ChiRoPing Deliverable: D3.5.2

Evaluation of computational models versus the bats they model

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Dissemination:

Abstract:

This deliverable documents attempts to evaluate the results of the ChiRoPing project from a biological point of view and to link the computational models as well as the physical embodiments to the bats` behavior. The results are evaluated in terms of i) concrete comparisons between biomimetic robots and bats, ii) new hypotheses about biology arising from robot results, and iii) the general value of the cross-disciplinary collaboration in ChiRoPing.

Theme 3: Biomimetic Engineering

WP 3.5 Characterisation and Evaluation of Biomimetic Models

Deliverable due: Month **36**

Introduction

The goal of the ChiRoPing project was to develop versatile and robust robots, which can orient and dicriminate and localize objects using sound. Echolocating bats have used this “technology”, echolocation or biosonar, for around 50 MY with a massive speciation resulting in more than 1200 extant and very diverse species inhabiting most of the Earth. Their success speaks to their expertise. Thus, it is natural to seek inspiration from those “masters” when attempting to build biomimetic robots. The performance of the robots have been compared to the models, the bats, which have provided feed-back to biology to suggest new experiments to test bats and also to seek new specific data *from* bats, for example re. attention, to integrate in next-generation biomimetic robots.
The goals and general success of the ChiRoPing project is to a large extend due to the active and efficient cross-disciplinary interaction between the engineers and biologists involved in the consortium.

1. Comparing Robotic Model to Bats

1.1 Comparing Robotic Model of <u>Trawling</u> Bats (D3.2+3.1) to real bats, mainly *Myotis daubentonii* and *Noctilio leporinus.*

Capture behavior, approach flight

Trawling bats approach prey at a small angle. The results from the biomimetic robot provide an explanation model for this behavior. Measurements with the robotic system indicate that the glancing incidence of the emitted beam results in a 3–6 dB improvement in signal-to-noise ratio in the “quiet zone” compared to a steeper or shallower tilt angle (See Deliverable 3.4.2). It is very likely that bats make use of this acoustic fact to increase their chance of detecting prey. Previously, it has been suggested that the low flight height of trawling bats ensonify the target both by the direct sound and by the sound reflected

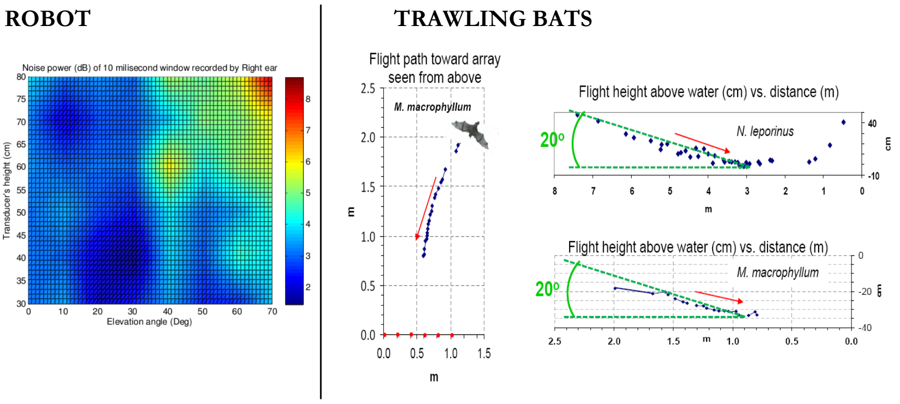
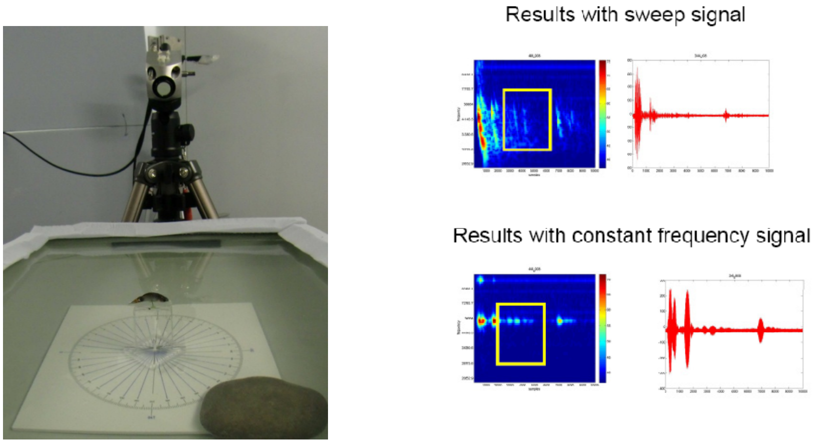


