For this iteration of the project, we successfully implements CA for glucose detection, respectively, considering biosensor behaviors and communication time required for Wi-Fi with the web app.

Due to the nature of chronoamperometry, the resulting data of any valid CA test will be a curve following Cottrell equation, which states current decay over time [21, 34, 44]. Typically, the resulting data of all solutions is compared at the same time after the solution is applied [2, 26, 29]. As such, our system records and uses the data exactly 15 seconds after initial contact of biosensor with liquid. The initial contact with feline urine is determined by both cat detection via the distance sensor and sensing a spike in current in the potentiostat.

Oscillation in data is an expected noise due to limitations in the potentiostat hardware, such as circuitry materials, capacity, and the sampling rate [6, 42, 43]. Due to the predictable sinus behavior, we treated the oscillation by manipulating calculation and sampling rate to consider data wavelength, as to use the average point of curve amplitude as point of reference. We average three seconds of data starting from 15 seconds to use for estimating concentration level.

3.1.2 Form Factor. Figure 1c and 2b show the adapted two-layer litter box with integrated hardware. The bottom layer houses the potentiostat system and fluid-absorbent pee pad. Two layers of sift and funnel are located beneath a plastic surface covered with non-absorbent cat litter; enabling fluid flow to the biosensor [37, 38]. The upper layer incorporates the distance sensor to detect cat entry and triggers an electrochemical test, CA, upon cat exit, accounting for loitering time, informed by past research on cat pee time [8, 23, 27].[1].

3.2 Activity Sensor Mat

In order to unobtrusively detect the number of times the cat intakes water, we created a pressure sensitive mat. The mat uses Velostat material with copper conductive fabric on either side, adhered with conductive tape. This sensor is connected to a ESP8266 ESP-01 microcontroller that sends a timestamp signal to the database whenever pressure is sensed to be above a threshold, when a cat is present. This mat can be used to track other activities beyond water intake.

3.3 IoT

In this Internet of Things (IoT) environment, devices send data to our database, and a web application, both shown in 1b, displays data and communicates among devices, including commercial Smart Home systems. For example, we use Amazon Alexa in our system to perform possible notifications to user, or communicate to other media.

3.3.1 Web App. To facilitate data visualization, we incorporated a web application as a modular component of Firebase that connects to our database and the Smart Home system, acting as a mediator (Figure 3), visualizing received data or commands from the database and sending relevant messages or requests to Smart Home devices. For example, if abnormal level data is detected from GluCAT, the web app can trigger Alexa to alert the caregiver with a notification sent to their preferred Alexa compatible device. The settings for such notifications are determined by the caregiver's preferred Alexa device settings.

3.3.2 Database. To encompass data transmission, storage, and manipulation of the cirCAT's devices, we implemented a database and hosting using Google Firebase [2] and Cloud Firestore (Figure 3). The Realtime Database handles live urine data from GluCAT. Data

[1]https://github.com/anonpapersandsuch/purrwifi
[2]firebase.google.com

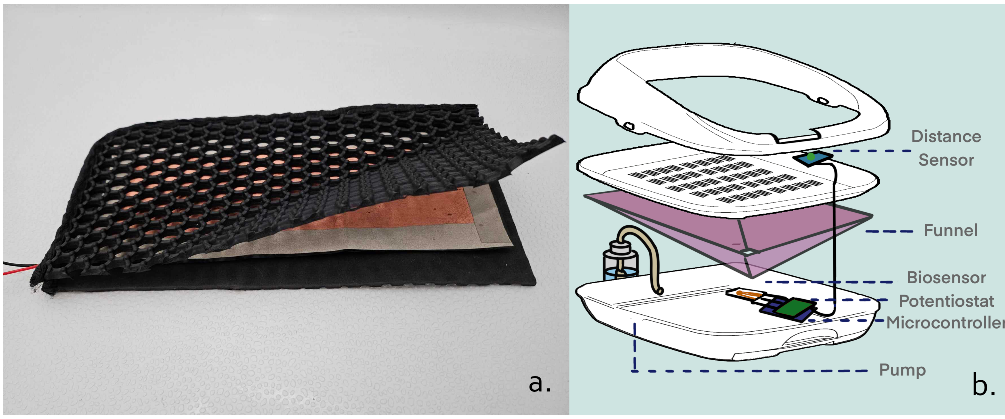

Figure 2: a. Activity Sensor Mat: Pressure sensor embedded into pet's mat, b. layers of the litter box with placement of electronics

