RFID-BASED BUTTERFLY LOCATION SENSING SYSTEM

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ABSTRACT

In this paper, we describe the implementation of an RFID-based location sensing system which is intended for monitoring the movement and activity of butterflies for biological research purposes. We present the design and characteristics of the developed RFID tags, the antenna and system configuration, as well as the non-linear Kalman filtering and smoothing based tracking algorithm. We also present experimental results obtained in an anechoic chamber as well as in field test environment.

Index Terms— RFID, UHF, location sensing, extended Kalman filter, RTS smoother, butterfly

1. INTRODUCTION

A great variety of telemetric and remote sensing methods for sensing movements and location of insects are developed for the demands of biological and agricultural studies. A survey of the methods can be found in [1].

Remote sensing methods do not require a physical interaction to the target, and examples of remote sensing methods include radar (typically used to track insect swarms), machine vision, optical interferometers, X-ray imaging, infrared (IR)-imaging, and passive and active (SONAR) acoustic methods. The advantage of remote sensing methods is that they do not need to affect the insect behavior. However, they typically provide unreliable target identification, if any, and require certain operation conditions. For example, passive machine vision requires certain lighting conditions and a line-of-sight to the target.

In telemetric techniques, the target is equipped with a transponder. Telemetric techniques include the harmonic radar, active and passive radio frequency identification (RFID), and radio beacons. Active RFID and radio beacons require a battery whose mass ($\sim$0.1 g) limits them only for large pedestrian insects.

In the harmonic radar concept, the target is equipped with a transponder containing a passive mixer connected to an antenna. When the transponder is actuated at one frequency, it radiates harmonic frequencies that are detected by the radar. Harmonic radar and tags were first proposed for traffic applications. The concept was later generalized for all harmonic tones [2] and it is successfully used to track insects [3–5]. Harmonic radar concept is also used for locating avalanche victims [6] and wireless read-out of passive sensors [7–10]. However, the harmonic radar may be an expensive solution for insect tracking as such radars are not commercially available and it does not necessarily comply with the frequency regulations due to potentially large frequency offset required. In addition, different targets cannot be identified in a straightforward way.

Passive UHF RFID is used for example to follow the activity and movements of a butterfly called Granville Fritillary (*Melitaea cinxia*) in an indoor cage [11]. RFID has several advantages as compared to other telemetric techniques. Inexpensive UHF RFID readers are commercially available and they provide object identification. In addition, the RFID complies with the frequency regulations and operates reliable also in dark, in a presence of vegetation, in loud noise etc. opposite to several other methods. Most importantly, RFID provides a possibility to simultaneously track and identify virtually any number of objects within the read range.

The first generation of the UHF RFID butterfly tracking system presented in [12] used the received signal strength indicator (RSSI) for location sensing. However, RFID can also provide time-of-flight based location sensing [13]. This paper presents an upgraded system for the same purpose. Instead of using the inherently inaccurate RSSI measurements, the system uses the phase of the received signal for location and speed estimation. The first system developed by the authors was capable for 2D tracking [14].

In the present system the object tracking and enhanced location estimation is realized with a dynamical model for the objects that is solved with an extended Kalman filter (EKF) and Rauch–Tung–Striebel (RTS) smoother [15] by an extension of the approach used in [14]. This paper describes the system in detail including the RFID butterfly tags, the indoor cage and reader antenna configuration, and the tracking algorithm. In addition, we show verification results of the system that are measured in an anechoic chamber and also preliminary experiments in the field environment used to study butterflies.

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2. RFID TAG FOR BUTTERFLIES

Due to the small size of butterflies, we have developed a special RFID tag for our location sensing system. The RFID tag should ideally not affect the behavior of butterflies, which sets very stringent criteria for the mass, form factor, and the moment of inertia of the tag. We have ended up using a transponder somewhat similar to those generally used with the harmonic radar (see e.g. [3]), where the tag antenna is a small dipole aligned vertically on the thorax of the insect. In this setup, the thin metal wire acts both as an electrical conductor and mechanical support.

