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Supplementary Materials for

Optimized flocking of autonomous drones in confined environments

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Other Supplementary Material for this manuscript includes the following:

(available at robotics.sciencemag.org/cgi/content/full/3/20/eaat3536/DC1)

Movie S1 (.avi format). Simulation of the old flocking model (algorithm A) with 100 agents.
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Movie S7 (.mp4 format). Summarizing documentary with simulation, flight log visualization, and footage on real flights.

Supplementary Movies

- Movie S1. Simulation of old flocking model (algorithm A) with 100 agents, available at `https://youtu.be/viEfowBXzho`

- Movie S2. Simulation of new flocking model (algorithm B) after evolutionary optimization with 100 agents, available at `https://youtu.be/t8kr79k3DUQ`

- Movie S3. Simulation of flocking for different speeds (4-32 m/s), flock sizes (30 to 1000 agents) and scenarios, available at `https://youtu.be/KPVfi9Pwuq8`

- Movie S4. Flight log visualization of 30 drones at 4 m/s in a diagonal flight pattern, available at `https://youtu.be/JMMGIQm7Ris`

- Movie S5. Flight log visualization of 30 drones at 6 m/s with obstacles, available at `https://youtu.be/YW5zDD70x8o`

- Movie S6. Flight log visualization of 30 drones at 8 m/s in a circular flight pattern, available at `https://youtu.be/GoiunzowSG4`

- Movie S7. Summarizing documentary with simulation, flight log visualization, and footage on real flights, available at `https://youtu.be/E4XpyG4eMKE`

Supplementary Tables

Table S1. Optimized model parameter values and working ranges in simulation. $F^{\max}$ represents the highest achieved fitness values during optimization, while $\bar{F}$ shows average ($\pm$ std) fitness values calculated from 100 stochastic evaluations of the optimized solutions. Optimized model parameter values are shown below. Numbers in brackets indicate the range where solutions existed during the optimization with fitness above $\bar{F}$, representing a reasonabe working range of the parameter space. The number of these high-fitness evaluations (out of 150000) is shown by N. Note that as r_0^{frict} is optimized to a high value, the value of p^{frict} and a^{frict} has no effect.

	param	unit	v^{flock} = 4 m/s	v^{flock} = 6 m/s	v^{flock} = 8 m/s	v^{flock} = 16 m/s	v^{flock} = 32 m/s
	$F^{\max}$	-	0.918	0.873	0.798	0.910	0.892
	$\bar{F}$	-	0.812 ± 0.101	0.776 ± 0.086	0.728 ± 0.075	0.789 ± 0.120	$0.629 \pm 0.\ 227$
	$N(F \geq \bar{F})$	-	1835	2118	2030	2515	4364
Rep.	r_0^{rep}	m	25.6 [17.3, 28.2]	41.1 [30.8, 51.0]	52.9 [46.0, 63.5]	103 [85.7, 120]	200 [144, 200]
	p^{rep}	1/s	0.13 [0.08, 0.37]	0.07 [0.03, 0.16]	0.06 [0.04, 0.09]	0.03 [0.02, 0.06]	0.03 [0.02, 0.11]
Friction	r_0^{frict}	m	85.3 [51.3, 87.8]	88.5 [58.5, 100]	86.8 [52.2, 114]	182 [95.6, 198]	228 [148, 252]
	C^{frict}	-	0.05 [0.02, 0.27]	0.05 [0.03, 0.22]	0.06 [0.04, 0.17]	0.07 [0.04, 0.23]	0.09 [0.04, 0.21]
	v^{frict}	m/s	0.63 [0.07, 1.88]	0.93 [0.30, 2.70]	1.48 [0.81, 3.10]	2.47 [1.60, 4.99]	3.46 [0.02, 4.89]
	p^{frict}	1/s	3.20 [0.0, 10.0]	5.32 [0.38, 9.67]	6.87 [1.66, 9.97]	5.92 [0.02, 7.72]	5.38 [2.65, 9.47]
	a^{frict}	m/s/s	4.16 [0.0, 10.0]	9.94 [5.04, 10.0]	0.98 [0.0, 2.89]	2.57 [0.0, 5.25]	0.70 [0.0, 3.35]
Wall	r_0^{shill}	m	0.3 [0.0, 15.1]	0.5 [0.0, 9.3]	0.1 [0.0, 3.5]	0.5 [0.0, 14.2]	4.2 [0.0, 25.7]
	v^{shill}	m/s	13.6 [9.4, 15.0]	19.7 [17.5, 20.0]	22.8 [17.8, 34.1]	49.2 [39.2, 56.3]	76.4 [68.6, 82.2]
	p^{shill}	1/s	3.55 [0.26, 10.0]	5.44 [0.48, 9.96]	8.12 [4.32, 10.0]	9.49 [3.42, 10.0]	4.87 [0.95, 7.04]
	a^{shill}	m/s/s	3.02 [1.24, 9.99]	3.54 [2.53, 5.12]	4.18 [2.39, 9.99]	9.50 [6.72, 10.0]	9.99 [8.92, 10.0]

