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Evolved Neuromorphic Control for High Speed Divergence-based Landings of MAVs

Jesse J. Hagedaars¹, Federico Paredes-Vallés¹, Sander M. Bohté², and Guido C.H.E. de Croon¹

Abstract—Flying insects are capable of vision-based navigation in cluttered environments, reliably avoiding obstacles through fast and agile maneuvers, while being very efficient in the processing of visual stimuli. Meanwhile, autonomous micro air vehicles still lag far behind their biological counterparts, displaying inferior performance at a much higher energy consumption. In light of this, we want to mimic flying insects in terms of their processing capabilities, and consequently show the efficiency of this approach in the real world. This letter does so through evolving spiking neural networks for controlling landings of micro air vehicles using optical flow divergence from a downward-looking camera. We demonstrate that the resulting neuromorphic controllers transfer robustly from a highly abstracted simulation to the real world, performing fast and safe landings while keeping network spike rate minimal. Furthermore, we provide insight into the resources required for successfully solving the problem of divergence-based landing, showing that high-resolution control can be learned with only a single spiking neuron. To the best of our knowledge, this work is the first to integrate spiking neural networks in the control loop of a real-world flying robot. Videos of the experiments can be found at <https://bit.ly/neuro-controller>.

Index Terms—Aerial systems: perception and autonomy, autonomous vehicle navigation, spiking neural networks, neuromorphic computing, evolutionary algorithms.

I. INTRODUCTION

FLYING insects are everything we would like micro air vehicles (MAVs) to be: units that can navigate autonomously in cluttered environments through fast and agile maneuvers, despite being strongly limited in computational and energy resources. Like most animals that can see, these insects rely heavily on patterns of visual motion, or *optical flow* [1], for many important behaviors. During landing, for instance, honeybees maintain a constant rate of expansion, or *divergence*, of the optical flow field to ensure a smooth approach [2].

Insects perceive visual motion in a *spike-based* manner through light-sensitive cells and networks of interconnected neurons that react to brightness changes in the environment [3]. The sparsity and asynchronicity of such a spike-driven approach have inspired researchers to come up with

artificial substitutes, referred to as *neuromorphic*, that could potentially be used by insect-scale MAVs [4], [5] for efficient vision-based navigation. Event cameras [6], whose pixels register brightness changes as events, take the place of the retina. *Spiking neural networks* (SNNs) [7] assume the role of the underlying networks, subsequently transforming these event streams into estimates of visual motion.

Although the interest for event cameras is growing rapidly in the field of robotics [6], SNNs have not yet become widespread in control applications. The cause of this lies partially in the difficulty of training: the discrete spiking nature of SNNs severely limits the use of gradient-based optimization algorithms. Instead, most learning is based on the relative timing of spikes, often in combination with a surrogate gradient [8] or global reward signal [9] to allow the specification of desired behavior or goals. As far as robot control is concerned, these learning rules currently seem to be limited to either simulated applications [10], [11] or simple real-world problems resembling classification [12].

Artificial neural networks (ANNs), on the other hand, have been employed successfully for real-world vision-based control. For instance, [13] used *neuroevolution* [14] to optimize ANNs for performing divergence-based landings of MAVs. This work aims to demonstrate that we can evolve SNNs to solve the same control problem while keeping energy consumption at a minimum. The generality of evolutionary algorithms with respect to the characteristics of the evolved individuals [15] makes this, in our opinion, the most promising current approach to SNN learning.

This letter contains two main contributions. First, we demonstrate learned neuromorphic control for a real-world problem through evolving SNNs for performing divergence-based landings of an MAV. To the best of our knowledge, this work is the first to integrate SNNs in the control loop of a real-world flying robot. Second, we study how to substantially reduce the spike rate of the SNN controller, corresponding to considerable energy savings if it were to be run on neuromorphic hardware. Besides investigating the effect of pruning neurons (as also done in [16], [17]), we introduce the inclusion of network spike rate as an objective in the multi-objective neuroevolution. Fig. 1 presents an overview of the proposed system.

The remainder of this letter is structured as follows. Section II provides related work concerning robot learning. The control problem, SNN configuration, and learning procedure are discussed in Section III. Next, Section IV covers the performed experiments and lists their findings. Conclusions drawn from these findings are then stated in Section V.

