

RVC-NMPC: Nonlinear Model Predictive Control with Reciprocal Velocity Constraints for Mutual Collision Avoidance in Agile UAV Flight

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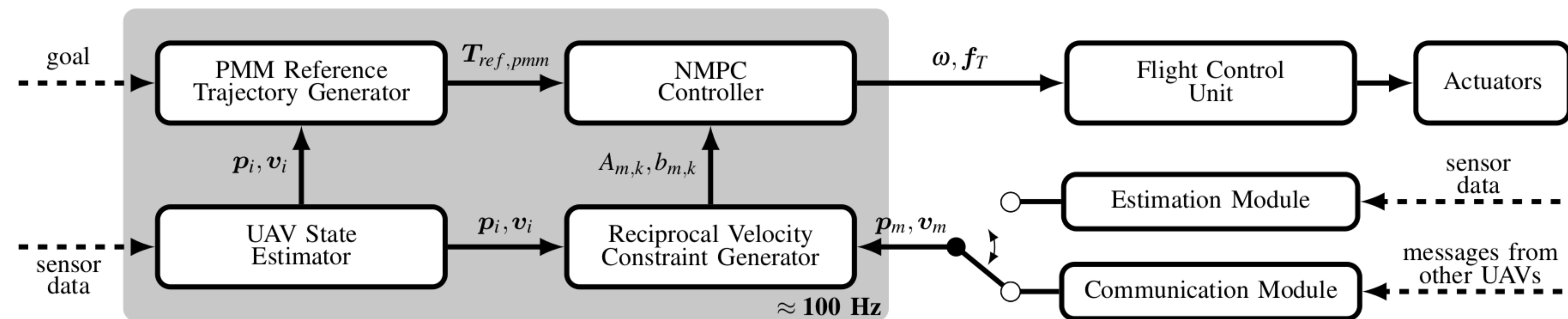
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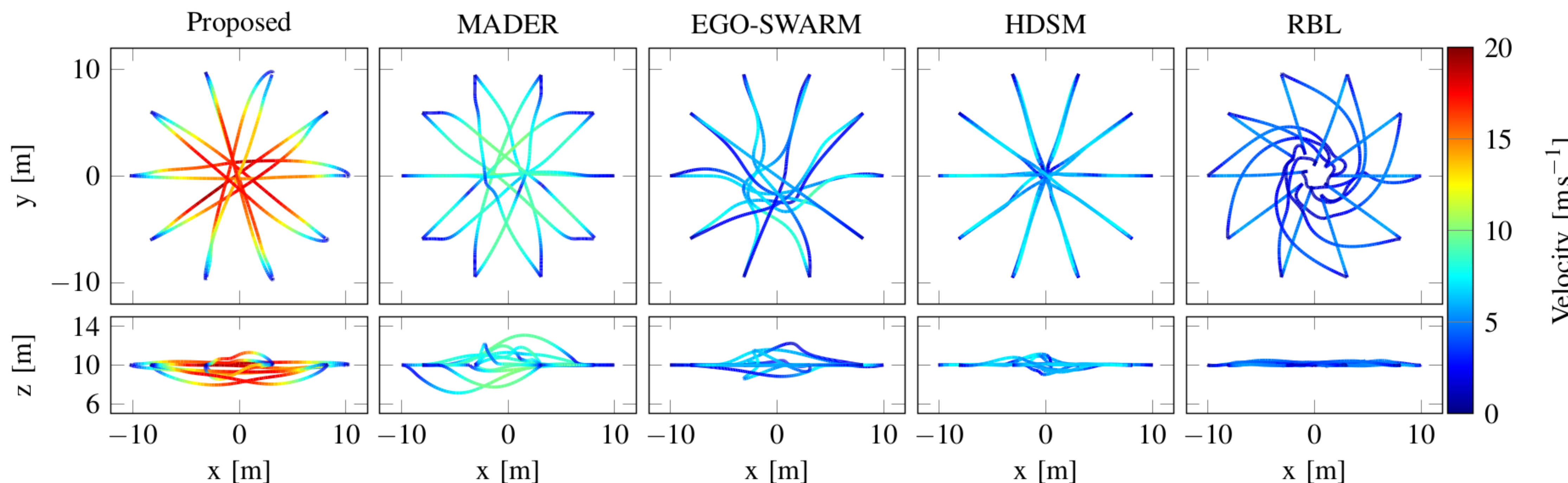
SUMMARY

