Ratpack: Wearable Sensor Networks for Animal Observation

Okuary Osechas, Johannes Thiele, Jó Bitsch, and Klaus Wehrle

Abstract— **The goal of our project is to describe the behavior of rats. For this purpose we are using wireless sensor networks, monitoring various quantities that yield important information to complement current knowledge on the behavioral repertoire of rats. So far, on the sensing and processing side we have developed innovative, minimalist approaches pointing in two directions: vocalization analysis and movement tracking. On the data collection and routing side we have adapted to the known burrowing habits of rats by developing new methods for synchronization and data aggregation under the paradigm of sporadic connectivity in a sparse, dynamic network.**

I. INTRODUCTION

One of the core motivations for the research in sensor networks is the vision of deploying sensor networks in nature to observe environmental phenomena. In this paper, we discuss our contribution to make this vision a reality. With the help of sensor networks, we plan to observe several aspects of rat behavior.

Currently, we are equipping rats with standard sensor nodes (mica2dot) and developing a custom sensor suite, consisting of a microphone and a 3-D accelerometer, adapted to the task of rat observation. Motes are attached to laboratory rats with the help of a custom leather harness, fitted with a pocket for the sensing equipment. The long term goal is to attach (or even implant) the sensor nodes to wild rats; this will have consequences on the accessibility of the data.

In the wild, rats live in underground burrows and so radio communication is limited. Therefore, sensor nodes can only communicate among each other when the rats carrying them meet within a certain range. As a result, the sensor nodes are only sporadically connected and the network topology is highly dynamic, making our deployment scenario significantly different from the typically envisioned static networks.

The remainder of this paper is structured as follows: first, section II discusses other deployments of sensor nodes and compares our deployment scenario to these. Section III describes the quantities we are interested in measuring and the type of information we hope to obtain from them, while section IV discusses our approach to the issue of sporadic connectivity, our algorithms and protocols. Finally, section V offers some concluding remarks on our work.

II. RELATED WORK

Recently, a considerable number of sensor networks have been deployed in the environment [1], [2]. Most of these deployments – except ZebraNet[1] – are static networks. In these, researchers placed sensor nodes at locations of interest and ensured that the nodes could communicate with each other and the base station.

The ZebraNet project equipped zebras with customized sensor nodes. The animals' position and other relevant quantities were monitored via GPS. In addition, the sensor nodes recorded when and where zebras met. From this data, biologists evaluate the zebras' movement and social interactions.

The DTAG project [3] works in a communication scenario similar to ours: whales spend most of their time (up to 95%) underwater, making radio communication unfeasible. Their approach is to record relevant data and detach the recording tag from the whale, once the memory full. The tag then floats to the surface to be collected by the researchers. While this approach is very elegant for underwater animals, it is not feasible for research on burrowing animals.

III. NODE DESIGN

The scheme we are developing for studying the behavior of rats differs from existing methods in that it allows us to monitor rats directly in their natural environment (as opposed to traditional laboratory experiments). One fascinating prospect is the possibility of studying the structure of a burrow with a minimally invasive method, as this was previously done by excavating existing ones, thus disturbing the natural course of its inhabitants. Our research activities have been focused on two aspects of rat behavior: estimating their motion and observing their vocalizations.

A. Physical Design

The constraints governing the design of our current platform came from two sources: rats' physical characteristics and their known habits.

The most restricting *physical characteristic* of rats is their size. An average adult Norway rat measures 25 cm in length and weighs 250 g [4]. It is important that our sensor nodes do not significantly restrict rats in their natural movements. Our first setup consisted of a mica2dot mote (from Crossbow technologies), powered by a coin cell battery and supporting a number of custom made sensor boards (discussed in the following subsections). It was attached to the rats using a custom leather harness, as described in [5]. This harness has openings for the front legs and wraps around the rib cage and the back of the rat. It is under continuous revision and

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O. Osechas and J. Thiele are at the faculty of biology, Tübingen University, 72076 Tübingen, Germany `firstname.lastname@uni-tuebingen.de`