Table S2. Statistic evaluation of optimized simulations. Table contains average and standard deviation of measured order parameters (average speed, average distance from closest neighbor, collision risk and number of collisions) and fitness values at model optima. Values are gathered from 100 stochastic evaluations of the simulations for all tested flocking speeds. Other conditions of the simulations, like arena size and communication range are also given for each case.

v^{flock}	4 m/s	6 m/s	8 m/s	16 m/s	32 m/s
L	250 m	250 m	250 m	500 m	1000 m
r^{C}	80 m	80 m	80 m	160 m	320 m
ϕ^{vel} (m/s)	3.78±0.10	5.60±0.02	7.26±0.02	15.01±0.04	29.6±0.15
$\bar{r}_{ij}^{\mathrm{min}}$ (m)	12.2±0.4	13.4±0.06	14.7±0.07	23.2±0.23	41.7±0.70
Φ^{coll} (E-6)	0.94±1.3	1.6±1.9	1.0±1.8	2.1±2.8	6.0±8.1
N^{coll}	1.18±1.25	1.65±1.34	0.89±1.19	1.57±2.08	3.53±3.61
F^{disc}	1±0	1±0	1±0	1±0	1±0
F^{coll}	0.945±0.071	0.911±0.098	0.943±0.094	0.892±0.133	0.769±0.235
F^{wall}	0.997±0.008	1±0	0.997±0.018	0.998±0.015	0.941±0.171
F^{cluster}	1±0	1±0	1±0	1±0	1±0
F^{corr}	0.916±0.015	0.923±0.003	0.904±0.005	0.949±0.003	0.957±0.003
F^{speed}	0.938±0.062	0.923±0.006	0.857±0.007	0.934±0.005	0.908±0.012
F	0.812±0.101	0.776±0.086	0.728±0.075	0.789±0.120	0.629±0.227

Table S3. Explanation of flocking model parameters.

	param	**name** and description
Repulsion	r_0^{rep}	**Repulsion range**. The distance at which local repulsion kicks in. Larger values create sparser flocks with less collision. Optimization tends to increase this above intuitive levels together with decreased gain value, resulting in a smoother and spatially extended repulsive interaction. Suggested value scales linearly with flocking speed according to the optimization.
	p^{rep}	**Repulsion gain**. The strength of repulsion (analogous to the spring constant of the half-spring repulsion model). Higher values result in more emphasized repulsion which acts agains collisions in free space but also induces oscillations in confined spaces. Should be tuned together with repulsion range.
Friction	r_0^{frict}	**Stopping point offset of alignment**. The distance of the stopping point in front of agents according to the optimal velocity reduction curve. Below this value alignment reduces all velocity difference above the given small velocity slack threshold. Optimization tends to increase this value above intuitive levels to maximize inter-agent alignment in the whole communication range without spatial dependence.
	C^{frict}	**Coefficient of velocity alignment**. Linear coefficient of the velocity difference error reduction in the velocity alignment term. Higher values create stronger damping between agents which helps reducing repulsion-induced oscillations but makes motion more sluggish. Optimization tends to decrease this value below intuitive levels.
	v^{frict}	**Velocity slack of alignment**. This parameter sets the velocity difference level agents are allowed to have at all times. Having a non-zero value reduces local overdamped dynamics a bit and thus increases the information spreading capability within the flock during turns, which results in increased flock-level agility around obstacles and at walls. Some velocity slack also helps eliminating roll and pitch oscillations arising in real systems due to strong alignment and the delayed response between tilting and velocity change. Should be kept at small levels as too large values disable alignment completely.
	p^{frict}	**Gain of braking curve**. Linear gain of the optimal braking curve used in determining the maximal allowed velocity difference. Note that linearity is only expressed in the v-x plane, while the parameter has a nonlinear effect in behaviour. Large values approximate the braking curve to the curve of constant acceleration. Small values elongate the final part of braking (at small speeds) with decreasing acceleration and smoother stops.
	a^{frict}	**Acceleration of braking curve**. The maximal allowed acceleration in the optimal braking curve used for determining the maximal allowed velocity difference between agents. Higher values assume that agents can brake quicker and thus make aligment more local. Too high values result in the inability of agents to react to too large velocity differences in time and thus lead to collisions.

