A microactuator device to mimic ant vibrations for termite deterrence on life plants

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Abstract. Termites cause over US$40 billion in damages and repairs worldwide annually in wooden infrastructure, and agriculture. Traditional termite control treatments rely on toxic chemicals like Fibronil, which are harmful to the environment (plants, pollinators, water contamination) and humans (chronic diseases, carcinogenic). To address this, a non-chemical, vibration-based repellent system (MiAC-S) is developed to leverage their vibration-based communication for eusocial behaviour. MiAC-S, built using an STM32 microcontroller and piezoelectric actuators, simulates the biomechanical model of a walking ant updated with experiments. It was tested in food-choice bioassays using Giant Northern termites on Mango and dwarf Macadamia saplings in a greenhouse and environmental chamber setting. Preliminary results show that termites generally avoided the signal-emitting side, with more soil being moved to the non-signal side. Soldier termites tended to stay on the signal side, while nymphs preferred the control side. When termites were found in the soil, they were mostly located near the roots farthest from the stem. Though sample numbers are low, these early results indicate that MiAC-S has the potential to be applied as a non-toxic vibration-based termite control to protect agriculture and forestry industry. Future planned field trials need to verify its effectiveness in orchards and for timber growers.

1 INTRODUCTION

Annual termite damage exceeds US$ 40 billion worldwide, significantly impacting housing, wooden infrastructure (Hassan and Nanda, 2024), agriculture (horticulture, forestry) especially mango, avocado, cashew, and macadamia seedlings and timber production such as sandalwood or mahogany (Radomiljac et al.,1998; Dele et al., 2023). While termites (and ants) are in general beneficial to soil quality especially in arid and semi-arid regions and often called soil-engineers (Evans et al., 2011; Joquet et al. 2018), they also cause millions of dollars in losses annually in crop yield (fruit, nuts) in Australian plantations and reduction in timber harvests by an estimated 25%. Often damaged plants do not survive termite attacks, especially when saplings are contacted.

Physical barriers for the protection of housing or timber infrastructure are costly and not applied in agriculture. Chemical controls are widely used to protect live plants by applying insecticide such as Fibronil, a strong Phenylpyrazole chemical that affects the insect's nervous system and leads to hyperexcitation, paralysis and death (Rosa et al., 2024). Fibronil is usually applied to the soil and then absorbed by the plant; insects foraging on the plant or in contact get affected. However, while effective against termites it damages the general ecosystem, including other arthropods such as pollinators and contributes to the general insect decline in this world (Asad et al., 2021). It has also been shown to cause chronic health problems in mammals, and severe toxicosis due to overdose (Gupta & Anadón, 2018). Fibronil has therefore been banned, especially in connection to food producing crops and animals in the EU, China and the US (Chen et al., 2022); from a medical point of view, it is considered in the US and the EU as possibly human carcinogen. Fibronil is not banned in Australia yet, but currently reviewed by the Australian Pesticides and Veterinary Medicines Authority.

To find alternatives to chemical treatments, a non-chemical termite control system that is cheap and effective for agriculture/forestry applications is being sought and can be used within an integrated pest management (Mandal et al., 2023). Rather than locating termites and killing them, it is preferred that termites in the first instance do not contact and attack the host plant. Termites are eusocial insects (social cockroaches), which live in colonies of up to several million individuals and communicate their actions and decisions largely through a range of different vibrations (Pailler et al., 2021). Drywood and subterranean termites have been shown to drum alarm (Inta et al., 2009, Sillam-Dussès et al. 2023), and they can detect nestmates and avoid competitors based on foraging signals (Evans et al., 2005, 2009), and predators based on their footstep vibrations (Oberst et al., 2017). Since vibrations are used for the communication of the colony and its organisation a vibration-based repellent has been envisaged to be ideal in manipulating termite decisions and hence their behaviour.