We have used the Monza 4 UHF RFID chip. The chip is commercially available and provides one of the lowest reported power sensitivities (-17 dBm). The antenna is conjugate matched to the input impedance of the chip ($11 - j143$ Ohms at 915 MHz) using two surface mountable 120 nH inductors (Murata LQW15ANR12J00D). The RFID chip and the inductors are soldered on a tiny piece of PET inlay (Mylar$^{\mathrm{TM}}$) with etched copper conductors. Because of the size and weight constraints, conjugate match would be very challenging to realize with other means. Currently tags are manufactured manually under a microscope. A schematic layout of the tag (insert) and a photograph of a butterfly (*Heliconius*) equipped with it is shown Fig. 1.

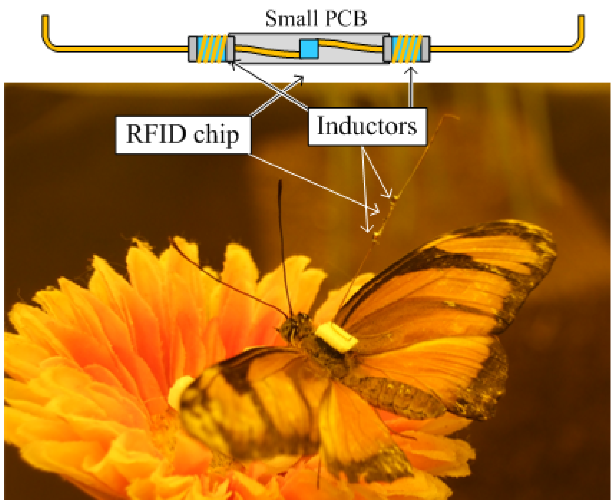
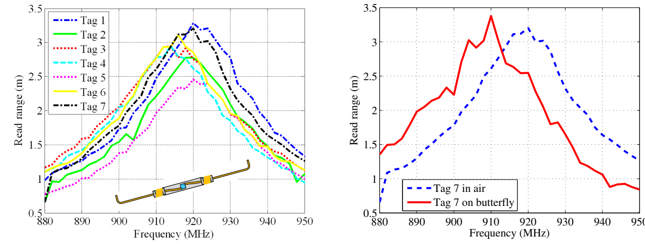


Fig. 1: Butterfly RFID tag consists of a small dipole antenna made of thin copper-wire, two matching inductors, and an RFID chip in the middle. The tag is mounted vertically on upper side of thorax. The figure is not to scale.

The power sensitivity and the modulated radar cross section of the tag were measured with an RFID test equipment (Tagformance lite). The transmit and receive channels of the RFID test device are coupled to a single reader antenna (SPA 8090/75/8/0/V) through a circulator (V24). The measured forward read range (assuming 33 dBm ERP transmit power) of 7 tags is shown in Fig. 2a. The tags are in free space conditions during the measurement.



(a) (b)

Fig. 2: *Left (a):* Measured read range of butterfly UHF RFID tags as a function of the frequency. The tags are in free space conditions during the measurement. *Right (b):* Measured forward read range of tag 7 in free space (dashed blue) and on butterfly (solid red).

The read range of the tag peaks between 910 MHz and 920 MHz, where it varies from 2.5 m to 3.2 m. The read-out range limits the largest cell size. The proximity effect of the butterfly is studied by characterizing tag 7 both in free space conditions and on butterfly. Fig. 2b shows the measured forward read range of tag 7 in air and when mounted on a butterfly.

Butterfly lowers the resonance of the tag by approximately 10 MHz but does not significantly affect the maximum read range. According to this result and our experience, tag antennas of this type can be fully tuned prior attaching them on a butterfly. However, the reader frequency is selected (910 MHz for tag 7) to maximize the read range.

3. ANTENNA SETUP

We set up the location sensing system both in laboratory environment (anechoic chamber) and in the actual field environment at the Lammi biological test station. In each of these locations we used a setup, where four RFID reader antennas were positioned on the vertical edges of a box-shaped test cell. The antennas were also located at different heights for better spatial diversity in vertical direction. The antennas are operated with an RFID reader (INfinity$^{\mathrm{TM}}$ 510 UHF Reader) with four antenna terminals. A schematic layout is shown in Fig. 3.