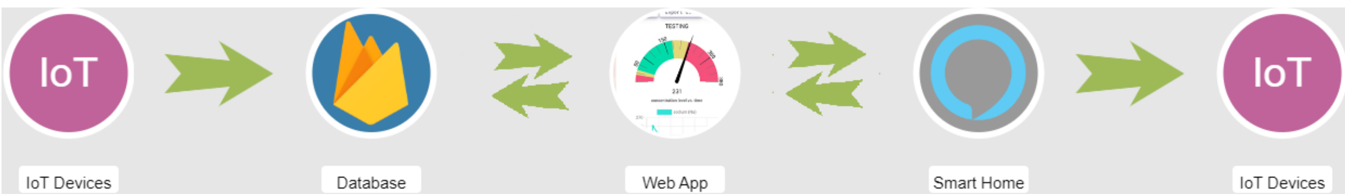

Figure 3: Communication flow of the devices and softwares within the system

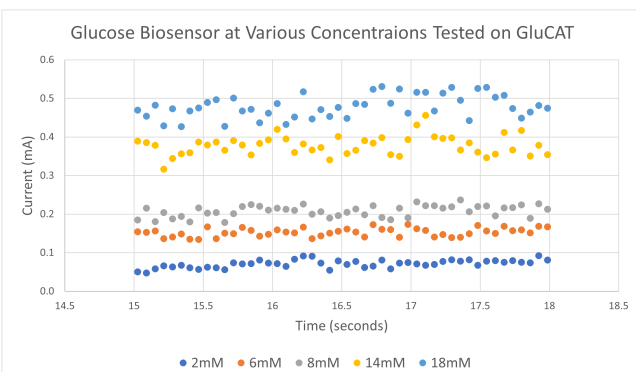

Figure 4: Chronoamperometric measures for each glucose solution with GluCAT

from the litter box, mat, or other future devices are sent and stored in the database.

4 TECHNICAL EVALUATION

4.1 System Evaluation

To evaluate our implemented chronoamperometry (CA) system, we tested the system with 5 controlled glucose solutions: 2, 6, 8, 14, and 18 mM. Those concentrations were picked to evaluate the precision in detecting small concentration changes and to establish the system's working range. Each solution, measuring 50 μl was applied to a commercial platinum electrochemical biosensor activated to exclusively detect glucose [3]. The chronoamperometric data for each solution is presented in Figure 4. As can be seen in our results, at the range of 15 to 18 seconds after initial contact with solution, each concentration stabilized to a curve of unique amplitude. During this time range, the curves exhibit such pronounced stability that any exponential growth becomes imperceptible, allowing for the clear identification of the corresponding glucose level. Notably, higher concentrations correspond to higher current values. Consequently, we can map the values of each solution to estimate their concentration based on the current. This mapping is depicted by the trendlines in Figure 5. It is important to highlight that our system's results align with those from previous research employing industry-grade glucose meters, maintaining a consistent trendline with an r-squared value of 0.98 [9, 20, 26, 34].

4.2 Urine Sample Test

For validation of our system, we tested with real urine samples and compared our results with current standards for glucose testing in feline urine. Nine urine samples from diabetic cats were provided from a veterinary research laboratory. We used previously obtained portions of samples that would have otherwise gone unused, ensuring ethical use of resources, thus qualified for an exemption from IACUC review. Before receiving the urine samples, the veterinary lab had already conducted laboratory-grade tests on each sample. These tests were aimed at determining the corresponding glucose levels in the urine samples, including any associated blood glucose levels of the cats at the time, if applicable.

[3]https://www.zimmerpeacocktech.com/

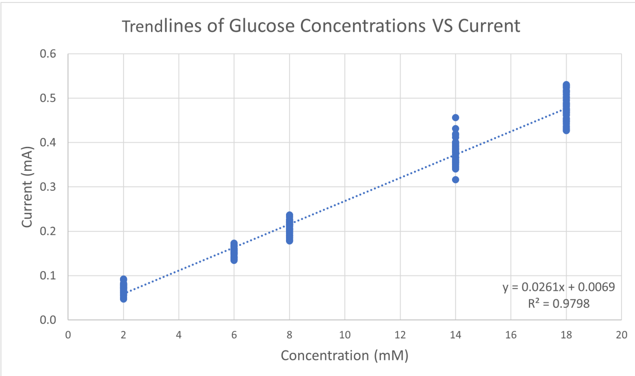

Figure 5: Trendlines of current values for each concentration at 15-18 seconds after application of solutions