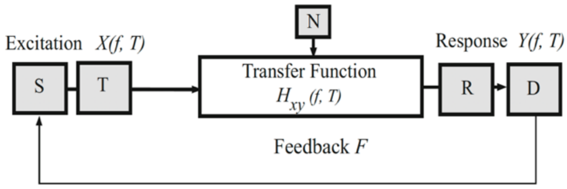

*Figure 1. Taken from Oberst et al. (2019) a schematic of the noise control engineering principle; X(f,T) and Y(f,T) with frequency f and period length T = 1/f [s], represent the Fourier transforms of the source term x(t) (excitation signal) and the receiver signal y(t), the substrate response commonly recorded for playback experiments. Further depicted are the information source (**S**) – which is the walking insect in our case, the transmitter (**T**) – as the leg and insect foot transmitting the motion of the ant to sound, the receiver (**R**) – the subgenual organ in the termite leg (Sansom et al., 2022). The destination is depicted as (**D**) – the foraging termite, and the noise as (**N**). **N** acts on the communication channel (the substrate) represented by the transfer function $H_{xy}(f,T)$, and F represents the feedback which is not implemented in our system (Shannon 1949).*

Here we describe the design of such a device which is based on mimicking predator walking signals. Following Fig. 1 and as suggested by Oberst et al. (2015, 2019), we aim to synthesise the excitation signal *X(f,T)* to mimic a predator walking signal without the contribution of the substrate. This is very different to traditional playback experiments (Evora et al., 2024) and should provide a more universal approach for behavioural ecology, especially if high signal discrimination of the species is expected. Due to the fast-changing nature of the signals, which is in the order of nanoseconds, a digital system, comprising a microcontroller (MCU) and a piezoelectric (PZ) actuator, has been designed (MiAC-S = **Mi**cro**AC**tuator + **S**oftware). A mathematical model of a predatory ant based on a traditional (bipedal) spring inverted pendulum SLIP (BSLIP) biomechanical model is chosen here, assuming walking and running, in the alternating tripod gait (Blickhan, 1987; Geyer et al. 2006; Ramdya et al. 2017). The model is experimentally validated and implemented on a PCB with STM32 MCU and specific fast responding circuit. MiAC-S is then tested for feasibility in a food-choice bioassay setting, using the voracious Giant Northern termite (*Mastotermes darwiniensis*) on Mango (*Mangifera indica*) and dwarf macadamia (*Macadamia integrifolia*) saplings in a greenhouse as well as a temperature and humidity-controlled environmental chamber setting.

2 MATERIALS AND METHODS

2.1 The microactuating device MiAC-S

MiAC-S has been developed with two basic functionalities, to test wooden structures using micro-impact testing in a networked structure (cf. Oberst et al. 2023) and as an actuating device using termite attracting/repellent signals. Fast-response circuitry, based on STM MCU and a cheap off-the-shelf piezo (buzzer) element has been developed, to validate manufacturing and commercial scaling of MiAC-S to be competitive on the market.

2.1.1 Mathematical model of ants walking

Insects show either a walking or running gait (Reinhardt et al. 2009; Reinhardt and Blickhan, 2014) using their legs in a tripod configuration, ie legs move simultaneously eg as 2 legs left and 1 leg right; followed by 1 leg left and 2 legs right, and so forth. In our model, the legs of the ants' tripod during their walking and running gait also hit the ground simultaneously, and even though it has been shown not to be true when studying the detail (Oberst et al. 2015) it is a valid simplification if the location of the source point of excitation (the ant) is distant enough from the receiver point (the termite). Also, we assume a bipedal model (BSLP) which switches to the SLIP model and so adopts different gaits; SLIP and BSLIP are sufficiently described theoretically in past publications for larger animals (Blickhan 1989; Blickhan and Full, 1993; Geyer et al. 2006, Gan et al. 2018). Assuming further a rigid surface the reaction force is equal to the actioning force, which is the excitation of our system (cf. Oberst et al. 2019). Figure 2 shows that the BSLP model is validated by results from the literature. From video recordings in the experimental arena (Oberst et al. 2017) it was observed that after a cool down period of 20 mins, ants were

