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An autonomous system of detecting and attracting leafhopper males using species- and sex-specific substrate borne vibrational signals

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ABSTRACT

In leafhoppers that are among the most important vectors of plant diseases, mate recognition and location are mediated exclusively by species- and sex-specific vibrational signals exchanged in precisely coordinated duets. These pests are currently managed primarily by insecticide treatments, however, current legislation and consumers' concerns and demands require that the risks and impacts of pesticides be reduced. We present a proof-of-concept low-cost autonomous digital processing system (AS), capable of recognizing the male calls of the leafhopper *Aphrodes bicincta* "Dragonja" and generating female replies. Such a device could be used as a vibrational trap. We chose this species since its duet structure is complex, with the female replies having to appear in short (47–175 ms) intervals between continuously repeated elements in the male call in order to trigger male searching behaviour. The AS male call recognition algorithm is based on linear prediction cepstral coefficient (LPCC) feature vectors and a multilayer perceptron classifier (MLP). To prevent the noise-based feature vectors from feeding into the classifier, a bandwidth-limited linear prediction call activity detector based on spectrum peak tracking was designed. We tested the efficiency of the AS in behavioural experiments with live males. The MLP classification method successfully classified vibrational calls of male *A. bicincta* "Dragonja" from background noise. The fast real time identification enabled a synchronized playback of female vibrational reply with latencies as short as 130 ms. This mimicking of a duetting female by autonomous system also attracted the males to the source of the female reply. The AS is also a useful tool to enable further studies of vibrational duets that are needed to develop effective alternative control strategies.

1. Introduction

The interest to exploit vibrational signals in pest management has increased in recent years (Čokl and Millar, 2009; Mankin, 2011, 2012; Polajnar et al., 2015). This can be attributed to raised awareness of communication via substrate-borne acoustic signals being widespread among insects (Virant-Doberlet and Čokl, 2004; Cocroft and Rodríguez, 2005), the availability of highly-sensitive equipment able to register substrate vibrations, progress in computer technology, and the development of algorithms for vibrational signal recognition (Ganchev and Potamitis, 2007; Lampson et al., 2013; Rach et al., 2013). Applications include the use of incidental vibrational signals induced by walking and feeding insects for monitoring (Mankin et al., 2000, 2010; Zorović and Čokl, 2015), the use of species-specific vibrational signals emitted in sexual communication for automatic detection (Lampson et al., 2013), the interruption of mating behaviour by playback of disruptive vibrational signals (Mazzoni et al., 2009; Eriksson et al., 2012), and attracting insects to traps by playback of species-specific vibrational signals used in sexual communication (Mankin et al., 2013, 2014). Vibrational communication is common in the Hemiptera, which includes many major insect pests, like psyllids, leafhoppers, planthoppers and stink bugs. In particular, in leafhoppers and planthoppers that comprise of more than 30,000 species and are among the most important vectors of plant diseases (Weintraub and Beanland, 2006), mate recognition and location of the partner are mediated exclusively by vibrational signals (Čokl and Virant-Doberlet, 2003). In these insects the communication between partners is based on a coordinated exchange of species- and sex-specific vibrational signals (i.e. on a duet). In most species the exchange is initiated by a male advertisement call to which a sexually receptive virgin female responds, thus triggering the male search for the female on the plant (Hunt and Nault, 1991;

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Nomenclature

ARM	advanced reduced instruction set machines
AS	autonomous digital processing system
CPI	chirp–pulse interval
FFT	fast Fourier transform
FIR	finite impulse response
GMM	Gaussian mixture model
LPC	linear predictive coding
LPCC	linear prediction cepstral coefficients
MFCC	mel-frequency cepstral coefficients
MLP	multilayer perceptron
PC	personal computer
PNN	probabilistic neural network
PRT	pulse repetition time
RMS	root mean square
SD	standard deviation
VQ	vector quantization
USB	universal serial bus
SRAM	static random access memory
SD-Card	secure digital card
API	application program interface

Mazzoni et al., 2009). Populations of leafhopper and planthopper pests are currently managed primarily by insecticide treatments (Weintraub and Beanland, 2006). In order to reduce pesticide use, one of the remaining challenges in agriculture is to develop alternative approaches to monitoring pests that do not rely on chemical communication. Here we use a leafhopper species from the genus *Aphrodes* as a model species in a proof-of-concept study to develop an automated approach of attracting leafhopper males. Even though leafhoppers from this genus are vectors of phytoplasmas that cause plant diseases (Lee et al., 1998; Weintraub and Beanland, 2006) the research on the biocontrol of these leafhoppers is practically non-existing (Solomon et al., 2001). We chose a currently non-described species from this complex since its species-specific duet structure and male searching behaviour present a significant challenge for an automated system. In particular, a female reply has to appear in the short silent intervals between the continuously repeated species-specific sound elements in the male call (Table 1, Fig. 1b).

