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A MIXED SLIP-BSLIP WALKING MODEL WITH UNCERTAINTY TO MIMIC INSECT GROUND REACTION FORCES

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Bioassays are useful to determine the behavioural response of natural organisms in considering controlled and numerous uncontrolled variables. This is especially relevant in technology-driven projects that study insect responses to vibration or acoustic stimuli. However, insect vibrational communication often involves natural substrates of rather complex nature. So far in the literature, only the system response is recorded and employed in playback experiments without considering the complexities introduced by the substrate.

Based on studying experimentally the walking behaviour of ants and incorporating standard ground reaction force models from bipedal locomotion research in biomechanics and robotics, we have developed a mixed walking model with uncertainty. This model implements a random walk pattern but mimics the ground reaction forces of both running and walking using the Spring-Loaded Inverted Pendulum (SLIP) and the Bipedal Spring-Loaded Inverted Pendulum (BSLIP) models.

The model is updated using an experimental database of statistical data obtained from insect walking. The substrate response is generated through multiplication in the frequency domain using an experimentally measured veneer disc in accordance with the noise control engineering principle. By using the feedback mechanism and nonlinear filtering, the quality of the signal is controlled and its digitisation and implementation into a microcontroller device to conduct bioassays on timbers are discussed. The signal model enables the synthesis of insect motion and its application with a micro-exciter allows for the excitation of any structure without the residual effects of the substrate.

Keywords: Insect motion, excitation mechanism, biotremology, noise control engineering principle

1. Introduction

Insect locomotion studies, especially on cockroaches and stick insects [1, 2], have informed hexapod robot design by revealing principles of gait dynamics, energy conservation, and sensory feedback mechanisms. Wilson [3] provides a foundational review on insect walking, covering key aspects such as peristaltic and metachronal waves, six-legged gait patterns, and adaptive plasticity when limbs are lost. Blickhan and Full [4] explored similarities in multi-legged locomotion across species, describing insect movement as "bouncing like a monopode," and utilized the FROUDE number to compare speeds across various animal sizes. Notably, slow-walking arthropods, such as stick insects, locusts, and leaf beetles, use an alternating tripod gait, while cockroaches adopt this gait only at higher speeds, relying on stability-driven quadrupedal or bipedal gaits when running quickly [4]. Seidl and Wehner [5] distinguish two primary modes of insect locomotion: sensory feedback-driven gaits in slow-moving insects like stick insects, and dynamically stable, rapid bouncing gaits in fast-moving cockroaches.

To simplify the analysis of locomotion, minimal models were developed for the center of mass dynamics with fewer degrees of freedom, addressing a classic challenge of BERNSTEIN's degree of freedom problem [6]. The spring-loaded inverted pendulum (SLIP) model in the sagittal plane and the lateral leg spring (LLS) model in the coronal/horizontal plane are widely used to characterise grounded running, trotting, and hopping in animals with sprawled postures, such as insects [4]. Schmitt et al. [7] developed a 3-DOF model, similar to the LLS model by incorporating intermittent ground contact and compliant legs, to study the effects of mass, inertia, and leg stiffness on yawing motions in the cockroach *Blaberus discoidalis*. Although multi-legged locomotion shares some dynamics with bipedal gaits, unique factors, such as leg count and gait pattern, affect system stiffness and stride frequency [9]. Blickhan and