We present an approach to **mutual collision avoidance** for an agile UAV flight based on **Nonlinear Model Predictive Control (NMPC)** with time-dependent **Reciprocal Velocity Constraints (RVCs)**. It relies solely on observable information about other robots, reducing communication needs. An efficient RVC computation, **integrated into NMPC on a control level**, enables real-time control at 100 Hz. The method was evaluated through extensive simulations in scenarios involving up to 10 UAVs and **velocities of up to 25 m s^{-1}** , and in real-world experiments with **accelerations up to 30 m s^{-2}** .

BLOCK DIAGRAM OF A SINGLE ROBOT CONTROL AND NAVIGATION PIPELINE



QUANTITATIVE AND QUALITATIVE COMPARISON WITH STATE OF THE ART



Approach	max. vel.	Success rate [%]	Flight time [s]		Flight distance [m]		Flight velocity [m s^{-1}]		Min. mutual dist. [m]	
	max. acc.		mean	std. dev.	mean	std. dev.	mean	std. dev.	mean	min
MADER [1] - per axis	20 m s^{-1}	94.0	5.31	0.53	21.13	0.21	4.75	0.17	0.75	0.38
MADER [1] - norm		98.0	5.28	0.35	20.93	0.20	4.70	0.16	0.72	0.51
EGO-SWARM-2 [2]		99.0	8.16	0.50	21.15	0.37	3.61	0.22	0.67	0.47
HDSM [3] - per axis		100.0	3.43	0.17	20.43	0.10	6.96	0.16	0.67	0.57
HDSM [3] - norm	40 m s^{-2}	100.0	4.46	0.19	20.50	0.10	4.78	0.18	0.67	0.56
RBL [4]		100.0	11.59	0.74	26.20	0.83	2.54	0.05	0.87	0.63
Proposed		100.0	3.07	0.08	21.15	0.06	7.36	0.06	0.98	0.81
Proposed with drag		100.0	3.84	0.06	21.62	0.05	5.93	0.05	0.98	0.82

Figure 1: Comparison of approaches for the solution of a simultaneous navigation of 10 UAVs to antipodal positions on a circle of radius 10 m. The results are averaged over 100 trials. The robots are considered to be spheres with a radius 0.25 m for collision avoidance evaluation. The individual approaches have been parametrized with a focus on minimization of flight time while keeping the success rate close to 100%. The experienced collisions, deadlocks and optimization failures causing drops in success rates could be avoided by choosing another parametrization as the authors of all compared methods demonstrated 100% success rate in evaluations of their methods. Terms *norm* and *per axis* indicate whether the per axis kinematic constraints are adjusted such that they guarantee that the norm of the velocity and acceleration will not exceed the limit, or whether they are applied per axis, which can lead to violation of given constraints.

KEY FEATURES AND PERFORMANCE METRICS

- Distributed approach to collision avoidance based on current position and velocity of other robots only.
- Reciprocal velocity constraints for mutual collision avoidance integrated on the controller level.
- Suitable for high-speed navigation. Tested with velocities and accelerations up to 25 m s^{-1} , and 40 m s^{-2} .
- Validated in three-hour-long simulation during which 10 UAVs navigated to more than 50000 random goals in a small environment without experiencing a collision.
- More than 31% reduction in flight time compared to state-of-the-art methods in challenging scenarios.
- Computational efficiency: algorithm along with the entire navigation pipeline runs on 100 Hz even on computer with 2 GHz ARM processor.
- Real-world validation: experiments with three UAVs, acceleration limits 30 m s^{-2} and velocities up to 18 m s^{-1} .