We chose this cell geometry, because we use commercially available reader antennas (SPA 8090/75/8/0/V) whose radiation pattern provides a good coverage for the box-shaped cell. In addition, this configuration also generalizes to multiple cells in which case the number of cells can be freely chosen without a loss of reader antenna spill-over radiation. For example, if reader antennas were omnidirectional, antennas on the edges of the tracking area would waste part of the radiated power outside of the observation area. Possible future development includes designing antennas with radiation characteristics tailored for the selected cell geometry. A photo-

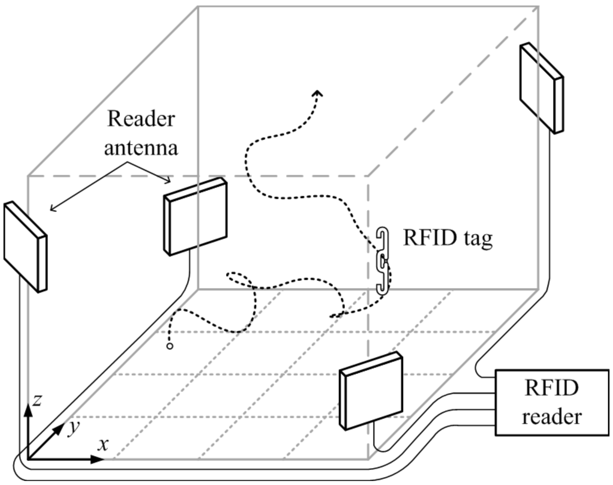


Fig. 3: Cell is approximately a rectangular box and reader antennas are placed on its vertical edges on different heights. The figure is not to scale.

graph of the butterfly indoor cage equipped with RFID reader antennas for location sensing is shown in Fig. 4. Currently the tracking system has only one cell, but more cells will be added in the future.

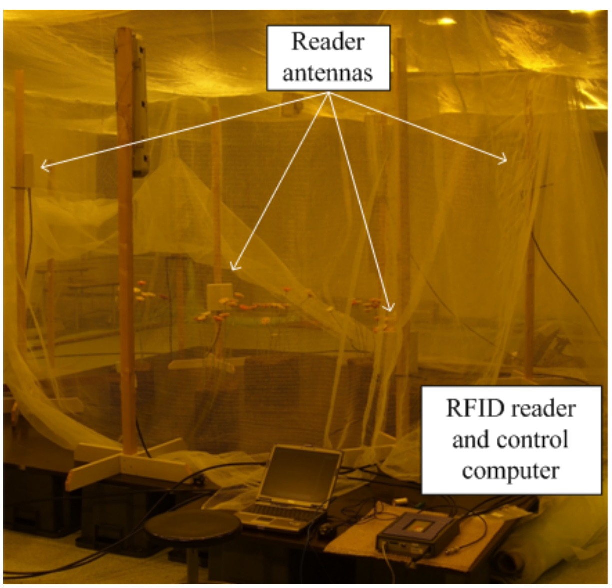


Fig. 4: Butterfly indoor cage equipped with an RFID reader and four antennas for location sensing of butterflies.

4. TRACKING ALGORITHM

We modified the tracking algorithm presented in [14] to provide 3D location data. That is, we modeled the 3D position $\mathbf{p}(t)$, velocity $\mathbf{v}(t)$, and the 4-dimensional antenna bias vector $\mathbf{b}(t)$ via a system of linear stochastic differential equations (see, e.g., [16, 17])

$$\begin{aligned} \frac{d\mathbf{p}(t)}{dt} &= \mathbf{v}(t) \\ \frac{d\mathbf{v}(t)}{dt} &= \mathbf{w}_v(t) \\ \frac{d\mathbf{b}(t)}{dt} &= \mathbf{w}_b(t), \end{aligned} \tag{1}$$

where $\mathbf{w}_v(t)$ and $\mathbf{w}_b(t)$ are Gaussian white noise processes. The 4-dimensional measurements $\mathbf{y}_k$ obtained at times t_k where modeled as

$$\mathbf{y}_k = \begin{pmatrix} \|\mathbf{p}(t_k) - \mathbf{a}_1\| \\ \vdots \\ \|\mathbf{p}(t_k) - \mathbf{a}_4\| \end{pmatrix} + \mathbf{b}(t_k) + \mathbf{e}_k, \tag{2}$$