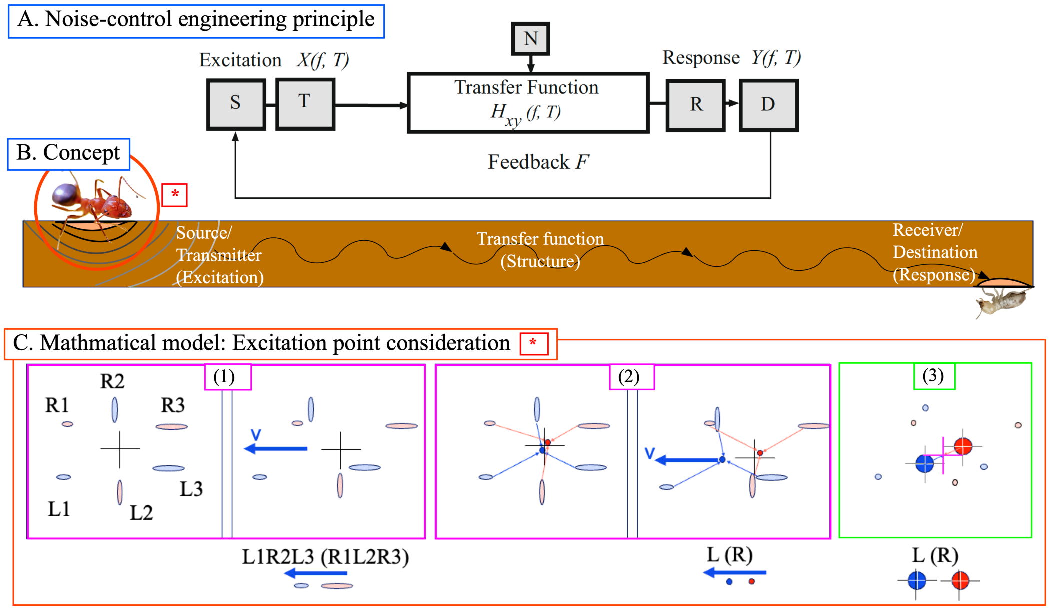

Figure 1. Conceptualisation of research idea. (A) Noise-control engineering principle [8]. (B) Its application to a wooden sample showing source, structure, and receiver. (C) Schematic bottom-up static model for ant excitation (red asterisk *): (1) alternating L1R2L3/R1L2R3 tripod gait at velocity v; (2) mechanical excitation point (MEP) at the centroid of simultaneous tripod GRFs; (3) static reduction (zero x-velocity) to alternating taps (pink cross).

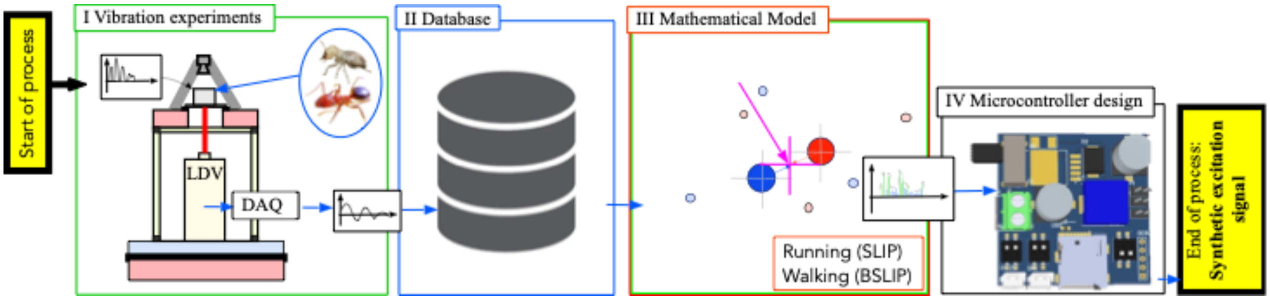

Figure 2. Overall workflow to utilise the model in Figure 1. (I) Simultaneous recording of insect motion using video tracking and their vibrations on a thin veneer disc using a laser Doppler vibrometer in an anechoic room; (II) storing features from statistical analysis of data in a data-base; (III) using data in the database to update static mathematical model to vary motion parameters of the model, to either follow a trajectory or to mimic a random walk, generating a synthesised GRF; and (IV) inputting synthesised GRF into a microcontroller device for playback through an actuator to generate a response following Fig. 1 A.