Fig. 1. The left panel (ROBOT) shows the noise power measured during the “quiet zone” interval between the ground return echo and eventual wall echoes, for a variety of transducer heights and tilt angles. The trough (lowest noise) is at an elevation angle of 20-30 deg. The right panel (TRAWLING BATS) shows approach flight for two of the three trawling species seen from the side. In addition the flight path is shown from above for one of them, *M. macrophyllum*. Both species approach the target at angles close to 20 deg.

off from the water surface, thus increasing the echo strength (see Siemers, B. M., Stilz, P., and Schnitzler, H.-U. (2001). The acoustic advantage of hunting at low heights above water: behavioral experiments on the European "trawling" bats *Myotis capaccinii, M.dasycneme* and *M.daubentonii. J.exp.Biol.* 204, 3843-3854), but there has been no functional explanation so far for the apparently stereotypical angle of approach to a target in trawling bat species.

Capture behavior, echolocation acoustics.
In general, there is a correlation between the size of bats and the main frequency of their echolocation calls, such that smaller bats emit higher frequencies. There are many exceptions to this general trend, but few as extreme as that of *Noctilio leporinus,* which is a very large bat (50-90 g) echolocating at an unusually high frequency, ca. 55 kHz. High frequencies are heavily attenuated in air, which decreases the detection range of the sonar severely. Thus, there must be a reason for emitting such high frequencies for a large fast flying bat, which needs to be able to detect objects at longer distance than smaller and more maneuvrable bats. The ChiRoPing ripple-ensonification results indicate that the high constant frequency component of the calls might be particularly well suited for detecting the ripples that occur, when small fishes, the prey of *N. leporinus,* break the water surface. Analysis is still in progress. It cannot be excluded that reflections from air-bubbles may have contributed to the echo patterns in addition to the ripples.


Results with sweep signal

Results with constant frequency signal

Fig. 2 The left panel shows the set-up of ensonification experiments with a biomimetic sonar head to measure echoes returning from ripples on the water surface. Ripples were generated in the lab on a smooth water surface and ensonified with 1 ms signals resembling the sweep (50 kHz – 20 kHz) and the constant frequency part (54 kHz) of the sonar calls emitted by *Noctilio leporinus.* Typical results are shown in the right panel for sweep and constant frequency signal. The yellow boxes indicate the ripple-echoes. The echoes are particularly obvious when the constant frequency signal is used.

In another set of experiments task-related differences in the echolocation behavior of *N. leporinus* could be linked to characteristic differences in echo fingerprints revealed by ensonification experiments with a biomimetic sonar head of the two targets. Echolocation behavior, in particular FM bandwidth, differed depending upon whether the bats caught a fish from the water surface or a mealworm in the air. The sonar head was rotated 180 degrees in 5 degree steps attempting to mimick the bat's approach towards the target. The mealworm in air reflected less energy than the fish on the water surface. The main difference in echo fingerprints from both targets is most likely associated with their presentation in space, i.e., fish on water, where the target is surrounded by a smooth surface that reflects most sonar energy away and mealworm in air without additional reflective surfaces nearby.

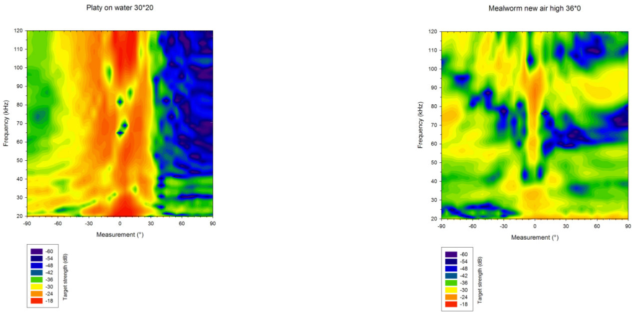


Fig. 3 Echo fingerprints of two targets, a fish on the water surface (left panel) and a mealworm in air (right panel).