Sample	Lab Results (Mg/dL)	Lab Results (mM)	GluCat (mM)
A	neg	0	0.03
B	neg	0	0
C	100	5.56	4.86
D	100	5.56	3.33
E	100	5.56	8.54
F	200	11.11	10.8
G	250	13.89	14.76
H	1000	55.56	73.27
I	1000	55.56	87.98

Table 1: Comparison of our system against results from the veterinary lab for real feline urine samples

We tested each urine sample with GluCat. The results obtained from our system and the laboratory-grade tests are compared in Table 1. These results highlight the accuracy and reliability of our system in measuring glucose levels in feline urine as our results closely align with the laboratory results received. It's important to note that the laboratory-grade tests, while precise, are constrained by their measurement range. Specifically, the lowest result provided for a test above 0 is 100 mg/dL (equivalent to 5.56 mM), and the highest is 1000 mg/dL (55.56 mM). In contrast, GluCat demonstrates its capability in sensing a broader range of values, from 0 to 5.56 mM and extending beyond 55.56 mM.

4.3 Case Study

In order to validate the functionality of GluCat in an in-the-wild setting, we conducted a 50-hour case study with a cat participant that interacted with our glucose-sensing litter box and water intake tracking mat. The participant was 11-year-old cat without diabetic conditions reported. Given the participant's non-diabetic status, we anticipated low glucose concentration levels, primarily aiming to validate the system's usability in a real-world setting. To ensure the accuracy of our tracking and to identify any potential false positive data, we recorded video footage of the litter box and mat area. Our study qualified for an exemption from IACUC review for observation-only of an animal with no direct manipulation.

To familiarize the cat with the litter box and mat, both were used three days prior to testing in the participant's residence during accustomization period. All usages of the system were voluntary, and alternatives were available to the participant. Once the cat was accustomed to the litter box and water fountain, we introduced the electronic components into the environment. The cat did not visibly appear to show any signs of additional interest or irritation.

During the 50-hour testing period, the participant used the litter box a total of four times, opting to use an alternative litter box once. The cat stepped on the mat eight times. These usage counts closely aligned with our video recordings of each device's activity. As for the electrochemical tests conducted during the times the litter box was used, all four test results indicated estimated glucose concentrations of less than 1 mM. This outcome was consistent with our expectations, considering the non-diabetic status of the participant.

5 LIMITATIONS AND FUTURE WORKS

The current state of the project uses a commercial electrochemical biosensor. We plan to accomplish DIY biosensor fabrication and extensive testing with glucose. Our case study serves as usability validation done with one non-diabetic cat. Continuing with our voluntarily usage based protocol including accustomization periods, we would like to conduct user studies with diabetic cats and their caregivers. Our plan is to recruit around 15 participants and conduct the studies for a week to ensure continuous monitoring.

Amount and duration for water intaking tracking will be done through weight based sensing. This improvement upon the mat will open up opportunities for cat weight tracking too. Our main goal would be to integrate our current system further to obtain a holistic understanding of a pet's welfare, enable automatic features to improve quality of life, and explore possibilities of incorporating IoT with feline fluid sensing. We would study how such a network of IoT devices designed for cats could enable pet owners to take proactive steps to manage their cat's health.

6 DISCUSSION

The introduction of the "Feline Biofluids IoT Hub" concept, embodied in the GluCat project, opens up a realm of new possibilities for the comprehensive monitoring of pet health. By seamlessly integrating biosensing capabilities with IoT devices, this concept allows for previously inaccessible biological data in a pet's fluids to become visible. This project opens new research directions in Animal Computer Interaction:

GluCat's future envisions a multiplexed potentiostat, facilitating concurrent analysis of feline urine markers, such as glucose, pH, and bacteria. This multi-pronged approach aligns with complex feline health diagnostics, accounting for diverse factors like dietary habits, weight fluctuations, and polyuria. The Smart Home-based GluCat aspires to correlate these aspects, delivering comprehensive pet health assessments.

Continuous at-home data collection by GluCat promises to provide veterinarians with invaluable urine data, strengthening the veterinary-care dynamic. This proactive monitoring enables early condition detection and management, enhancing the veterinarian-pet owner relationship. Empowering pet owners with health data and improving veterinarian communication fosters robust bonds among caregivers, pets, and veterinary professionals. Collaborative efforts hold potential for comprehensive and effective pet care strategies.

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