TIME-DEPENDENT RECIPROCAL VELOCITY CONSTRAINTS

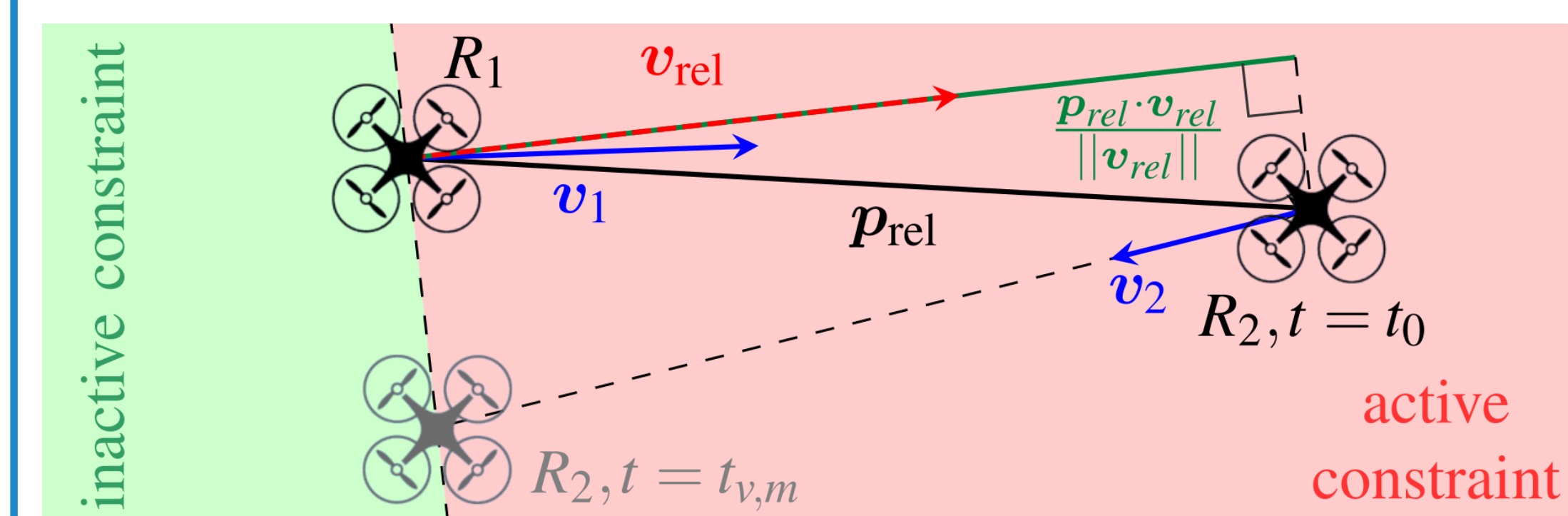
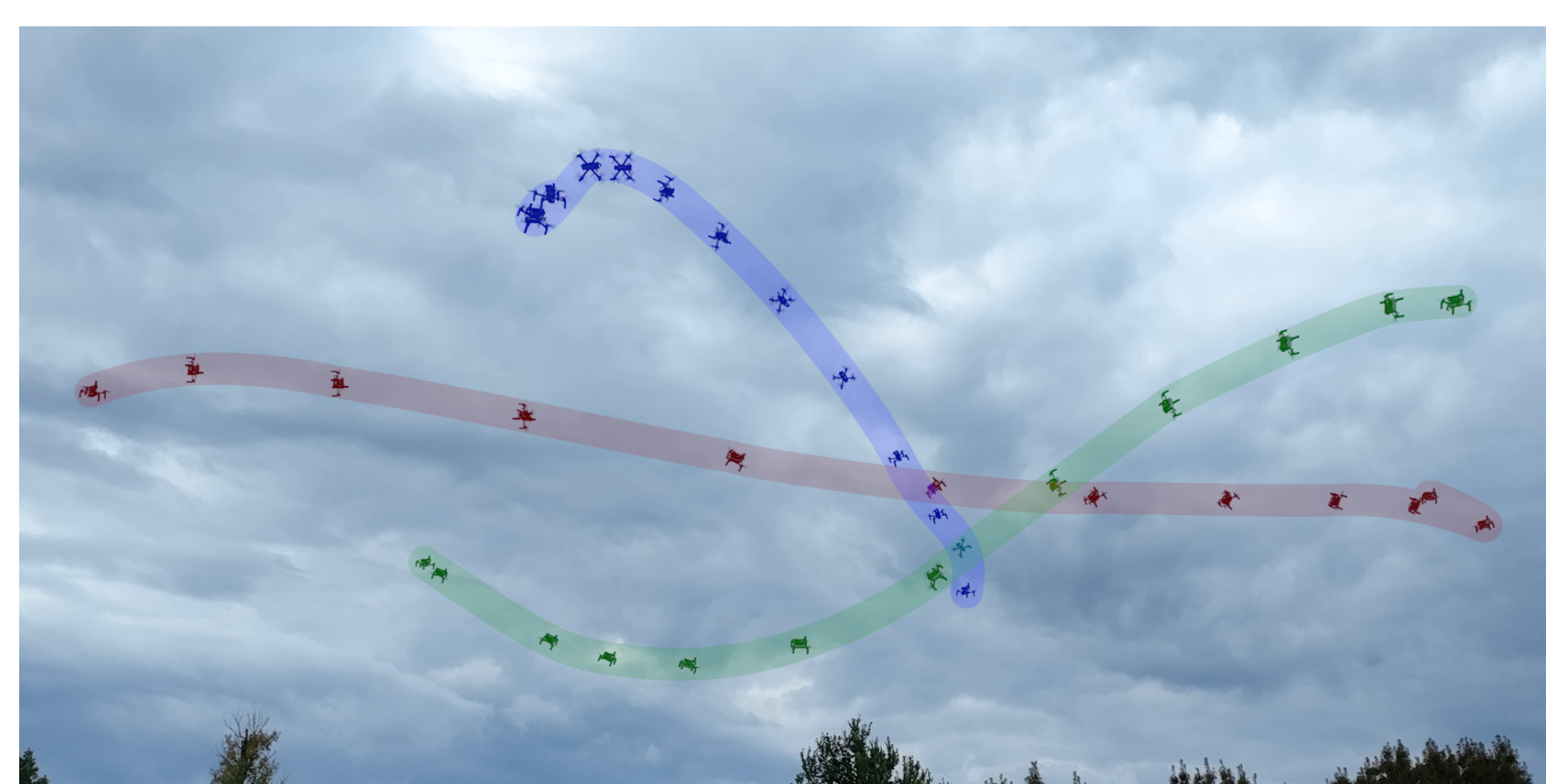