Object Discrimination

The object discrimination performance of a trawling-robot was tested by emitting typical *M. daubentonii* calls and capture echoes using the SDU scalable-array technology that also underlies the robot model system. Analysis of such echoes shows clear returns from targets such as mealworms on the water surface, with a good signal-to-noise ratio — most of the acoustic energy being reflected forward by the water surface rather than back toward the transducers. Typical results for the biologically relevant targets are summarized in Table 1 in Deliverable 3.4.2 demonstrating that the robot could discriminate correctly with ca. 60% success and subsequently localize the target. There are no data directly testing object discrimination in *M. daubentonii,* but during the on-going prey removal experiments with the same species, we have observed that the bats often go for the wire of the prey remover even without prey if it protrudes above the water surface. Data from the wild also indicate that *M. daubentonii* cannot discriminate between prey and other obstacles with high confidence: they avoid water surfaces if they are not smooth enough because of wind or duckweed. The present results indicate that the bats – like their robotic mimics – may have trouble with fine scale discrimination between edible food and “clutter-echo generators”, hence suggesting an explanation for bat behavior.

1.2 Comparing Robotic Model of Gleaning Bats (D3.2+3.1) to real bats *Micronycteris microtis*

In the wild the animalivorous gleaning bat *Micronycteris microtis* slowly flies along vegetation in the dense understory searching for prey. We successfully induced this search behaviour in greater detail in our flight cage on BCI where we trained the bats to take prey sitting on artificial vegetation. The bat behavior was documented with highspeed video cameras and simultaneous recordings of the bat’s echolocation behavior with multi-microphone arrays.

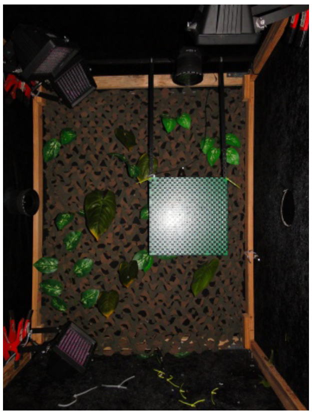


Fig. 4 Set-up of the flight cage for behavioral experiments with *M. microtis* including artificial vegetation on a clutter screen, a Lego plate (green quadrat) to test discrimination abilities of *M. microtis* and arrays of infrared lights, cameras and microphones.

After the bat had detected food, such as dragonflies resting on a leaf surface, *M. microtis* began to scan the leaf, hovering slowly in front of the target (distance 10 – 20 cm), moving back and forth and up and down. It continuously emitted steep, short, multi-harmonic FM echolocation calls, mostly in groups of two to three signals. Following positive identification of the target as edible, *M. microtis* flew towards the prey and bit into the thorax (detailed description of behaviour and echolocation calls see deliverable D2.2.1).

The flight paths of the bat were derived and correlated with its echolocation behavior. During scanning, the bat's head, noseleaf and ears were pointing towards the target, directing the sound beam onto the target and/or its edges. *M. microtis* consistently approached prey from below, an observation that was supported by ensonification experiments of dragonflies on leaves, indicating that this behavior may provide the most salient information on position and probably also on shape and size of the prey.

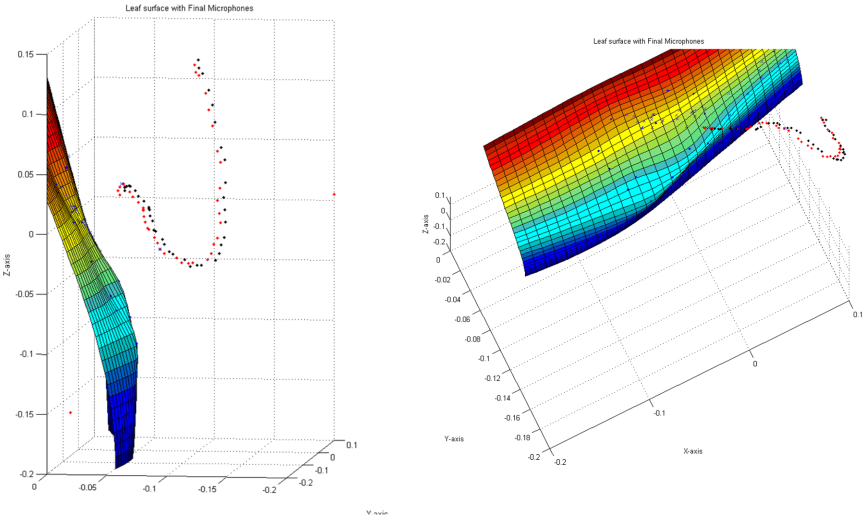


Fig. 5. Left panel: Approach flight of *Micronycteris microtis* (blue and red dots) from above. Right panel: same approach flight from the side. The colored surface represents the three dimensional structure of an artificial leaf. The flight path was calculated with a custom made MatLab script (UA) extracted from the images of two highspeed cameras (UUlm).