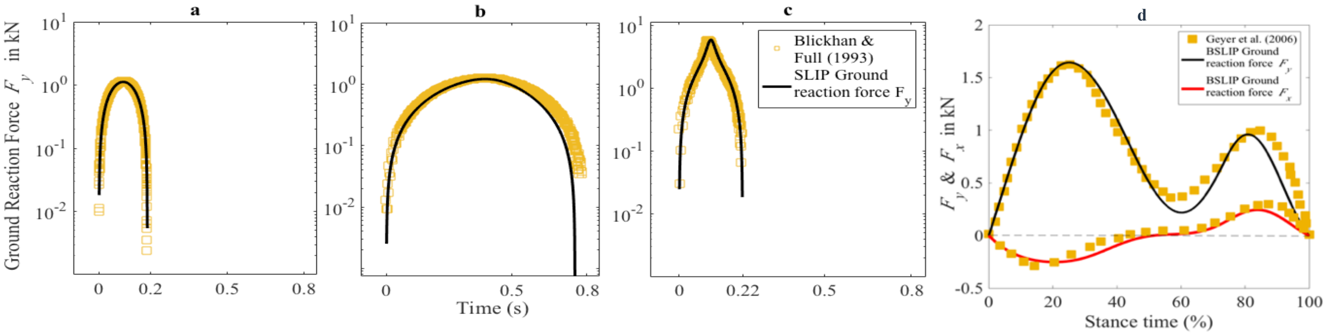

Figure 2. a-c The SLIP model is evaluated for different stiffnesses, angles of attack and velocities and masses (Blickhan & Full (1993), Figure 2); d shows the validation of the BSLP model in x- and y-direction. The data represented by the yellow markers have been imported directly from Blickhan & Full (1993) and Geyer et al. (2006) using Matlab's GRABIT function.

running in 34% of the cases (studied for 3 species and 3 video segments each). Cycles of running/walking were selected randomly from data of an enveloped insect vibration responses and their statistical distributions. Details of the coupled models and the experimental procedure have been presented in Oberst, Lai, Evans (2018) and Oberst et al. (2018). An example of the mixed signal model is presented in Figure 3. This mixed signal corresponds to $X(f,T)$ in Figure 1 and will be used as input to generate a synthesised ant walking signal for MiAC-S. This signal was down-sampled, converted into hexadecimal code and read into the MCU via µSD card.

2.1.2 Signal updating

Synchronised video recordings and vibration measurements were made using a laser Doppler vibrometer and a specifically isolated bespoke test rig in an anechoic room (details of the setup cf. Oberst et al. 2015, 2017). An adopted version of Wauthier (2011) was used to track ants in the arena quickly by adaptive down sampling of the image to avoid failing in case of crossing/ loss of contact for more than 2 ants by employing a vector in each point (Figure 2c). The tracking provided the scaled velocity of the ant, which was 5.2 [bl/s] (body lengths per second) for *Lasius niger* (black garden ant) and the angle of attack was 24°. The leg length was on average 2.070 mm and the mass was about 6.1 mg (*N*=3 measurements).

Using the distributions of footstep responses, attenuation times and breaks/stand still times have been determined by an enveloping analysis. After the recorded time series was filtered using the *ghkss* algorithm (Kantz and Schreiber, 2004) the enveloping analysis detected only responses as footstep, if the amplitude reached a certain threshold. An example is shown in Figure 2d.

2.1.3 Digital design and manufacturing of actuator and circuitry

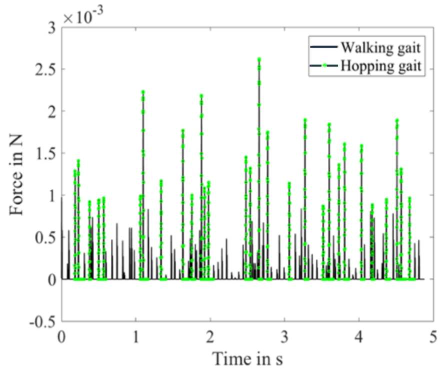

Figure 3. Excitation signal (corresponding to X(f,T) in Figure 1) using the coupled SLIP-BSLIP model experimentally updated to mimic walking of a single ant of species Lasius niger; scaling of amplitude can be achieved a-posteriori through different gain of the MiAC-S (Oberst et al. 2018).