Full [4] found that leg stiffness in hexapodal trotters is three times that of bipedal systems and twice that of quadrupeds, enhancing energy storage and usage [10].Dudek and Full [11] further suggested a passive, vertical hind leg spring with a hysteretic two-parameter damping model, which supports energy storage and dissipation, enhancing stability during fast locomotion. Zoellikofer [12] used video, footprint tracking on smoked glass, and geometric analyses to study the influence of speed and curvature, body morphology and load on the gait patterns of 12 ant species from 4 genera. Reinhardt and Blickhan [13] confirmed that *Formica polyctena* wood ants retain the tripodal stride pattern even during rapid, grounded running. Using a custom force plate capable of measuring minute forces (as low as 4 mN), they observed that the maximum vertical force was generated early in the tripod phase. This "climbing" stride, using front legs for propulsion, middle legs for stability and hind legs for lift, enables effective movement over uneven terrain. Ants communicate mainly via pheromone and visual rather than auditory cues. However, they can sense vibration signals through substrate [14–17] - an ability exploited by parasitic caterpillars for communication interference [18]. The sensitivity of ants vibratory detection highlights the complexity of ant navigation and social behaviour. In traditional bioassays to study the effect of vibro-acoustic stimuli, the recorded system response (Fig. 1) is employed in playback experiments. It would be desirable to use the source excitation rather than the response in playback experiments so that it is independent of the substrate. The aim of this study is to demonstrate (a) an approach for developing an ant walking model by incorporating existing SLIP and BSLIP models, updated using statistical data from experimental studies on insect locomotion (Fig. 2); and (b) the success in using this signal model as source excitation applicable to any substrate.

2. Model development

Here we outline the model formulation and experimental updating. The primary assumption is that ants mainly follow a grounded running pattern with occasionally a walking pattern [9]. Here the legs of the ants' tripod during their walking or running hit the ground simultaneously, which is not true [19] but this simplification is considered acceptable if the excitation source (the ant) is far enough away from the receiver insect. Thus a bipedal model and different gaits can be assumed, as described previously [4,20,21]. Assuming further a rigid surface the reaction force is equal to the excitation force [8]. The model has been presented at [22,23] and some results of applying a synthesised ant walking signal to deter termites from live trees have been published in [24]. In this section, the equations of motion for both the SLIP and BSLIP models are presented to estimate the ground reaction forces (GRF) for the running and walking gait. Then a Mixed SLIP-BSLIP with Uncertainty (MSBU) model is introduced. Finally the model is applied to measurement data of a aluminium disc and its response is deconvolved using spectral division, and Tikhonov regularisation according to [19].

2.1 Spring-loaded inverted pendulum

The equations of motion in x and y direction of the spring-loaded inverted pendulum (SLIP) model for hopping/running are [4]:

$$m\ddot{x} = k\left(\frac{l_0}{\sqrt{x^2+y^2}} - 1\right), \text{ and } m\ddot{y} = k\left(\frac{l_0}{\sqrt{x^2+y^2}} - 1\right)y - mg, \tag{1}$$

where m is the mass of the insect, x is the displacement orthogonal to gravity $g = 9.81$ ms^{-2}, y is the displacement in the vertical direction, k is the leg's stiffness, and l_0 is the undeformed leg length.

The stiffness k is calculated from

$$k = \frac{\max(F_y)mg}{\epsilon}, \tag{2}$$

where F_y is the estimated maximum force in z-direction, and ϵ is the estimated compression, calculated using the uncompressed leg length and a compression factor, which for ants is between 2% for walking and 8 to 13% for running.