Ensonification experiments of leaves with and without dragonflies were conducted to illustrate the challenge the bats are facing when approaching motionless prey on leaves where they have to discriminate a target amidst acoustic clutter and to better understand how the observed scanning behavior might contribute to the extraction of useful information from the echoes. The custom build biomimetic sonar head consisted of one or two 1/4" free‐field microphones (Type 40BF), a preamplifier 26AB and power module 12AA (G.R.A.S. Sound & Vibration, Holte, Denmark) and a custom‐built EMFi transducer and amplifier (Department of Sensor Technology, Friedrich‐Alexander University Erlangen‐Nuremberg).

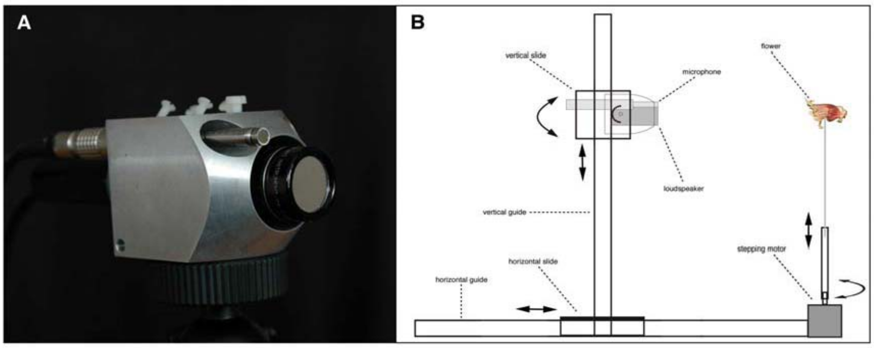


Fig. 6 Setup used to measure ultrasonic echoes. (A) The biomimetic sonar head with a ¼" G.R.A.S. microphone and a custom build EMFI-transducer. (B) Schematic illustration of the measuring setup.

The setup to measure ultrasonic echoes bouncing off from targets consisted of two main components, the biomimetic sonarhead and a unit to fix and rotate the objects. Both were installed on aluminum guides. To turn the objects and ensonify them from different directions, they were mounted on a thin extendable metal rod (25-50 cm) or a U-shaped metal frame attached to a computer-controlled, high precision stepping motor (Faulhaber GmbH, Schönaich, Germany).

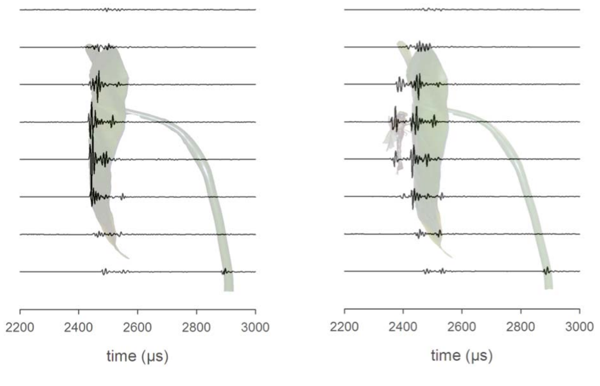


Fig. 7 Impulse responses of a leaf without (left) and with dragonfly (right). The impulse responses were measured at eight heights at 20 cm distance between the sonarhead and the target to reflect the natural behavior of the bat while scanning the leaf.

The objects were ensonified with a constantly repeated MLS (maximum length sequence) consisting of a periodic pseudorandom binary sequence. The recorded echo of the MLS signal was autocorrelated with the original MLS in a deconvolution process with a Dirac impulse to obtain an impulse response from the ensonified object. The spectra of the echoes were calculated from the impulse response with a fast Fourier Transformation FFT (rectangular window, 1024 samples).

The echo fingerprints of the insects, in particular dragonflies were clearly visible as separate amplitude peaks in the Impulse Response (IR) representations. However, as the peaks from the dragonfly and the peaks from the leaves were only about 50 µs apart they are difficult to resolve for the bats even with the short and high-frequency, multiharmonic echolocation calls of the *M. microtis*, with peaks around 200 µs.

As spectral information might be more informative for the bats, echo spectra of the targets were measured from different directions. This analysis revealed clear differences between the directional spectra of the leaf without and the leaf with a dragonfly on it. High energy echoes only returned when the leaves without dragonfly were ensonified from frontal directions. More lateral angles of the signals resulted in lower target strength (green and blue areas in the directional spectra). The presence of a dragonfly lead to more reflecting surfaces and ultimately to higher target strength also for lateral angles (red and yellow, see directional spectra). Moreover, as the amplitude peaks originated from different surfaces (e.g. wings, body, leaf surface) they interfered with each other and produced a complex spectral composition.