where $\|\cdot\|$ stands for the Euclidian norm, $\mathbf{a}_i$ is the 3D position of the antenna i, and $\mathbf{e}_k$ is a 4-dimensional IID Gaussian measurement noise vector. By defining the state as $\mathbf{x}(t) = (\mathbf{p}(t), \mathbf{v}(t), \mathbf{b}(t))$, and by using the standard equivalent discretization for linear stochastic differential equations (e.g. [17]) this model can be converted into a discrete-time state space form

$$\begin{aligned} \mathbf{x}(t_k) &= \mathbf{A}_k\, \mathbf{x}(t_{k-1}) + \mathbf{q}_k \\ \mathbf{y}_k &= \mathbf{h}(\mathbf{x}(t_k)) + \mathbf{e}_k, \end{aligned} \tag{3}$$

where the non-linear function $\mathbf{h}(\cdot)$ is defined by (2). As the above model is now a standard-form non-Gaussian state-space model, we can use the extended Kalman filter (EKF) and RTS smoother (see [15]) for estimating the state from the measurements. We also used a similar iterative solution as in [14] to improve the estimated trajectory via multiple iterations of the filter and smoother.

5. EXPERIMENTS

5.1. Laboratory Tests

The operation of the location sensing system was verified in an anechoic chamber. The reader antennas were positioned on fixed antenna stands on the vertical edges of a 3 by 3 m box. Two antennas opposite to each other were at 0.2 m height and the other two at 1.6 m height (marked with triangles in Fig. 5). The antennas were aligned to point to the center of the tracking area (box). The response of the tag was measured repeatedly from each antenna at 890 MHz. The average readout rate of a single antenna was 100 times/s.

We moved the tag along trajectories which were marked in the tracking area by straining a thin line between known coordinate positions. The RFID tag (Dogbon) was mounted on top of a thin wooden rod, which is used to manually move the tag along the strained lines during the measurement. The largest deviations between the intended and the actual tag trajectories were estimated to be in the order of 100 mm due to

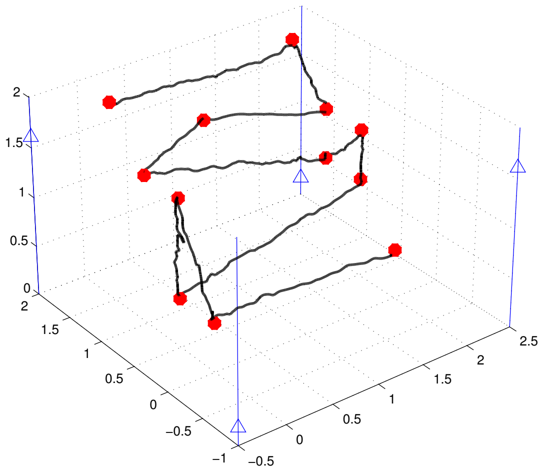


Fig. 5: Estimated 3D trajectory of a tag in an anechoic chamber. The red dots denote known reference positions on the trajectory of the tag.

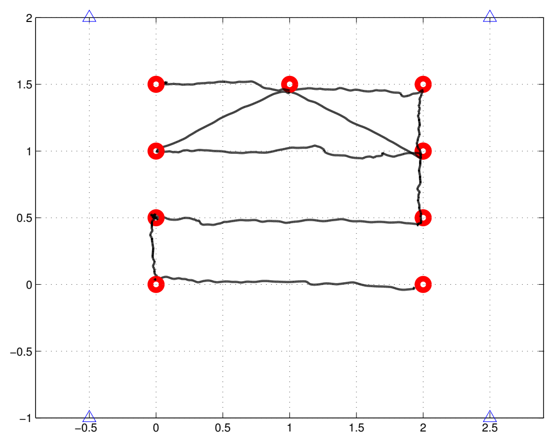


Fig. 6: The 3D trajectory shown in Fig. 5 depicted directly from above.

relatively inaccurate manual movement of the tag. An example of a result is shown in Fig. 5 and its 2D projection depicted from above is shown in Fig. 6. The red dots in the figures are measured corner points of the reference lines. The positioning accuracy can be estimated to be around a few centimeters.