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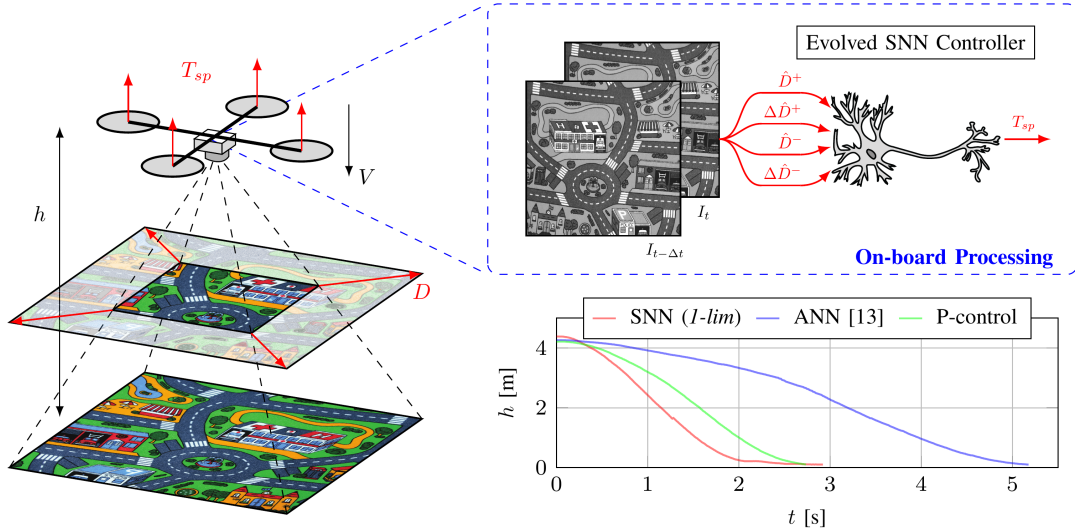


Fig. 1. Overview of the proposed system. An MAV with downward-facing camera is controlled to perform vertical landings based on the divergence D of the optical flow field. As the MAV moves towards the surface, its field-of-view covers a smaller portion of the original pattern, and distances between any two tracked points on the camera’s pixel array increase. This increase is proportional to D . Two subsequent video frames $I_{t-\Delta t}$ and I_t can thus provide estimates of divergence \hat{D} and its temporal derivative $\Delta\hat{D}$, which can subsequently be used by an evolved SNN controller to regulate the thrust setpoint T_{sp} . Our controller compares favorably against a state-of-the-art ANN controllers [13] and a proportional controller during real-world tests.

II. RELATED WORK

Not all approaches are equally well suited to the problem of learning real-world robot control, which can be characterized as the optimization of some behavioral function in a complex, uncertain environment. One of the more popular paradigms for solving these kinds of problems has been *reinforcement learning* (RL) in combination with deep ANNs [18]. In pursuit of more efficient methods, we investigate SNNs as an alternative to these deep ANNs, knowing that the respective energy savings can be as large as an order of magnitude for comparable networks [19]. Through the related work, we aim to show the immaturity of current RL-inspired approaches to SNN learning, called *reward-modulated*, as well as the promise of neuroevolution.

A. Reinforcement Learning in SNNs

SNNs trained through reward-modulated learning have so far only been successfully applied to problems that are either relatively simple or simulated. For instance, [12] succeeds in training an SNN for a real-world MAV obstacle avoidance task using a reward-modulated rule, but only after the problem has been preprocessed to a much simpler (almost one-to-one) mapping between discrete inputs and outputs.

In simulation, [11] demonstrates vision-based neuromorphic lane-keeping control of a two-wheeled robot. Although a reward-modulated rule is used for learning, the task is set up in such a way that its complexity remains limited: rewards are tailored to each individual neuron, so that increased firing inevitably results in a self-centering policy. In [10], the authors employ the same learning rule for training an SNN to control a simulated robotic insect. Reward is based on the deviation from an externally generated trajectory, however, making it essentially a lane-keeping task.

B. Neuroevolution for Robot Control

Reviews of the field of neuroevolution show its promise for learning in ANNs [20] and SNNs [14]. Furthermore, neuroevolution exhibits qualities relevant to real-world learning: it scales well in terms of parameter space and compute, and can even be more sample efficient than RL [20]. So far, evolved SNN controllers have only been successfully applied to simulated MAVs [21], [22], or rudimentary real-world ground robots [23]. ANN neuroevolution, on the other hand, has been applied to more complex real-world problems. For example, the authors of [13] evolve ANNs to learn event-based optical flow control of a real-world, landing MAV. It is shown that a small, three-layer network is sufficient to perform high-resolution control, with only the weights being evolved. Following their success, we directly extend this approach to SNNs, in order to obtain a more energy-efficient solution.

III. METHODOLOGY

A. Divergence of the Optical Flow Field

In this work, we use the optical flow formulation from [24], which assumes a downward-looking camera over a static planar surface, as depicted in Fig. 1. With this configuration, moving the camera along the Z -axis (as for a vertical MAV landing) causes an optical flow, in this case divergence, to be perceived. Physically, this divergence corresponds to the ratio of vertical velocity and height above the surface, or $D = V/h$. To estimate divergence from a camera, we can use the relative, temporal variation in the distance between tracked image points (corners) [25]. Referred to as *size divergence*, this method results in a computationally efficient and reliable

estimate of divergence \hat{D} , when averaged over a set of N_D pairs of points:

$$\hat{D}(t) = \frac{1}{N_D} \sum_{i=1}^{N_D} \frac{1}{\Delta t} \frac{l_i(t - \Delta t) - l_i(t)}{l_i(t - \Delta t)} \quad (1)$$

with Δt the time step, and $l_i(t)$ the distance between a pair of tracked points at time t . The proposed SNN controller receives as input an estimate of divergence \hat{D} , as well as its temporal derivative $\Delta\hat{D}$.