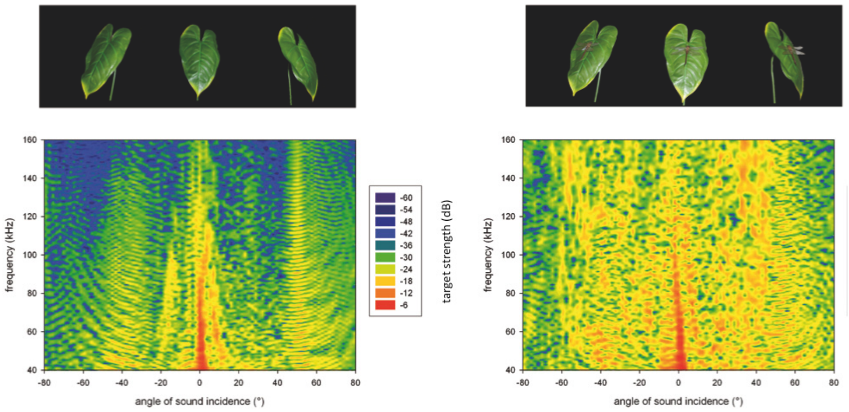


Fig 8 Images (above) and directional spectra (below) of a leaf without (left) and with dragonfly (right).

Spherical measurements where echoes were measured that originated from points of a sphere enclosing the leaves led to distinct differences in the echo acoustic reflection properties of the target. Most notably, roughness and spectral target strength were addressed for different frequency bands. Although impulse response roughness has been suggested as a decisive cue in object classification tasks there was no obvious pattern or cue that could assist the bats to detect a perching insect. Furthermore, there were only marginal differences between a leaf with and without dragonfly in the spherical target strength for the frequency band of 50 - 60 kHz. However, the frequency band between 110 and 120 kHz was highly informative especially for lateral angles, where distinct differences in spectral target strength occurred. This concurs very well with the echolocation call design found in *Micronycteris microtis*. The frequency band of the 2nd and 3rd harmonic of their calls seem to be well suited to detect motionless insects in clutter, i.e., on leaves. Moreover, lateral ensonification angles favor detection of motionless

Comment [A1]: ? I don't really understand this?

insects that perch on leaves even further.

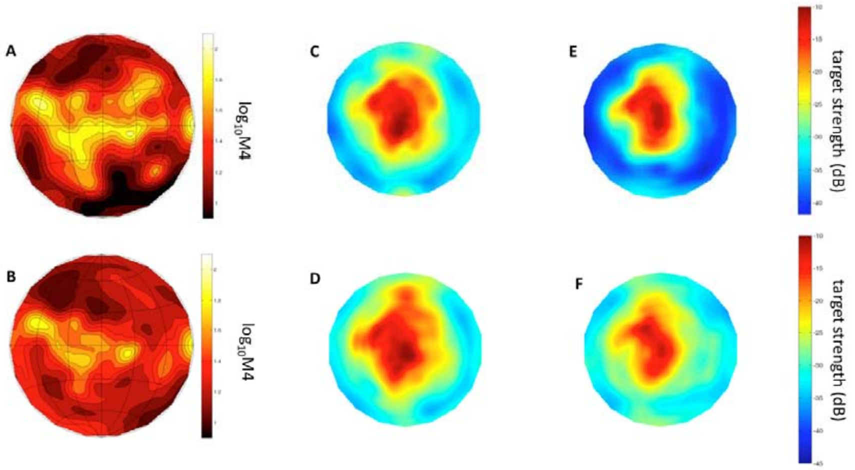


Fig. 9. Spherical measurements of the leaf without (upper rows A, C, E) and with dragonfly (lower row, B, D, F). (A, B) roughness of the impulse responses quantified as the Log10 of the 4th Moment. (C, D) target strength in the spectral band between 50-60 kHz. (E, F) target strength in the spectral band between 110-120 kHz.

Comment [A2]: ?? what does that mean?

The results of the ensonification experiments correspond very well with the behavioral observations, in particular the scanning behavior of *M. microtis* when it hovers close to the target and its approach to the target at steep angles. It is highly likely that the bats use a combination of spectral information, intensity differences and probably also temporal information from the targets as guide to find food within clutter. We exposed *M. microtis* to plastic plates (Lego) with a large number of several millimeter tall, raised bumps. The Lego plates scatter echolocation calls in all directions. We subsequently offered motionless dragonflies on those plates. Preliminary analysis suggests that it took the bats longer to make a decision as the challenge was more complex but they were capable to find motionless dragonflies also on those surfaces. Again, approach was from below. Data analysis of these results is still in progress.