2.2 Bipedal Spring-loaded inverted pendulum

In the bipedal spring-loaded inverted pendulum model (BSLIP) for walking , two legs are in contact with the ground Eqs. (1) and (**??**) have to be modified: [20,21].

$$m\ddot{x} = ky\left(\frac{l_0}{\sqrt{x^2+y^2}} - 1\right)x - k\left(\frac{l_0}{\sqrt{(d-x)^2+y^2}} - 1\right)(d-x), \tag{3}$$

$$m\ddot{y} = k\left(\frac{l_0}{\sqrt{(d-x)^2+y^2}} + \frac{l_0}{\sqrt{(d-x)^2+y^2}} - 2\right) - mg, \tag{4}$$

Here, d is the horizontal spacing between the two spring bases — the two points on the ground where each leg/spring attaches. In insect-like models this accounts for the distance between legs in a tripod pair; in SLIP-like bipod models it accounts for step width or stance base and it defines how wide the support structure is. We obtain the ground reaction force $GRFx = kx(D_r - 1)$, considering the touch-down/take-off condition $x^2 + y^2 > l_0^2$, with $D_r = l_0/r$ being the leg compression, and $r = \sqrt{x^2+y^2}$, and $D_r - 1$ being the non-dimensional compression. The total mechanical energy

$$E = \frac{1}{2}mv^2 + mgy + \frac{1}{2}k(l-l_0)^2 \tag{5}$$

acts as a key constraint, ensuring that the simulated dynamics remain within a physically plausible regime where energy E is conserved (or has a defined budget per step). In both the single and double support phases, Eq. (5) is used to calculate the allowable horizontal velocity v by assuming no energy loss through damping, friction, or impact, hence idealising the leg as a perfect linear spring. Such an assumption is common in template models like BSLIP as it simplifies analysis by emphasising passive dynamics; however, this limits realism - real walking/running insects and robots require muscular work or actuators to offset energy losses and maintain gait stability, however, as a first approach we consider these assumptions as valid here. Both the SLIP and BSLP models have been validated for human mass and stiffness values (see Fig. 2 in [24] using data in the literature [4,10].

2.3 Joint model, its algorithm and connection to measurements

The two different gaits (running and walking) were coupled. From video recordings in the experimental arena [25] after a cool down period, ants were observed to walk in 34% of the cases (3 species and 3 video segments each). Cycles of running and walking were hence selected randomly following

$$\text{rand} \longrightarrow= \text{uni}(0,1) = \begin{cases} \leq 0.66, & \text{for running gait} \\ \text{else}, & \text{for running gait} \end{cases} \tag{6}$$

where ‘rand’ stands for drawing randomly a realisation from a univariate ($uni(0,1)$) distribution.

Since stiffness scales with mass similar to $k \propto m^{2/3}$, the stiffness of an insect leg is estimated to be about 0.03 to 0.5 Nm^{-1} [26] from an approximate stiffness of 10 kNm^{-1} for a human leg. Figure 3 shows a representative example of the mixed signal model with insect-realistic parameters, corresponding to $X(f,T)$ in Fig. 1(A). The GRF in Fig.3 is in the expected range which can be estimated as follows. The weight force mg of a typical meat ant is $\approx 0.09, \mathrm{mN}$. The peak vertical force during stance (walking gait) for many insects is on the order of 1 to 1.5 × body weight, implying $F_{y,\max}^{\text{walk}} \approx$ 0.09–$0.14\,\mathrm{mN}$. The peak vertical force during running or "bouncing" gaits for cockroaches and ants is about 2–$3\times$ body weight, so $F_{y,\max}^{\text{run}} \approx$ 0.18–$0.27\,\mathrm{mN}$. Horizontal forces F_x are generally smaller—often 0.2 to 0.6 × body weight in walking and somewhat higher in rapid gaits—so $F_{x,\max} \approx$ 0.018–$0.054\,\mathrm{mN}$.[1]. The Mixed SLIP-BSLIP with Uncertainty (MSBU) model is implemented here in its 'static-dynamic' configuration which combines a static (passive), bottom-up model (of spring-mass-damper subcomponents), with active updates from a statistical database. This active updating is variable itself and can encompass most key system parameters. In contrast, the active-active configuration would use a reservoir computing approach to reconstruct and denoise a time series [27]; its learning of a trajectory over a feedback mechanism is an area of ongoing research. This synthesised signal has served as the input for the MiAC-S device validated as a vibration-based non-chemical termite control device in [24]. It can be applied in a substrate-independent manner to replicate vibrations generated by any synthesised insect on any surface (Fig. 1(A)).