B. Spiking Neural Network Architecture

In SNNs, neurons are connected through *synapses*, which have a certain weight. Incoming spikes contribute to the *membrane potential* $u_i(t)$ of a neuron in an additive or subtractive manner. In case no inputs are received, $u_i(t)$ decays to a resting potential u_{rest} . On the other hand, if the quantity of inputs is large enough to push the potential above a threshold θ_i , the neuron itself emits a spike s_i , after which the potential is reset to u_{rest} .

The neuron model employed in this work is the often-used *leaky integrate-and-fire* (LIF) [26]. Discretizing this model using forward Euler leaves us with the following equation for the membrane potential:

$$u_i(t) = u_i(t - \Delta t) \cdot \tau_{u_i} + \alpha_{u_i} i_i(t) \quad (2)$$

where we assumed $u_{rest} = 0$, and take the membrane decay as a factor τ_{u_i} . $i_i(t)$ is the forcing function working on neuron i , which corresponds to the incoming spikes multiplied by their respective synaptic weights, i.e., $i_i(t) = \sum_j w_{ij} s_j(t)$, or to incoming currents $c_j(t)$, i.e., $i_i(t) = \sum_j w_{ij} c_j(t)$. The influence of the forcing function on the membrane potential is scaled with a constant α_{u_i} .

To prevent excessive firing while ensuring responsiveness to small/low-frequency inputs, θ_i can be made dependent on the neuron's firing rate, resulting in an adaptive LIF [27]:

$$\theta_i(t) = \theta_i(t - \Delta t) \cdot \tau_{\theta_i} + \alpha_{\theta_i} s_i(t) \quad (3)$$

with τ_{θ_i} being the corresponding decay factor, and α_{θ_i} the constant scaling the emitted spike.

The binary nature of SNNs requires functions that transform real-valued signals to binary spikes and vice-versa, i.e., *encodings* and *decodings*. This work makes use of a pair of non-spiking neurons per input observation, one for positive and one for negative values, with at most one of the two neurons active at any given time. The proportional currents $c_i^+(t)$ and $c_i^-(t)$ coming out of the respective neurons can be expressed as:

$$\begin{aligned} c_i^+(t) &= |\max(0, o_i(t))| \\ c_i^-(t) &= |\min(0, o_i(t))| \end{aligned} \quad (4)$$

with $o_i(t)$ the observation variable belonging to neuron i .

For decoding binary spikes to real-valued scalars $a_i(t)$ (actions) in a range $[r_1, r_2]$, the *spike trace* $X_i(t)$, which is essentially a low-pass filter over a neuron's emitted spikes, can be combined with a simple scaling:

$$\begin{aligned} a_i(t) &= r_1 + (r_2 - r_1) \cdot X_i(t) \\ X_i(t) &= X_i(t - \Delta t) \cdot \tau_{x_i} + \alpha_{x_i} s_i(t) \end{aligned} \quad (5)$$

TABLE I
SAMPLING DISTRIBUTIONS OF MUTATED PARAMETERS

Parameter	Distribution
w_{ij}	$\mathcal{U}(-w_{ij} - 0.05, 2w_{ij} + 0.05)$
$\alpha_{u_i}, \alpha_{\theta_i}, \alpha_{x_i}$	$\mathcal{U}(\alpha_* - 2/3, \alpha_* + 2/3)$, clamped to $[0, 2]$
$\tau_{u_i}, \tau_{\theta_i}, \tau_{x_i}$	$\mathcal{U}(\tau_* - 1/3, \tau_* + 1/3)$, clamped to $[0, 1]$
θ_i	$\mathcal{U}(\theta_i - 1/3, \theta_i + 1/3)$, clamped to $[0, 1]$

The SNN used for the control task in this work is kept relatively simple, with only a single hidden layer of not more than 20 adaptive LIF neurons, and a single output LIF neuron. We consider vertical control to be one-dimensional, with the SNN controller setting the thrust. Two pairs of non-spiking neurons encode the inputs \hat{D} and $\Delta\hat{D}$, as in Eq. (4). See Fig. 1 for an illustration.

C. Evolving Energy-efficient Neuromorphic Controllers

Each evolution starts off with a randomly initialized *population* of μ SNN individuals. We opt for a *mutation-only* approach, given that crossover tends to work best when natural building blocks are available, and could lead to difficulties like the permutation problem when applied to neural networks [28]. Weights and hyperparameters are mutated with $P_{mut} = 0.3$ according to the distributions in Table I. *Offspring* λ is combined with the previous population and evaluated in a highly stochastic simulation environment (see Section III-D), where the repeated evaluation (along with resampling of the environment) of the previous generation decreases the chance individuals live on only because they received 'easy' environmental conditions (little noise, small delay, fast-responding motors, etc.). The *fitness* of an individual consists of four objectives: time to land (f_1), final height (f_2), final vertical velocity (f_3), and total spike rate of the network (f_4). Selection is carried out using the multi-objective genetic algorithm *NSGA-II* [29].