2. Using Robotics to test and control Biological hypotheses about Bat Echolocation

There is no doubt that the development of biomimetic robots will allow for a new level of biological experimentation, because the robots provide what biology cannot: the possibility of control. The comparisons described above showed remarkable resemblance between the natural performance of the bats, and the optimal performance indicated by the robots, in terms of angle of approach flight and frequency of echolocation signals. The object recognition of the robot was not perfect, but neither is that of the bats as indicated by empirical evidence from field studies.

The results of the ChiRoPing project have shown many unexpected and exciting new aspects for both the biologists and the engineers. For the biologists, new venues open up for further research on biological phenomena, as for example the ensonification experiments have shown. Here, the high frequency echolocation in *N. leporinus* and the extensive scanning behavior of *M. microtis* start to make sense from the functional point of view. Preliminary results on *N. leporinus* suggest that the high frequencies of their calls coupled with CF call components are particularly well-suited for detection of ripples on the water surface. In case of the gleaning bat *M. microtis* it turned out that differences in spectral and intensity information in the echoes from leaves with or without insects promotes discrimination by the bats. With this novel information at hand, biologists will design new sets of behavioral experiments

Undoubtedly, robot technology will permit more controlled experiments also in the future to elucidate the functional significance of morphological as well as acoustic characteristics of the many different bat species. In ChiRoPing we have investigated two bats that emit signals through the nostrils, which are surrounded by elaborate nose-leaves. Although the role of the nose-leafs ist still not fully resolved, it is clear that they are heavily involved in classification and localization of prey. By comparison, robots can be made not only with and without nose-leaves, but also with scalable nose-leaves to test relation between size and frequency. Similarly, robots will allow for testing how ear-size affects target detection. Some bats, most notably the "long eared bats" (e.g. *Plecotus auritus*) have extremely long ears approaching a length equal to their body length and robots will allow us to test the significance of this morphological adaptation.

These are only a few examples of how biomimetic robots will greatly advance our understanding of the biological significance of specific morphological and acoustic adaptations. Our results call for specific and focused experiments comparing both trawling bats and gleaning bats with robots, which allow for full control over sonar signals and morphology.

Presently it seems most realistic to mimic trawling and gleaning bats, because they do not fly freely in open space, but move close to surfaces, such that they can be mimicked by either rolling robots for the trawlers or a sonar head on an arm for the gleaners. However, our first successful behavioral trials with aerial catches performed by *N. leporinus* give hope that this part of the bat's behavior is also soon ready for more investigations.

3. Impact of ChiRoPing project: strong active interaction between Biologists and Engineers

The ChiRoPing project has had several outcomes. The concrete deliverables and engineering embodiments of biological mechanisms copied from bats are only part of the results. The project has entailed several meetings every year, joint data collection in Denmark, Ulm, Antwerp and Panama, as well as student exchange to learn techniques from the partners. Thus, there has been ample opportunity for personal contact, which proved to be perhaps the most important effect of the project. The common goal paved the road for exchange of ideas and for sharing the different types of knowledge and know-how, which come with experience in fields as different as ecological biology, acoustics, vision research and robotics.

The collaboration has been characterized by an open curious spirit inciting all consortium collaborators to throw out ideas and questions – sometimes to be met by a "but that is completely impossible" by the experts, but at least as often by a "oh, that sounds interesting, we haven't thought of that". We believe that ChiRoPing is an example demonstrating that cross-disciplinary teamwork can be very efficient and fruitful. This type of relationship between biologists and engineer has encouraged the biologists involved in the project to make use of more technologically advanced methods to approach some of the questions, which have hitherto been difficult to answer using more traditional methods, e.g. the obvious question of why nose-emitting bats look so strange or why all aerial hunting and trawling bats (and echolocating dolphins) produce extremely trains of short calls emitted extremely fast (terminal buzzes) right before capture.

Conclusion

ChiRoPing has resulted in many interesting results and techniques, but equally exciting is the vast number of new possibilities for future technology development and advanced biological research. Overall, the interaction between biologist and engineers has proven to contribute substantially to the "added value" which was the main goal of ChiRoPing to bring researcher together from very different disciplines and to unite them with a common theme and truly interdisciplinary research approaches. To our understanding we have fully reached this goal.