In addition to fully predefined tag trajectories, we moved the tag (quasi)randomly in the tracking volume to mimic the actual flight path of a butterfly in a more realistic way as compared to piece-wise linear trajectory. To have some means to evaluate the sensing accuracy, instead of arbitrary trajectories we attempted to form recognizable shapes to 3D space. Fig. 7 shows the result of attempting to draw a flower to air (left) as well as a 3D spiral (right). In the spiral case we measured the starting position and the end position which are marked in red. As can be seen in the figures, the shapes have the intended shape and the starting and ending points of the spiral

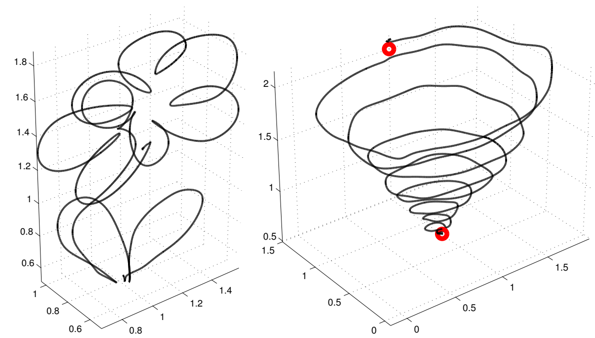


Fig. 7: Results of tracking a more freely moving tag in 3D space – on the left the shape of the trajectory should resemble a (naive) flower, and on the left we should have a 3D spiral which starts and ends at the reference positions marked in red.

are in the correct positions (accounting for the inaccuracy of the manual movement of the tag).

5.2. Field Experiment

The field test experiment was done at the Lammi biological test station of University of Helsinki in a butterfly indoor cage. We used placed the antennas to the corners of the cage (size 2.4 m times 2 m) and the antennas were at the heights 0.8 m and 1.7 m. We used stands to mark a set of reference points in known locations and the tag was moved though a trajectory which passed though these points.

An example of result is shown in Fig. 8. The reference positions are shown in red. The difference to the anechoic chamber tests is that the radio environment is now much more challenging due to disturbances caused by the surrounding metallic structures of the building. As can be seen, this causes the location accuracy to be worse than in anechoic chamber and the location error is in the order of tens of centimeters. For the intended purpose of monitoring the activity of butterflies this kind of accuracy is already sufficient, but it also could be greatly improved by taking the radio environment requirements better into account in the shielding of the surrounding structures.

6. CONCLUSION

In this paper we have presented the design and implementation of an RFID-based location sensing system which is designed to be used in biological experiments on butterflies. We have described the design and characteristics of the small RFID tags, the used antenna and system configuration, and the tracking algorithm used to compute the final result. In addition, we represented experimental results obtained in an anechoic chamber as well as in field environment, which show that the concept also works in practice.

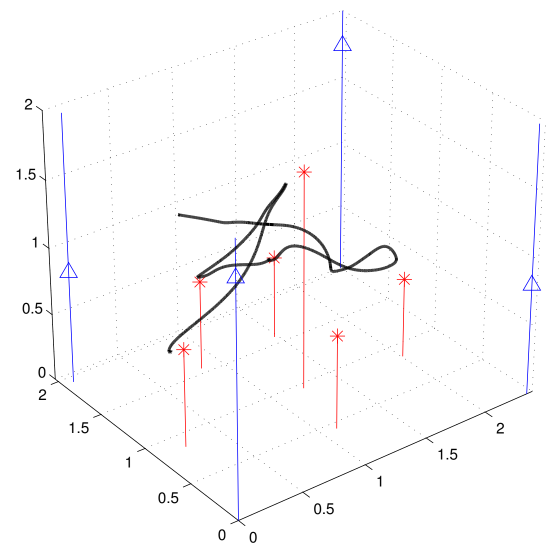


Fig. 8: Example of tracking a tag at the Lammi biological test station. The location accuracy is not as good as in anechoic chamber, but still the shape of the trajectory is right and is not too far away from the known reference points (marked in red).

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