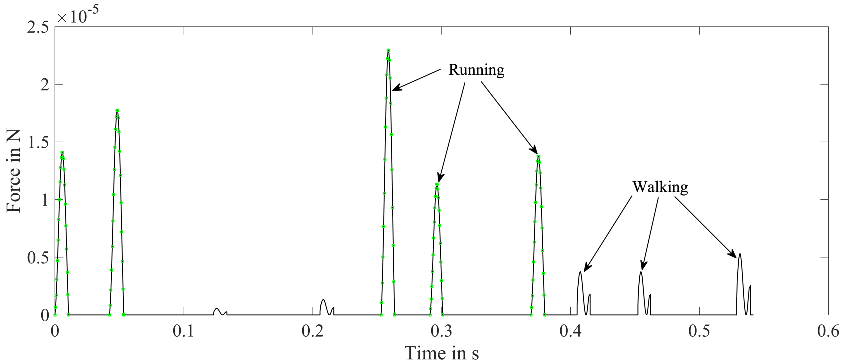

Figure 3. Mixed SLIP-BSLIP model with insect-realistic parameters with force in y direction; parameters for the simulation are $m = 9.1E-6$ kg, $\alpha_0 = \{75°, 29.38°\}$, $k = \{0.55, 0.25\}$Nm^{-1}, $u = \{0.005, 0.020\}$ms^{-1}, compression of the 8 mm long leg of *Iridomyrmex purpureus* was assumed to be 2% for walking and 8% for running. Probability to walk was set to 66%., amplitudes and attenuation times were extracted from experimental distributions, cf. Figure 2.

3. Generation of responses on veneer disc

Here we illustrate how the synthesised signal can be combined with experimental data to generate a realistic response on a given substrate and how to recover the synthesised signal from the response, using Tikhonov regularisation [19].

Prior to inputting the signal into the microactuator (MiAC-S)(Fig. 2), it has to be down-sampled and zero-padded in the time-domain to remove any inaccuracies due to downsampling at the pause times (true zeros). While the signal can have a high sampling rate, $X(f,T)$ can be as low as 100 Hz or 200 Hz, to generate the impacts required to excite a structure up to 5 kHz to 10 kHz, and hence a much higher sampling rate is required for measuring the response. Here a high sampling rate of 25 kHz is used to illustrate the excitation signal deconvolution process.

The signal y is perturbed by additive Gaussian noise, expressed through $y \leftarrow y + \text{noiseAmp} \cdot n_{\text{fac}} \cdot \max(|y|) \cdot \mathcal{N}(0,1)$, where noiseAmp denotes the global noise amplitude; n_{fac} is a dimensionless scaling factor; $\max(|y|)$ is the peak absolute value of the original signal y; and $\mathcal{N}(0,1)$ is a vector of normally distributed random variables with zero mean and unit variance, having the same dimensionality as y. This

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[1] and staying within the 1 to 3 times body-weight range provides a straightforward check that SLIP/BSLIP parameters remain insect-realistic

formulation scales the additive noise proportionally to $|y|$, preserving the relative signal dynamics while introducing realistic stochastic variability in noise due to e.g., noise contamination during operation of the device caused y electromagnetic interference, digital switching noise, environmental field effects. In non-shielded prototypes running at 3V, RMS noise levels are typically 100 µV to 3mV. Figure 4 illustrates how the synthesised excitation signal can be employed to generate a walking-like response on various substrates, including non-natural materials such as an aluminium disc (1 mm thickness, 60 mm diameter) [25]. The aluminium substrate yields exceptionally clean measurements, enabling straightforward spectral division using the clean excitation signal (not shown). However, even a small amount of additive noise 0.1% in $x(t)$ - as typically introduced when the signal is digitised and applied via a microactuator—renders direct inverse deconvolution through spectral division ineffective. Remarkably, Tikhonov regularisation enables recovery of the original excitation signal with high fidelity, as shown in Figure 4(d3), confirming in principle results presented on experimental data of ants walking [19].