J. Bitsch and K. Wehrle are at the Department of Computer Science, RWTH Aachen University, 52072 Aachen, Germany `firstname.lastname@cs.rwth-aachen.de`

Fig. 1. A Norway rat wearing a RatPack

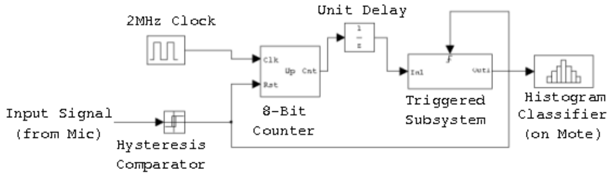

Fig. 2. Model of the *Vocalizations* sensor board

the current version can be seen in figure 1, including the sensor node.

As for the *behavioral restrictions*, the main constraint in studying rats is their habit of burrowing. Radio communication is not available for most of the time (which is why we speak of a sparse network in section IV), nonetheless data logging is still desired. At the same time, memory capabilities are also limited by the size of our system and so a trade-off must be found.

In order to reduce memory and processing complexity we are working on a number of sensor boards, made up mainly of analog electronic components, that allow us to increase the abstraction of the data recorded by our sensors without burdening the processor. The following subsections describe two of these sensor boards: one for vocalization analysis and one for motion detection.

B. Vocalizations

Norway Rats live in burrows, usually shared in groups, which naturally leads to the formation of social hierarchies [4]. The communication between these rats is partially based on ultrasound vocalizations Several scenarios of interaction between rats have been studied under laboratory conditions (mother/child, resident/intruder, infant rats' ludic sounds). We have developed a setup to monitor their calls that meets our energy and size restrictions, as described in subsection III-A, while it still allows the classification of the vocalizations in question. The vocabulary we matched our data to was taken from [6], while the actual data used in the design phase came from [7]. Another set of data was taken from [8].

1) Hardware: The hardware consists of some basic mixed-signal elements used for feature extraction that feed a firmware classifier on our mote (see figure 1. The electric signal is generated in an ultrasound microphone, conditioned by an active band-pass filter and fed to a comparator. Feature extraction consists of measuring the time between zero-crossings, following the concept of "generalized frequency", as used in [9]. In our setup this is done by an 8-bit counter with a clock frequency of 2 MHz. The resulting measurement is fed to the aforementioned classifier on the mote.

2) Firmware: The classifier in question gathers the time measurements from the counter in a histogram with 256 bins that is refreshed automatically when a call ends. Currently the two simplest classification features available are: the most frequent value in this histogram and the sum of the counting values. Intuitively, the former loosely corresponds to the strongest frequency in the call, while the latter corresponds to the call's length. In principle, the whole histogram can be used as a classification vector but this procedure requires significantly more computational power.

3) Experimental Setup: Although rats do communicate some information through sound, under normal laboratory circumstances their vocalizations are sporadic. As it requires a significant amount of work to "chase" these sounds our classifier was not trained on live rat vocalizations, but rather on recordings thereof. With the help of an ultrasound recording and playback setup, as well as data from [7] we trained a classifier that appears to be able to discern the vocabulary in [6]. Extensive testing is still under way.

4) Preliminary Results: The described scheme was tested using a hardware in the loop approach. Recordings of rat vocalizations (available from [8]) were played back to the vocalizations sensor board. Corresponding feature vectors were obtained and compared to distinguish between different calls. This serves as proof of concept to show that our technical solution is viable; but it needs to be extensively tested for validation and reliability.

C. Motion

Knowing how rats move about in the environment may enable us to describe their foraging habits, as well as the layout of its burrow. This may also allow us to draw conclusions as to the actual use of different sections of the burrow, in a non-destructive fashion. The first approach to this problem has been to estimate the displacement of a rat from acceleration measurements, with some work on heading estimation still under way. Our sensor nodes are attached to rats on the outside of their body (rather than implanted); this has two important consequences: the distance between the sensor and the centre of gravity is not negligible, and the orientation of the accelerometers changes in time, as they slip off rats' backs. As it is currently not feasible to implant sensor nodes into our rats, these problems were dealt with by using a step-counting-like approach, estimating the velocity of rats by measuring the time between peaks in our accelerometer signal. The main differences between our approach and step counting approaches with human subjects, as in [10], are: (i) our setup has a lower ratio of step time to the available sample period and (ii) accelerometers cannot be attached to the rats' feet.