We developed an autonomous digital signal processing system (AS) capable of recognizing male vibrational advertisement calls and reproducing female replies in real time. The AS was designed to respond to significant variations of male calls while still maintaining recognition accuracy (i.e. the percentage of correctly detected male calls), the short response latency of a live female, and insensitivity to incidental noise. Hardware compatibility with the laser vibrometer output impedance and signal level had to be met, while still maintaining the vibrational signal sensitivity. The AS not only needed to operate autonomously, but also had to support alteration of the female response playback signal and its parameters such as the response latency and volume. A sufficient quality of the female response playback signal in terms of amplitude resolution and sample rate also needed to be met in order to emit the non-distorted signal to the male. This required that the impedance and the maximum signal level of the AS output fit within the operating specifications of the vibration exciter.

Table 1
Temporal and spectral properties of *A. bicincta* "Dragonja" male advertisement call. For duration, means with standard deviations are shown, while for dominant frequency, medians, minimum and maximum measured values (in brackets) are given. Number of males (N) = 10, total number of calls analysed (n) = 50, 5 calls per male for complete call S1, S2, S2P, S2C; N = 20, n = 200, 10 calls per male for CPI, PRT. For details about call sections see Fig. 1.

Male call parameter	Duration (s)	Dominant frequency (Hz)
Complete call	30.894 ± 19.764	–
S1	5.426 ± 1.79	222 (59–1406)
S2	18.424 ± 14.781	–
S2-pulse (S2P)	0.206 ± 0.033	210 (164–1594)
S2-chirp (S2C)	0.038 ± 0.003	1617 (492–3445)
Chirp–pulse interval (CPI)	0.081 ± 0.042	–
Pulse repetition time (PRT)	0.351 ± 0.063	–

In previous work, signal analyses that had greatest success in classifying vibrational signals and discriminating them from the background noise used linear frequency cepstral coefficients (LFCC) (Ganchev and Potamitis, 2007; Lampson et al., 2013; Potamitis et al., 2009), mel-frequency cepstral coefficients (MFCC) or wavelet based features (Rach et al., 2013; Jorge et al., 2013; Potamitis et al., 2009). Classifiers were realized using probabilistic neural networks (PNN) (Lampson et al., 2013; Ganchev and Potamitis, 2007), Gaussian mixture models (GMM) (Pinhas et al., 2008; Lampson et al., 2013; Ganchev and Potamitis, 2007; Potamitis et al., 2009), vector quantization (VQ) (Pinhas et al., 2008) or euclidean distance (Rach et al., 2013). With the exception of Rach et al. (2013), the above-mentioned recognition systems were mostly realized on a personal computer and focused on species with fairly simple signal structures in terms of frequency and amplitude variations (Ganchev and Potamitis, 2007; Pinhas et al., 2008; Rach et al., 2013; Virant-Doberlet and Čokl, 2004; Mankin, 2011) in comparison to the model species used in our study. Most of the identification methods above are also computationally too extensive to be used directly on a hard real time execution (Kavi et al., 2009) on a low-cost microcontroller system.

2. Materials and methods

2.1. Study system

Leafhoppers of the genus *Aphrodes* (Hemiptera: Auchenorrhyncha: Cicadellidae: Aphrodinae) are abundant, widely distributed over the Palearctic and have been introduced to North America (Bluemel et al., 2014). This genus is considered a taxonomically challenging group and comprises several morphologically very similar, closely related species. Species in this genus could even be considered cryptic since they have been classified as ecotypes of a single species in the past, with even trained experts often still designating the leafhoppers merely as a nominal *Aphrodes bicincta* s.l. species group (Bluemel et al., 2014). As in other Auchenorrhyncha (leafhoppers, planthoppers, treehoppers, spittlebugs) the mate recognition and location in *Aphrodes* leafhoppers is mediated exclusively via substrate-borne species- and sex-specific vibrational signals (Derlink et al., 2014; Mazzoni et al., 2009). Recently discovered in Slovenia are *Aphrodes* leafhoppers characterized by a distinct, previously unknown species-specific male advertisement call and associated clear female preferences for a such call (Fig. 1) (Derlink, 2014). This new species has not yet been formally described; according to the locality where it was found first (the Dragonja Valley) and its genetic relatedness to other species in the genus we currently refer to it as *A. bicincta* "Dragonja". This species is widespread across Slovenia. Males use