param		**name** and description
Wall	r_0^{shill}	**Stopping point offset of walls**. This parameter is the same as r_0^{frict} but for wall alignment interactions. Larger values make agents start to brake at larger distances from walls.
	v^{shill}	**Velocity of virtual shill agents**. Wall alignment uses shill agents with this velocity magnitude. These virtual agents move inwards from walls and outwards from obstacles. Shill agent velocity is typically at least twice as large as the flocking speed as wall-agent interactions are not symmetric (shill agents do not align) thus agents need to take care of reducing the full velocity difference themselves. Larger values push agents away from walls with higher intensity and implicitely also at higher distances already. Suggested value scales linearly with flocking speed according to the optimization.
	p^{shill}	**Gain of braking curve for walls**. This parameter is the same as p^{frict} but for wall alignment interactions.
	a^{shill}	**Acceleration of braking curve for walls**. This parameter is the same as a^{frict} but for wall alignment interactions.
Spp	v^{flock}	**Flocking speed**. The preferred speed of the agents. Higher values in general require stronger repulsion and larger shill agent velocity.
	v^{max}	**Maximum speed**. The maximal allowed speed of the agents. Should be higher than flocking speed. If too high, cumulated interaction terms can speed up agents too much, which can be dangerous.

Table S4. Model parameter values used on real drones. Values are mostly within the optimal working ranges of the simulation with some notable expections (highlighted with bold face), mostly due to the precautious attutide necessary in real experiments. The changes from simulation optima are explained for each parameter in the last column. Values are shown for different flocking speeds in different columns.

	param	unit	4 m/s	6 m/s	8 m/s	comments on tuning
Rep.	r_0^{rep}	m	**15**	35	50	At 4 m/s system was safe enough to reduce repulsion range and get a tighter flock.
	p^{rep}	1/s	**0.3**	**0.1**	**0.1**	Gain was somewhat increased as a precaution to prevent collisions.
Friction	r_0^{frict}	m	45	65	80	
	C^{frict}	-	**0.5**	**0.5**	**0.5**	Increased substantially to minimize possible oscillations.
	v^{frict}	m/s	1	2	2	
	p^{frict}	1/s	1	1	1	Some reasonable value was selected as optimization neglected this parameter with high r_0^{frict}.
	a^{frict}	m/s/s	3	3	3	Some reasonable value was selected as optimization neglected this parameter with high r_0^{frict}.
Wall	L^{arena}	m	200	260	260	
	r_0^{shill}	m	0	**5**	**30**	Increased distance from walls and obstacles as a precaution.
	v^{shill}	m/s	10	**14**	**14**	Decreased shill velocity is enough when r_0^{shill} is higher, resulting in lower interaction magnitudes at walls.
	p^{shill}	1/s	2	2	2	
	a^{shill}	m/s/s	2.5	2.5	2.5	

Table S5. Environmental parameters of the realistic setup.

parameter name	symbol	value	unit
communication delay	t^{del}	1	s
velocity relaxation time	τ^{CTRL}	1	s
maximal acceleration	$a^{\max}$	6	$\mathrm{m/s^2}$
communication range	r^{c}	80	m
sensor update rate	t^{s}	0.2	s
sensor noise	σ^{s}	0.005	$\mathrm{m^2/s^2}$
outer noise	σ	0.2	$\mathrm{m^2/s^3}$

Table S6. Parameter settings of the evolutionary optimization. The used CMA-ES optimizer algorithm was obtained from https://pypi.python.org/pypi/cma). The most important parameter values are shown below. Parameters not listed here were used with default values.

parameter name (meaning)	value
population size	100
termination condition	150 generations
elitist survivor selection	False
variable mutation step sizes	True
dimension of parameter space	11