1) Hardware: For this purpose we are using data collected with ADXL330 accelerometers sampled at 20 Hz, attached to rats (as described in III-A) moving in an artificial burrow, constructed from drain pipes. The accelerometer signal is

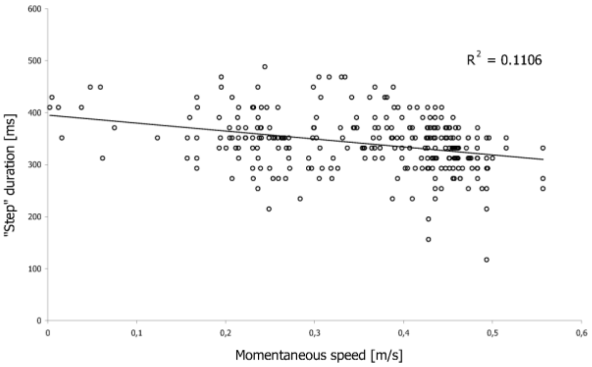

Fig. 3. Dependence between pseudo-step duration and walking speed

filtered and passed to a comparator for detecting spine twists, to which we refer as *pseudo-steps*.

2) Firmware: The task of the firmware is measuring the time between *pseudo-steps* and calculating the estimated speed. When no stepping is measured, it is able to record the estimated elevation (or pitch) angle relative to gravity. This is useful in characterizing rats' exploratory habits.

3) Experimental Setup: Our data was collected from rats moving in an artificial burrow, constructed from drain pipes and wooden boxes. Feedback on the actual position of the rat was given through light barriers installed along these pipes. This position information was then related to the time between pseudo-steps.

4) Preliminary Results: The time between two pseudo-steps has been observed to correspond with the velocity measurement obtained from the light-barrier data. Figure 3 shows a scatter plot of step duration versus measured speed, with a least squares fit. It is apparent that the estimation of a rat's speed from the duration of these pseudo-steps is not reliable, but considering the design constraints discussed in III, the result suits our current requirements. Ongoing work is focused on inferring on the actual gait of the rat from the stepping pattern. Accurate ground-truth on the actual velocity of the rat should be available from a treadmill, similar to the set-up in [11], also used for studying rodent gaits.

IV. NETWORK ARCHITECTURE

At present research focus in the sensor network community lies on continuously connected sensor nodes. Thus, although the network topology may vary slightly over time, (e.g. due to node failure or changing radio conditions) the network structure mostly remains the same. Today's algorithms and protocols such as Medium Access Control (MAC), routing, and data aggregation focus on this static scenario.

The requirements of our own scenario quickly showed that the available algorithms and implementations are not efficiently usable for various reasons. In the following paragraphs, we will discuss how the MAC and routing layer need to be adapted for our outdoor deployment.

A. Medium Access Control

Networks in a sporadically connected environment have slightly different requirements as compared to continually connected networks. Different nodes of the network are not in communication for most of the time. The challenge is therefore to (1) discover that another node is within communication range as fast and energy efficient as possible and then to (2) allow as fast and reliable communication as possible, since this period of connectivity is probably short. In embedded systems the need for energy-efficiency is even more relevant, as the amount of energy available is limited.

Existing Medium Access Control protocols for sensor networks such as [12], [13] focus on the energy-effiency in continually connected networks and limit the available bandwidth. The radio chip is powered and set to receive packets only up to 1% of the time. The sending node has to compensate by either long preambles or sending the same packet several times.