During evolution, a *hall of fame* is maintained, which holds the pan-generational Pareto front (all non-dominated individuals that have ever lived). This prevents the discard of well-performing individuals across generations. After N_{gen} generations, the individuals in the hall of fame are evaluated by letting them perform 250 landings in a randomized environment and quantifying the median and inter-quartile range for each evolutionary objective, giving us an idea of their robustness. The best-performing individuals are then selected for further real-world tests.

D. Randomized Vertical Simulation Environment

The vertical simulation environment in which individuals are evaluated makes use of domain randomization and artificial noise to improve transferability to the real world. The available observations are the divergence \hat{D} and its temporal derivative $\Delta\hat{D}$. Similar to [13], the simulated MAV is considered as a unit mass under the influence of gravity, and control happens

TABLE II
SAMPLING DISTRIBUTIONS OF ENVIRONMENT PARAMETERS

Parameter	Distribution
δ_D	$\mathcal{U}(1, 4)$ steps
σ_D	$\mathcal{U}(0.05, 0.15) \text{ s}^{-1}$
$\sigma_{D_{prop}}$	$\mathcal{U}(0.0, 0.25) \text{ s}^{-1}$
τ_T	$\mathcal{U}(0.005, 0.04) \text{ s}$
Δt	$\mathcal{U}(0.02, 0.0333) \text{ s}$
P_{jitter}	$\mathcal{U}(0.0, 0.2)$

in one dimension with the SNN controller selecting a thrust setpoint T_{sp} . This leads to the following dynamics model:

$$\begin{aligned} h(t) &= h(t - \Delta t) + \Delta t \cdot v(t - \Delta) \\ v(t) &= v(t - \Delta t) + \Delta t \cdot T(t - \Delta t) + W(t) \\ T(t) &= T(t - \Delta t) + \Delta t \cdot \frac{T_{sp} \cdot g - T(t - \Delta t)}{\Delta t + \tau_T} \end{aligned} \quad (6)$$

where the altitude h , vertical velocity v , and thrust T are updated using the forward Euler method, and τ_T represents the spin-up and spin-down time of the rotors. The thrust setpoint T_{sp} selected by the SNN is clamped to a realistic range of acceleration for the MAV, namely $[-0.8, 0.5] \text{ g}$. Lastly, W denotes vertical wind, and is given by:

$$W(t) = W(t - \Delta t) + \Delta t \cdot \frac{\mathcal{N}(0, \sigma_W^2) - W(t - \Delta t)}{\Delta t + \sigma_W} \quad (7)$$

with $\sigma_W = 0.1 \text{ ms}^{-1}$ being the standard deviation of the normally distributed wind.

Noise is added to the divergence estimation according to the model in [30]. The observed divergence \hat{D} is the result of adding a delay δ_D to the ground-truth divergence, along with white noise and proportional white noise:

$$\begin{aligned} \hat{D}(t) &= D(t - \delta_D \cdot \Delta t) + \mathcal{N}(0, \sigma_D^2) \\ &+ D(t - \delta_D \cdot \Delta t) \cdot \mathcal{N}(0, \sigma_{D_{prop}}^2) \end{aligned} \quad (8)$$

where σ_D and $\sigma_{D_{prop}}$ are the standard deviations for the added noise and proportional noise, respectively. Additionally, computational jitter is introduced in order to simulate the case in which the estimated divergence is not updated due to, for instance, insufficient corner points. Each time step, there is the probability P_{jitter} that the estimated divergence from the previous step is used (for a maximum of one step).

The evaluation of an individual consists of four landings, from initial altitudes $h_0 = 2, 4, 6, 8 \text{ m}$. The environment is bounded in altitude and time: $[0.05, h_0 + 5] \text{ m}$ and 30 s . Individuals start out without initial velocity and acceleration, and are left to settle for 0.5 s . Each landing has its own, differently randomized environment, with parameters (Table II) being redrawn at the start of each generation, such that all individuals experience the same four environments. Fitness is averaged across the four landings, with extra punishment for individuals that do not manage to land.

IV. EXPERIMENTS

A. Experimental Setup

1) *Simulation*: Per configuration, four randomly initialized populations of 100 individuals are evolved for 400 gener-

ations, after which their final halls of fame are combined. Initial synaptic weights are drawn from $\mathcal{U}(0, 1)$, and other hyperparameters are initialized as constants: $(\alpha_{u_i}, \alpha_{\theta_i}, \alpha_{x_i}) = (0.2, 0.2, 1.0)$, $(\tau_{u_i}, \tau_{\theta_i}, \tau_{x_i}) = (0.8, 0.8, 0.8)$, and $\theta_i = 0.2$.