The microactuating device MiAC-S was designed based on a circuit previously tested for a Raspberry Pi© (RPi) device (Oberst et al. 2020). The piezo actuator was tested prior to that using various commercially available stacked actuators, namely the P-841.1 of Physik Instrumente©, and the precision actuator MTK12S18f25000 from Mechanotransformer© (Tofigh et al. 2022); both with a travel range of less than 15 µm and a fast response time. Since these actuators were prohibitively expensive (orders of thousand AUD), they were compared against a simple piezoelectric sensor/actuator AB3342. Rapid excitation signals in the order of ms (Oberst et al. 2015) require minimal circuitry response times to enable proper actuation of the piezo elements, and occur within micro or even nanoseconds. This is even much faster than e.g. measuring the rate change in strain (Chahoud et al. 2024). Hence, as first prototype a piezoelectric actuation system has been developed, incorporating a 24-bit digital-to-analogue converter (DAC), an amplifier and a RPi to control the system. To further reduce the cost, improve real-time response, and miniaturise the device, a novel microcontroller-based circuit using STM32F103RET6 from ST Microelectronics© with µSD reader and variable gain had been designed to easily manage various test data and drive up to 32V outputs to run the piezo actuator (Figure 4), with a potential cost of less than 10 AUD for large scale orders. Circuit simulation prior to fabrication was carried out using Proteus©. Altium Designer© was used for PCB design, while IAR Embedded Workbench© was employed for programming the microcontroller.

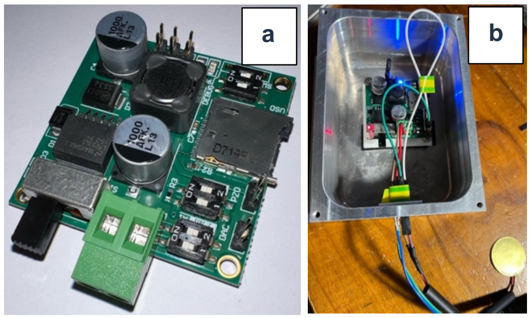

Figure 4. Current MiAC-S design (a) and metal box, connectors and piezo element (b).

The fabrication process is optimised through three different designs and tests. The current design uses an FR4-High Tg 180C as substrate with size of 45 mm x 45 mm x 1.6 mm and 105 μm finished copper weight; 0.4 mm vias, ENIG electroless nickel/immersion gold finish, with 5μm nickel and 0.35μm thickness of gold (for more reliable signal transmission and resilience), and a IPC2 inspection standard. As housing an aluminium box had been cut as ruggedised design using a CNC mill with rubber sealed lid and UV stable marine adhesive sealant (Sikaflex© 291) to prevent moisture from penetrating into the electronics. For the bioassays, due to limited available housings, cheap 500 ml plastic containers with lid were sealed using Sikaflex© 291 and placed in snap lock plastic bags. The piezo element is removed from its plastic housing and connected with superglue, centred on the countersunk head of 4Gx12 mm wood screws (Zenith©, zinc-plated).

2.2 Proof of concept experiments

2.2.1 Materials required for bioassays

For the bioassays with termites and saplings, *Mastotermes darwiniensis* were collected in March and April 2023 from Darwin, shipped to the biogenic dynamics labs at UTS TechLab, Sydney and stored in environmental cabinets. 25 Mango saplings (*Mangifera indica*) of ca 600 mm height and dwarf macadamia saplings (*Macadamia integrifolia*) of ca 400 mm height were sourced from Daleys Fruit Nut Nursery in March and April 2024 and stored in a greenhouse in Canberra. The mango saplings were of type Glenn (*N*=12) and R2E2 (*N*=13) and grafted on Bowen mango (Kensington pride) seedling rootstock. Macadamia saplings (*N*=25) were not grafted and raised through propagation. All saplings were first measured for their height and stem's circumference and then clustered according to these properties (Oberst et al. 2014) and paired according to cluster membership. The treatment side (signal) was presumed to be less attractive due to the playback of synthesised ant excitation signal; hence the larger plant with thicker stem was chosen as the more attractive choice. Of the Glenn and R2E2 saplings, *N*=2+3 plants were not used, mostly due to lack of activity of termites (see Results section); in the macadamia trial we did not use *N=5* plants due to their physiology (small and thick stem, more than one bifurcation at lower stem locations). Prior to running the experiments, termites were connected in a trial to soil samples (100 mg directly in termite jar, 1 week) to confirm that soil and plants were not treated with fipronil or other insecticides by the nursery.