Figure 2: The illustration of the introduced time validity of the reciprocal velocity constraints based on concept of velocity obstacles.

REAL-WORLD VALIDATION



Ref. acc. [m s^{-2}]	Number of flights [-]	Flight time [s]		Flight dist. [m]	Max. vel. [m s^{-1}]	Min. dist. [m]	
		mean	min			mean	min
20.0	2	5.84	3.94	23.46	13.88	2.59	1.79
30.0	7	4.18	3.49	23.35	17.74	2.61	2.20

ANALYSIS OF ROBUSTNESS OF THE RVC-NMPC APPROACH TO DATA LATENCY AND NOISE IN STATE ESTIMATION

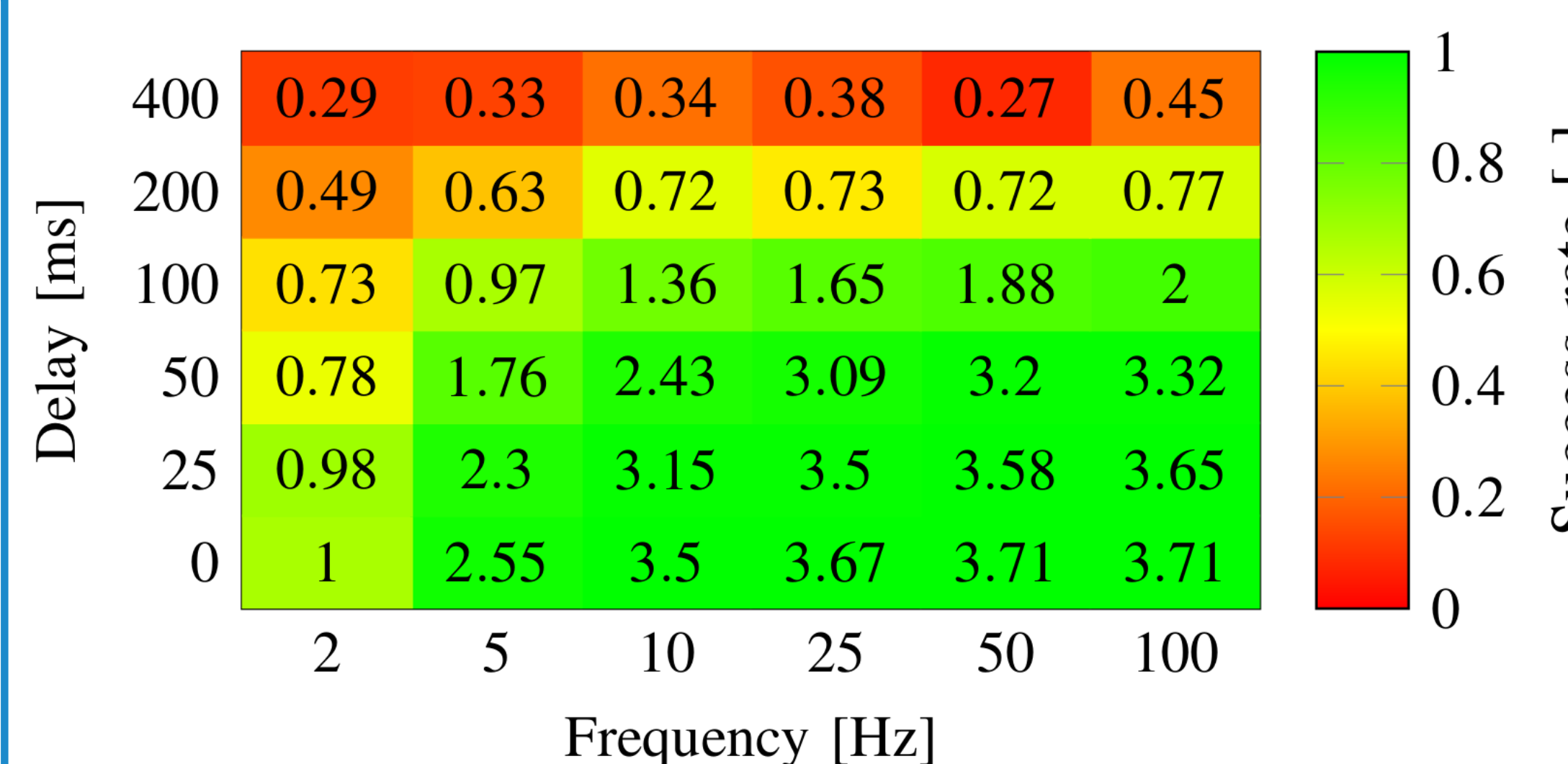


Figure 3: The success rate (shown in colors of the matrix) and minimum mutual distance between uav (shown as numbers in the matrix [m]) under varying delay and frequency of messages obtained from other robots. The results for every delay-frequency pair are based on 100 flights involving 4 uav in APCX scenario.