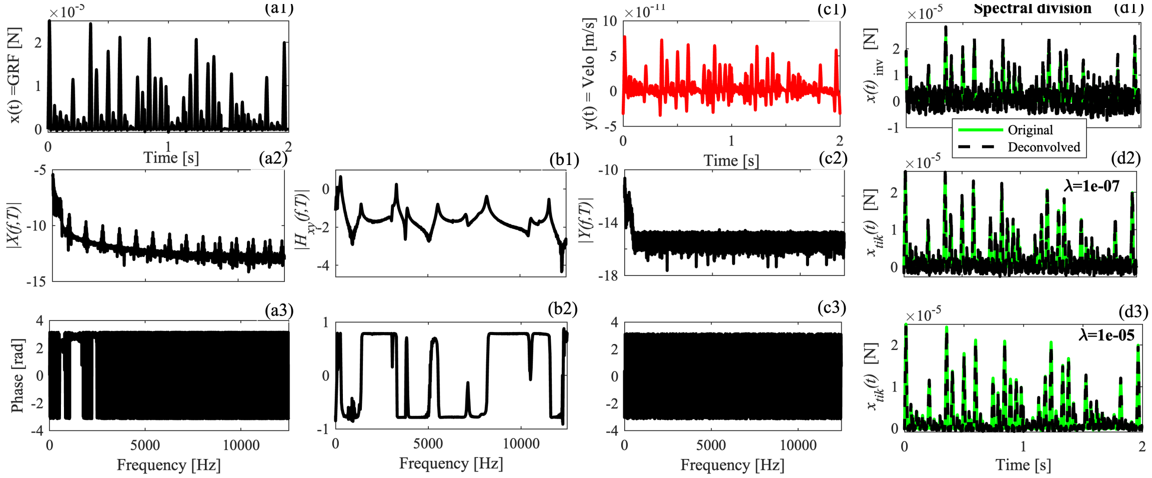

Figure 4. Experimental procedure of applying the signal to an aluminium disc and its extraction according to [19]. (a1) Excitation signal $x(t)$ transformed into the frequency domain (a2) magnitude and (a3) phase; (b) magnitude and phase of the aluminium disc; (c1) $y(t)$ time response signal obtained through inverse Fourier transforming the (c2) magnitude and (c3) phase of the response. Inverse deconvolution using (d1) spectral division, and Tikhonov regularisation using $\lambda = 1e - 7$ (d2) and $\lambda = 1e - 5$ (d3)

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4. Conclusions

In this work, we introduced and validated a novel Mixed SLIP–BSLIP with Uncertainty (MSBU) model that synthesises insect-realistic ground reaction forces (GRFs) by combining the Spring-Loaded Inverted Pendulum (SLIP) for hopping/running and the Bipedal SLIP (BSLIP) for walking gaits. By incorporating statistically derived parameters from an extensive database of insect locomotion measurements [25, 28], the model captures the inherent variability in ant gait dynamics, including cycle durations, amplitude distributions and inter-step “rest” intervals. A key feature of the model is its probabilistic gait switching which could be adapted to context-driven behaviours such as trail following.

We demonstrated that substrate-independent vibration excitation can be achieved by employing spectral multiplication of the synthesised GRF signal with measured frequency-response functions of arbitrarily chosen substrates (e.g., plywood, aluminium disc). This allows for bioassays on new substrates without residual imprint of the original substrate. We showed that Tikhonov-regularised deconvolution reliably recovers the original excitation within <5% error [19] in the presence of additive noise, highlighting the necessity of regularisation techniques in bioassays especially if feedback mechanisms for automatic signal adjustment is required.

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