2.2.2 Experimental design

As shown in Figure 5, two mango/macadamia plants were positioned in a 100 mm height saucer (300 mm diameter) placed in a propagation tray. Saucer and tray were filled with water for the plants. The saucer had marks to record the water consumption of the plants during the experiments, while the tray provided a constant water barrier to the termites. For the mango trial the piezo was setup at *L* = 300 mm using a 3 V driving voltage, the macadamia trial was set to run with piezo mounted at about *L* = 100 mm height, using 4.5 V. The signal side is the treatment (T) side, the non-signal side is the control (C) side. The termites were placed into 1 L glass jars with metal lid and brass adaptor for plastic tubing/ hose of about

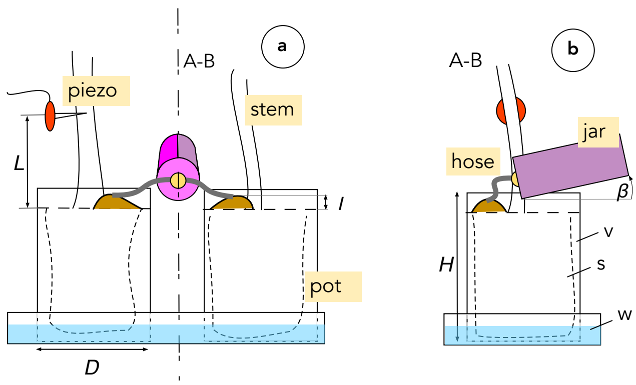

Figure 5. The experimental setup (a) front view and (b) side view. L is the installation height of the piezo element, l represents accumulated vermiculate (v), s is a potting mix coming with the sapling and w represents a water barrier; D and H are the diameter and the height of the pot. Saucer not shown for the sake of clarity.

200 mm length and 15 mm diameter to be connected (Figure 5). The glass jars were slightly inclined with $\beta \approx 15°$ above horizontal and held with Lego Duplo© pieces and brick. Since termites tend to move downwards, it was hypothesised that this incline would promote the subcolony to move out of the jar into one of the pots to nest underneath the plants. The hose was led to the planting pot and covered in vermiculate of ca 25 mm height. The setups were inspected once per day where the water was controlled and refilled to the 500 ml mark (every 2nd day for the mangos, every third day for the macadamia plants). In greenhouse the plants had the natural day and night cycle of light and temperature (between 18 ℃ and 30 ℃), and a humidity which was kept above 60% with an Able© Mist Humidifier (2 L). The environmental chamber had lights switched on from 9 am to 6 pm and a constant temperature of 28 ℃ and 80% relative humidity. The mango trial in the greenhouse lasted 4 weeks, while the macadamia trial was finished within 1 week per setup (2 runs).

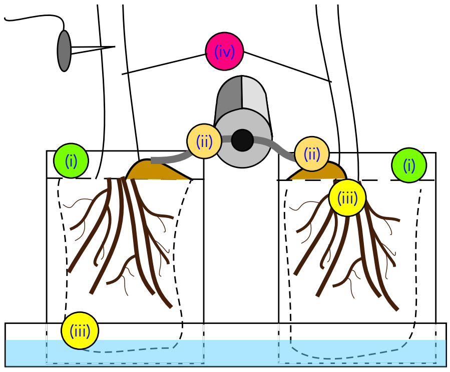

Figure 6. Shown are the different stages of observation: (i) termite exploration - ca 2 hours to 5 hours right after connecting; (ii) termite building up to 1 day; (iii) main foraging locations (after 4 and 1 weeks); (iv) sapling health measured one month after experiment.