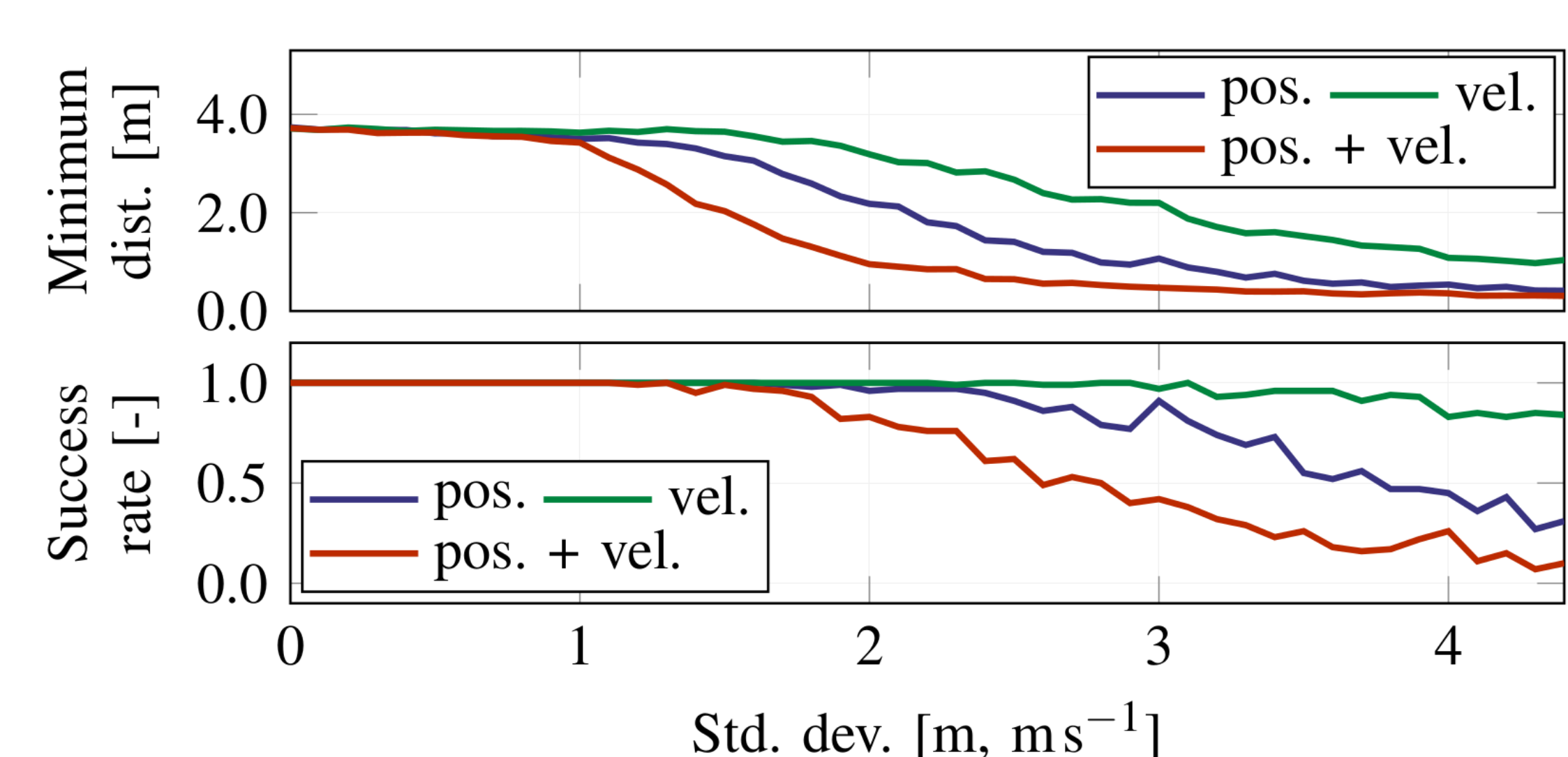


Figure 4: The minimum mutual distance between uav and a success rate under varying noise in estimation of position and velocity of other robots. The results for every standard deviation are based on 100 flights involving 4 uav in APCX scenario.

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