For simulating SNNs, we used Python and the open-source PySNN¹ library recently developed in our lab; for performing the evolutions, we used the DEAP [31] framework. The code for running the experiments² and the simulation environment³ is also publicly available.

2) *Real World*: The MAV used in this work is a Parrot Bebop 2 running the open-source Paparazzi⁴ autopilot on its 780 MHz dual-core ARM Cortex A9 processor. To also run the SNN on board, we developed TinySNN⁵: a framework for building small spiking networks in the C programming language. Its similarities with PySNN allow an almost seamless transfer of networks from simulation to the real-world hardware.

Landings start from an initial altitude of roughly 4 m and are ended at 0.1 m above ground (to prevent infinite D and compensate for the offset created by the MAV's landing legs at initialization). Horizontal guidance is provided by a motion capture system. Similar to [13], [32], divergence is estimated as size divergence using the Bebop's downward-looking CMOS camera, and a FAST corner detector [33] in combination with a pyramidal Lucas-Kanade feature tracker [34]. To limit computational expense, N_D is capped at 100 points. Divergence measurements are updated at a rate of approximately 45 Hz, while the control loop implementing the divergence-based landing runs at roughly 512 Hz.

Linearly transforming the thrust setpoint T_{sp} to rotor commands leads to poor tracking performance due to unmodeled drag and nonlinear aerodynamic effects that result from a descent through the propeller downwash. To close this reality

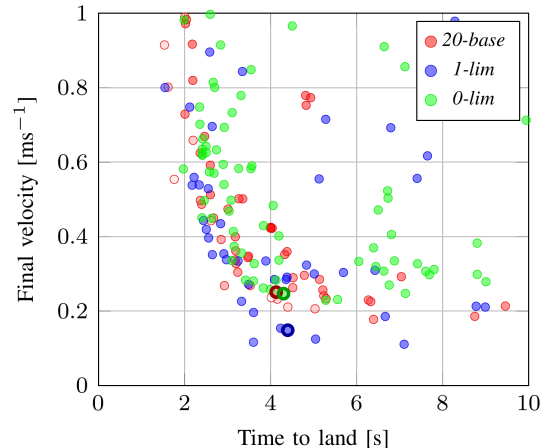


Fig. 2. Pareto front (based on median performance over 250 evaluations) of individuals in the final hall of fame. The dot's color shade is proportional to the spike rate median: lighter means a higher rate. Selected individuals are indicated in bold.