3 RESULTS

The observational outcomes of the two experiments using the environmental chamber or the greenhouse are quite similar and described in the following using Figure 6 for illustration. **(i)** Right after connecting the jars to the setup, termites started to explore the arenas on both sides. After a couple of hours termites were found on both sides, equally including soldiers and workers. However, only on the signal side soldiers were observed, if present at this exploration stage (in 2 cases of mango trial, 3 cases for macadamia). Also, more termites seemed to have initially explored the signal side, however, since no cameras were mounted this data is only based on observations. Termites were roaming freely on the surface of the planting pot and some of them fell into the water and drowned. The exploration stage happened in the greenhouse experiments during the day as temperatures were higher (up to 35 ℃) than at night (down to 18℃) due to the Canberra winter. In the environmental chamber the exploration happened any time after start of the experiment. **(ii)** After this exploration stage, termites started building tunnels; no termites were observed anymore on soil's surface. It became obvious that termites build on both sides, but that more of a constant soil filling activity was observed on the no-signal side (control) while on the signal side less soil was found. Building materials were mostly carried from the pot into the tube but also soil from the jar was moved into the tube, its ratio has not been determined though. **(iii)** The mango trial was finished after 4 weeks (greenhouse) and the macadamia trial after 1 week (environmental chamber).

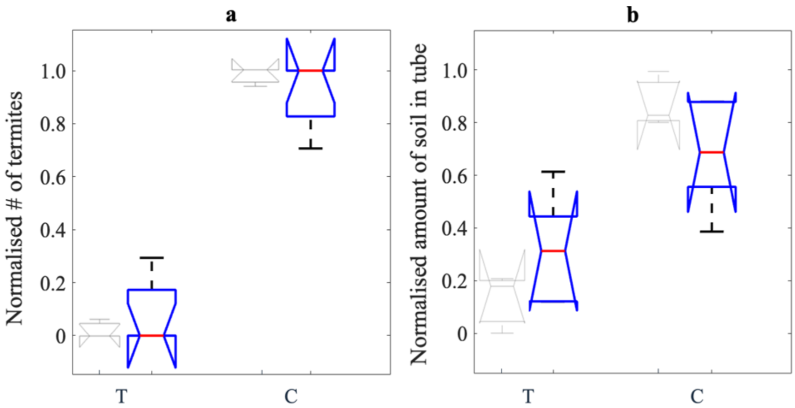

Figure 7. 1-way ANOVA results (N=3 for mango; N=5 for macadamia, blue) for a) the number of termites in the pot (excluding tube) and b) amount of soil moved into the tube for the macadamia trial (environmental chamber). Significantly more termites were found on the no-signal side (C-Control) than on the signal side (T-treatment). Significantly more soil was carried by the termites into the tube of the control side than on the signal side. However, due to the low sample number in both cases results can only be at most indicative.

Each of the experiments had 2 sets, but the first set of the mango trial was a failure as the temperature dropped suddenly so much in April, that heaters had to be purchased, and the circuits had to be modified with robust surge control and passive heating elements. The second set ran 4 weeks (N=5) and with C-T (3 success) and C-C (1 success, 1 fail) configurations. The macadamia trial had another delivery of termites from Darwin and was running in 2 sets, each of them for a week, but only in the C-T configuration. Unfortunately, these termites seemed to have been infested with a scuttle fly, hence infected jars were counted to be unsuccessful (*N*=14, 5 successful, 3 other sets also produced results but had signs of the scuttle fly).

After ending the experiments, the soil in the tubes and the termites in each pot (not tube) as well as their location and caste membership were recorded. For the signal side, termites were found at the edges of the pot and at its bottom near the water level (*N*=2). For the control side of the macadamia trials, termites were found directly within the roots (*N*=2) having visibly eating the plant from underneath. **(iv)** After about one month the plant health was inspected and 4 of the 10 plants (those of the control side) attacked by the termites were withered. The results of a 1-way Analysis of Variance (ANOVA) of normalised number of termites for the signal and the control side are shown in Figure 7a: grey and thin lines show the number of termites for the mango trial (*df*=5, *F*=1200.5, *p*=4.14 E-6) and bold lines the macadamia trial (*df*=9, *F*=8.41, *p*=0.0199). The ANOVA results for amount of soil (oven-dried) carried into the tubing are depicted in Figure 7b): grey and thin lines show the results of the mango trial (*df*=5, *F*=57.97, *p*=0.0016) and bold lines the macadamia trial (*df*=9, *F*=101.94, *p*=7.90E-6).