These low power listening schemes, can prove useful in a discovery phase, while a node is looking for other devices within communication range. However, as soon as a connection is established, they are of little use and the devices need to change into a different (high throughput) scheme to actually transfer bundles of data.

To support our claim that an adapted MAC protocol is needed, we performed radio performance experiments in artificial underground burrow systems with tubes of different diameters. Related work predicted a range of 0.3 m through ground, but to our knowledge, no previous study measured the actual propagation in artificial burrows which we found to outrange through-earth propagation threefold. Still, an active communication range of 0.9 m clearly shows the need for efficiently dealing with sporadic connectivity.

B. Routing

As we do not expect to know all exits of a rat burrow and some rats may stay in the burrow for long durations, we need the sensor nodes to exchange their measurements. Today's tree-based routing protocols [14] or even new any-to-any versions [15] are not suitable for this purpose. Similar to delay tolerant networks [16], data should be relayed from one sensor node to another when their bearers, i.e. the rats, meet within radio range.We place base stations at the exits of the rat burrow. When a rat passes a base station, all measurements collected by this rat's node, as well as the data passed on from other rats' nodes, are transmitted to the base station. In order to deal efficiently with these data packages, we have devised two multi-hop routing strategies: one is content based and the other is topology based.

1) Utility Based Forwarding: Depending on the biological insight gathered so far, researchers may want to assign different relevance to different types of data. While at the beginning, the actual physical layout of a rat burrow might be considered more important, the vocalization information might be deemed more important at a later stage. This relevance of data bundles can then be taken into consideration for forwarding decisions together with various other factors, such as: the availability of memory on another node, the expected delay of forwarding that data through a specific node to a base station and current energy levels. All these factors are combined into a forwarding utility function[17], so different decisions can be taken depending on specific situations.

2) Social Network Based Forwarding: Another interesting approach to data bundle forwarding is to facilitate the social stucture of the animals under observation. Most animal interactions seem to follow power-law[18] (for human beings this was shown in the Milgram experiment[19]). For routing, this can be leveraged if a receiver of a certain packet is not known to a sending node: it forwards it to the neighbor with a higher degree of neighbors. If no such node exists, data is forwarded along a random path[20].

C. Data Aggregation

Sensor nodes have very limited storage space. In our mica2dot-based system, it comprises 4 kB of RAM and 512 kB of additional flash space [21]. As previously mentioned, it may take some time until a rat passes one of the base stations. Thus, its sensor node needs to store potentially large amounts of measurement data. Since we are working with a stochastic routing strategy, data packages exchanged between motes are tagged with their entire routing history until they reach a base station; thus we are able to reconstruct the context (how and when) in which the data was generated.

Our sensor network is designed to integrate the acquired knowledge about rat behavior. Thus, we are implementing stream data mining techniques to automatically generate models from the incoming measurements. Due to the limited capabilities of the used systems, these models only approximate the real behavioral patterns. These approximated patterns are then transmitted to the base station and taken as *known*. Once enough of these patterns exist, the biologically interesting task is to find *outliers* and further refine the preliminary models to explain those.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

This paper describes the status quo of our rat monitoring system. We have developed a number of tools adapted to the special case of *Rattus norvegicus* but, in principle, adaptable to many other species. The major challenge we have been tackling is the space/weight constraint, which ultimately translates into an energy constraint. On the sensing level it has led to tradeoffs in accuracy for the sake of simplicity, while on the network architecture level it has driven us to reduce the number of messages sent across our network and the volume of duplicated data stored at different locations.

B. Further Work

Currently, our ongoing work focuses on improving the described features: new attachment devices for smaller platforms (CC-2430 based chips), heading estimation for 2-D motion reconstruction, prolonged battery lifespan. Once a fully functional prototype is obtained, it seems logical to aim for a System-on-Chip implementation of our project. Although the main deployment scenario is rat observation we think this architecture can be easily adapted to other species, such as Flying Foxes or Naked Mole Rats (*Heterocephalus glaber*), as their social interaction is highly complex. Newly available platforms have become sufficiently small to make it seem plausible to even study smaller bats.

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