¹ Available at <https://github.com/BasBuller/PySNN>

² Available at <https://github.com/Huizerd/evolutionary>

³ Available at <https://github.com/Huizerd/gym-quad>

⁴ Available at <https://github.com/paparazzi/paparazzi>

⁵ Available at <https://github.com/Huizerd/tinysnn>

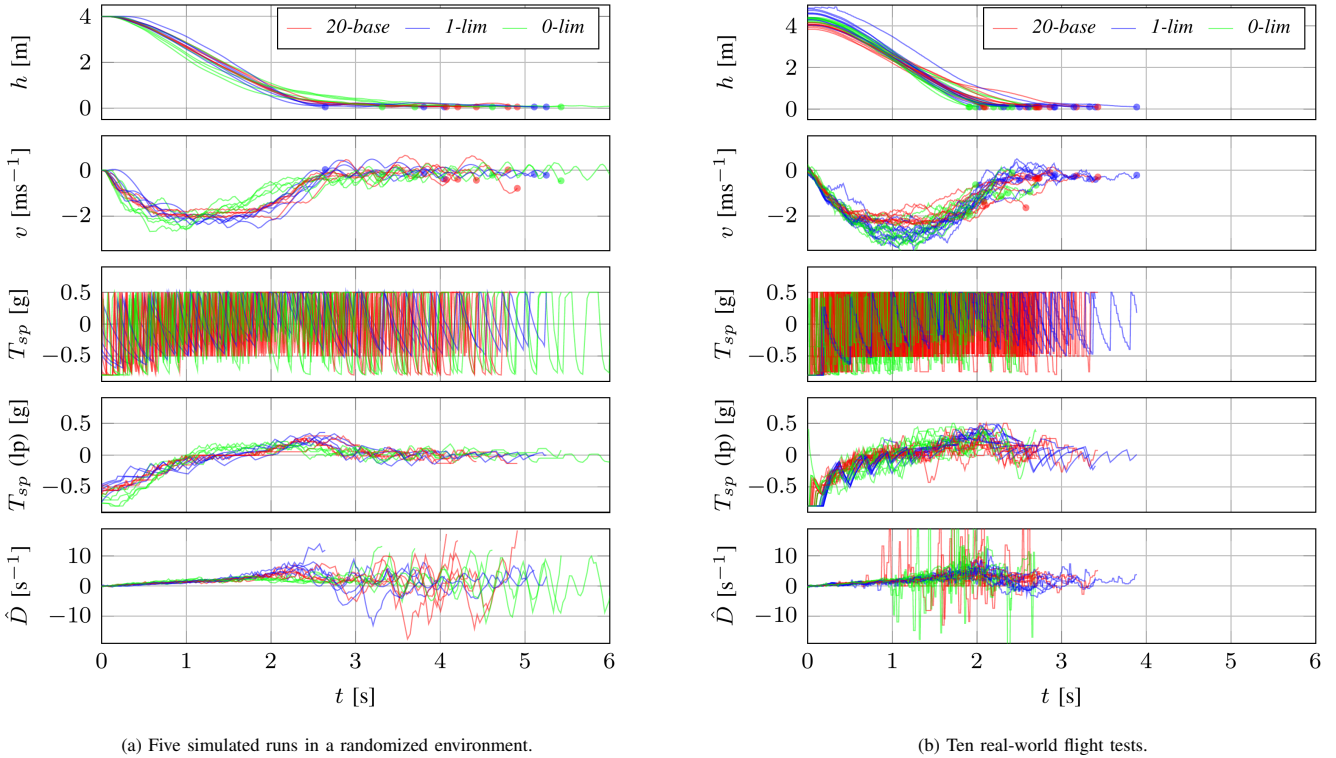


Fig. 3. Height, velocity, thrust setpoint (raw and 20-step moving average) and estimated divergence for simulated and real-world landings of selected individuals. Dots in the h and v plot mark the end of runs.

gap, a PI controller (with gains $P = 0.7$ and $I = 0.3$) was used to convert the thrust setpoint to motor commands [13].

B. 20 Hidden Neurons

The first SNN configuration considered here is *20-base*, which has 20 adaptive LIF neurons as hidden layer. The spike-minimizing neuroevolution allows us to start off with more neurons than necessary ([13] used eight), as redundant ones will ultimately be silenced. Fig. 2 displays the Pareto front of evolved individuals for this configuration in red. From this front, a single individual, indicated by a bold circle, is selected for further testing. Note that objective f_2 (final altitude) is not shown in Fig. 2, as it was almost consistently minimized for all individuals.

Looking at the simulated landings performed by this individual in Fig. 3a, we see that most landings are quite smooth (low touchdown velocity). Plots of the low-passed thrust setpoint T_{sp} likewise display a small bump that suggests braking before touchdown. The raw T_{sp} data, however, shows large-magnitude, high-frequency oscillations. This behavior is caused by the values of α_{x_i} and τ_{x_i} of the decoding, which cause instantaneous jumps and decays to maximum and (almost) minimum acceleration, respectively. Controllers that show this kind of *bang-bang* behavior are unlikely to transfer well from simulation to the real world due to their dependency on motor dynamics [13].

When taking the selected controller to the real world, we can conclude from Fig. 3b that this is indeed so, with higher touchdown velocities and quicker landings (2-3 s in reality

versus 5-6 s in simulation). The quick oscillations in T_{sp} cannot be followed by the motors, leading to lower values of acceleration than actually desired. Currently, the evolutionary process has little way of accounting for this discrepancy, because the bang-bang control leads to good landings in simulation. To account for this, we constrain the mutation of α 's (mutation magnitude halved, clamped to $[0, 1]$) and τ 's (clamped to $[0.3, 1]$) in the next section.

During the simulated landings of Fig. 3a, the spiking activity of each neuron was recorded. Fig. 4 gives the average spike rate per neuron, as well as the sign and magnitude of the connections. Looking at *20-base*, the number of inactive hidden neurons and weak connections suggests it can be made much smaller. In fact, the single yellow path from input to output layer, together with the single effectively active neuron in the hidden layer, leads us to believe divergence-based landings can be performed with only a single spiking hidden neuron (*1-lim*), or possibly none at all (*0-lim*).

C. One or No Hidden Neuron

Fig. 2 lets us compare the Pareto fronts for *20-base*, *1-lim* and *0-lim*, with the latter two limited in the mutation of α 's and τ 's. The front of *1-lim* outperforms both *20-base* and *0-lim*, suggesting there is a benefit to a significantly reduced parameter space as well as a hidden layer.

The comparison of simulated landings in Fig. 3a shows that, even though all selected controllers perform roughly the same in terms of time to land, *1-lim* often touches down with the least vertical velocity. The plots of T_{sp} show the

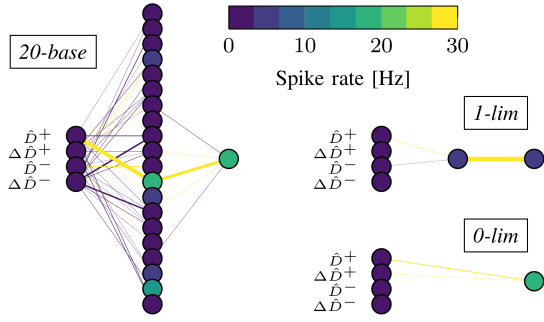


Fig. 4. Average firing rates and synaptic weights of selected individuals for the five simulated runs displayed in Fig. 3a. Vertex color is proportional to neuron firing rate, while synaptic weight is proportional to edge thickness. Edge colors indicate positive (yellow) or negative (purple) synapses.