4 DISCUSSIONS

This is the first time that we ran an experiment with a synthetic ant excitation signal generated with a biomechanical model and implemented on a proprietary micro controlling unit with actuation. Experiments were run on live plants in a green house and in an environmental setting, using also for the first time in vibration experiments the Giant Northern termite (*Mastotermes darwiniensis*). Results indicate that the MiAC-S device can effectively influence *M. darwiniensis* foraging behaviour using vibrations, similarly as observed for *Coptotermes acinaciformis* (Oberst et al., 2017) using playback of recorded signals (*Y(T,f)*, Figure 1). All successful setups show that termites moved more soil to the non-signal side (control); if soldiers were found, they were on the signal side (treatment). If nymphs (neotenic differentiation) were present, they were found on the control side. This may indicate that termites were at the beginning of moving their nest to the flowerpot of the non-signal side. If termites were found in the soil of the plant on the signal-side they were mostly found at the root complex furthest away from the stem and closer to the water reservoir. Overall, significantly more termites were found on the non-signal side in both experiments. The material carried into the tubing was provided from both, the flowering pot and the jar. Its exact composition and structure, however, has not been studied, but it was observed that the entry hole on the signal side was blocked sometimes (2 times in macadamia trial) while the soil on the control side did look more like a build-up of sheathing to block out light and activity. These differences in building activity should be more systematically studied in the future. Also, since sample number of successful setups is very low, the results may only be taken as an indication that the MiAC-S device works; past playback experiments also indicate that this is likely the case (Oberst et al. 2017).

A limiting factor of the mango trial was the high temperature difference in Canberra during wintertime, and the issues of maintaining a constantly high temperature throughout the day. The temperature distribution was less homogeneous as was the lighting and humidity, which followed a natural day-night cycle. Even significant sealing off the gaps in the greenhouse and modification of circuit breakers and maximum load of the heating elements, including the involvement of two split circuits did not help much. In this context, irrespective of the problems encountered it was astonishing to see how long *M. darwiniensis* survived under these non-ideal conditions. The greenhouse experiment should be repeated in summer or in a warmer region (e.g. at the Southcoast in NSW) as they represent a more realistic setting with varying yet controlled parameters (exclusion of insects) and approximate best field trial experiments.

Another complication was associated with the 2nd delivery of termites used in the macadamia trial; termite jars showed presence of a scuttle fly, species unknown. Scuttle flies can be attracted to the dead bodies of termites and their decomposition but are also known to be parasitic, e.g. in ants (Hymenoptera), cockroaches and termites (Isoptera) (Disney, 1986; Chen & Porter, 2020; Arafat et al. 2024). Yet, no parasitic scuttle fly which is specialised on termites is known in Australia. Those which are known can be found in Malaysia; they will impede the motion of termites with a fly eventually emerging from the abdominal part of the termite (Disney, 1986). Similar developments are also known in ants where scuttle fly larvae develop within their host, making them effectively useless to contribute to shared labour within the colony (Chen & Porter, 2020). Either way, whether these flies were attracted by dead termites or are parasitic, jars which showed signs of scuttle flies were excluded here from the analysis.

The signal itself was greatly simplified in its modelling. The exact leg's stiffness was not known and the leg itself was assumed to be incompressible. The parameters required to feed the mechanical model (Blickhan 1987, Geyer et al. 2006) were estimated from video recordings; and the ratio of walking to hopping was estimated over the amplitude and the speed of the video tracked recording and the vibration enveloped data and fixed at the same angle of attack. The response amplitude at receiver position (Figure 1) was varied over voltage and distance to excitation, but not measured. Whether the insect is truly walking or running/ hopping should be studied using a high-speed video recording in combination with a force plate setup, like the miniature force plate presented by Chahoud et al. (2024). The current assumption showed (based on video recordings and speed) that ants were mostly walking after the cooling off period, which is different to Reinhardt and Blickhan (2014); more and detailed research especially with regards to different situational context and the environmental setting is required. Even for the weak excitation case and long travel distance, termites were not accumulating at the root system but foraging in the soil and close to the water. This may indicate that termites sense the synthetic ant signal yet forage within the soil which is still nutrient rich.

While sample numbers are low the results are encouraging and highlight the potential of using vibration-based termite control in agriculture. However, whether this device can contribute to providing eventually a non-toxic control method within an integrated pest management framework, e.g. for mangos or macadamias, will need to be confirmed through further laboratory, greenhouse and eventually field trials and incorporating more complex conditions in a real plantation setting during dry and wet season in the NT and QLD.

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