control policy responsible for this: the slow decay and few output spikes of *1-lim* result in small ‘hops’ that decrease in magnitude as the ground nears. Nevertheless, the landings performed by the single-spiking-neuron controller *0-lim* also look promising. Like *1-lim*, decoding decay is slower, which allows a larger number of acceleration setpoints to be selected. Still, the high frequency and large magnitude of the oscillations will most likely prevent a good transfer to the real world. Looking at Fig. 3b, we see that this is indeed the case. The touchdown velocity of both *20-base* and *0-lim* is often higher than that of *1-lim*, whose slower decoding dynamics helped with a successful transfer from simulation to the real world. Some unsteady behavior is still present during the final landing phase, however, as can be observed from the supplementary video. These ‘self-induced oscillations’ are the result of the scale ambiguity in optical flow control [35]. Although SNN and ANN controllers are able to postpone these oscillations [13], getting rid of them completely requires additional measures [25].

The network activity during simulated landings in Fig. 4 indicates that, in the case of *0-lim*, further evolutionary optimization might decrease spike rate even more, as is shown to be feasible by the network of *1-lim*. The same goes for *20-base*, where the spiking of some hidden neurons is not used at all. This reflects in the large differences between the total network spike rates, which are 71.2 Hz, 7.5 Hz and 16.8 Hz for *20-base*, *1-lim* and *0-lim*, respectively. Without spike minimization as an evolutionary objective, *20-base* has a total spike rate of 201.2 Hz, meaning spike minimization is responsible for a 65% drop. A further decrease is possible given more generations or a smaller network (an additional 31% for *1-lim*). Based on energy measurements for the neuromorphic Loihi chip [36], the corresponding energy savings would be 11.4 nJ (59%) and 18.5 nJ (96%) for spike minimization and smaller networks, respectively.

Fig. 5 compares the transient and steady-state response of the selected individuals. Due to its slow decoding dynamics, the transient response of *1-lim* shows a much larger number of possible thrust setpoints than any other individual. Furthermore, it limits itself to a smaller T_{sp} range, preventing large-magnitude oscillations. Both *20-base* and *0-lim*, on the other hand, only have a distinct number of plateaus in their

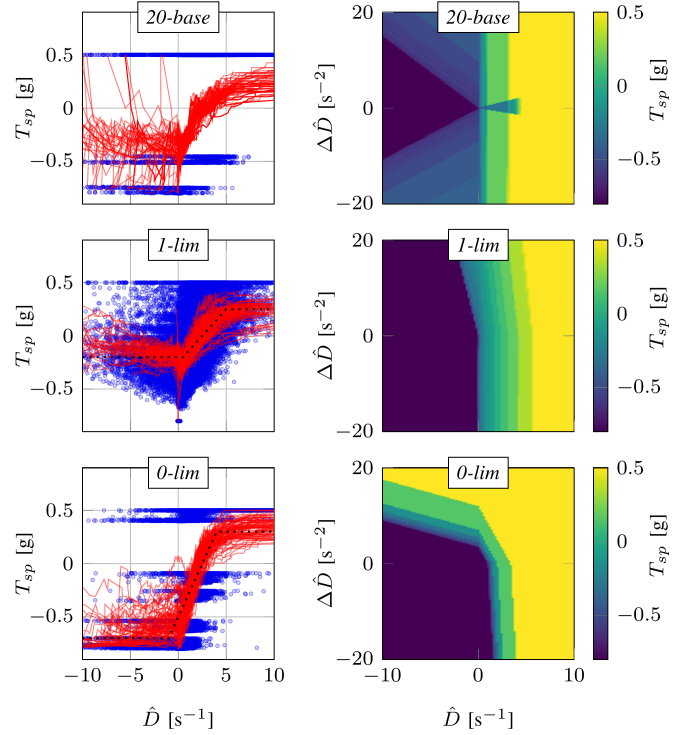


Fig. 5. Transient and steady-state response of selected individuals. Steady-state responses are obtained by subjecting the SNNs to 100 time steps of the same observation and subsequently averaging the last 50 steps. The transient response is made up of 100 simulated landings during which \hat{D} and T_{sp} are recorded (blue dots), and then sorted by increasing divergence and passed through a 40-step moving average (red lines). Comparable proportional controllers are indicated by a dotted black line.

transient response, and these have to cover the entire range $[-0.8, 0.5]$ g. Looking at the steady-state response, we see that *20-base* and *1-lim* mainly have a gradient in the \hat{D} -dimension, which makes sense given the connections in those networks to the respective encoding neuron. The fact that this gradient is mostly on the $+\hat{D}$ -side suggests that an indication of positive divergence alone might suffice (absence of $+\hat{D}$ activity relates to $-\hat{D}$). The response of *0-lim*, however, also has a significant gradient in the $\Delta\hat{D}$ -dimension, as this individual additionally has a positive connection to the $\Delta\hat{D}^+$ input neuron.

The transient responses of the proposed controllers in Fig. 5 all seem to approximate a sigmoid shape. In comparison, the response given by a proportional divergence controller, whose output thrust is directly related to the divergence error, would be a straight line, with its slope dependent on the controller’s gain. Analogously, the accompanying steady-state plot would show an even gradient along \hat{D} . The dotted black lines in Fig. 5 show P-controllers comparable to *1-lim* and *0-lim*.

D. Comparison with Existing Controllers

To compare the performance of the proposed SNN controllers with existing control methods for divergence-based landing, we evaluate the transient responses and landing characteristics obtained from real-world flight tests. The right column of Fig. 6 consists of current state-of-the-art control methods for optical flow landings. At the top, there is the

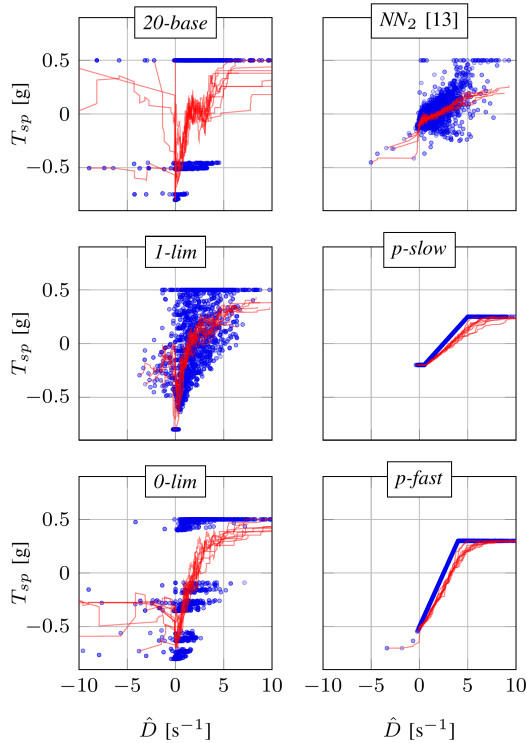


Fig. 6. Comparison of transient responses from real-world tests. Responses are made up of ten real-world landings during which \hat{D} and T_{sp} are recorded (blue dots), and then sorted by increasing divergence and passed through a 40-step moving average (red lines).

NN_2 controller from [13], an ANN evolved for divergence-based landing control with eight hidden neurons. The middle response is obtained from a pure P-controller, named p -slow. Mathematically, the thrust output of a P-controller can be represented as $T_{sp} = \frac{K_p}{g} \cdot (\hat{D} - D_{sp})$. p -slow has a gain $K_p = 0.98$ and a divergence setpoint $D_{sp} = 2.5 \text{ s}^{-1}$, and its output T_{sp} is clamped to a range $[-0.2, 0.25] \text{ g}$. Another P-controller, p -fast, is included at the bottom, which instead has a gain $K_p = 1.96$ and a thrust clamping to $[-0.7, 0.3] \text{ g}$. Both p -slow and p -fast were derived from the transient responses of SNN controllers in terms of gain (slope) and divergence setpoint (offset), with the former being based on 1 -lim, and the latter on 0 -lim (see Fig. 5).

Comparing the evolved SNN controllers with NN_2 , we see that the latter is characterized by a lower gain and a limited but high-resolution range of thrust setpoints, leading to slower but smooth landings. Looking at the P-controllers, the lack of stochasticity in their response is immediately obvious, making their landings smooth as well. Nonetheless, both 1 -lim and 0 -lim outperform their derived P-controllers p -slow and p -fast in terms of touchdown velocity while landing almost as quickly: $2.9 \text{ s} / 0.4 \text{ ms}^{-1}$ versus $2.4 \text{ s} / 1.0 \text{ ms}^{-1}$ and $2.2 \text{ s} / 1.0 \text{ ms}^{-1}$ versus $1.9 \text{ s} / 1.2 \text{ ms}^{-1}$, respectively. Also, 1 -lim performed better than NN_2 , whose landings averaged $4.4 \text{ s} / 0.5 \text{ ms}^{-1}$. Real-world landing profiles of 1 -lim, NN_2 and p -slow are shown in Fig. 1.

V. CONCLUSION

In this letter, we demonstrated, for the first time, that neuromorphic controllers evolved in a highly abstracted simulation environment are capable of controlling landings of real-world MAVs using only the divergence of the optical flow field. Further, by minimizing the amount of spikes during evolution, we provided insight into the resources required for successfully solving the problem at hand, and the potential energy savings of an implementation on neuromorphic hardware. A real-world comparison with state-of-the-art controllers showed that the proposed SNNs often land faster and touch down softer. Also, we found that SNNs consisting of only a single spiking neuron are equally capable of smooth landings as larger networks, all the while using only a fraction of their spikes. This is in line with [37], which implies that single biological neurons are capable of solving linearly non-separable problems. Future research should focus on achieving an end-to-end spiking solution to vision-based control, making use of an SNN capable of estimating global motion from an event camera [38].

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