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Reliable motion planning and coordination for a team of aerial drones

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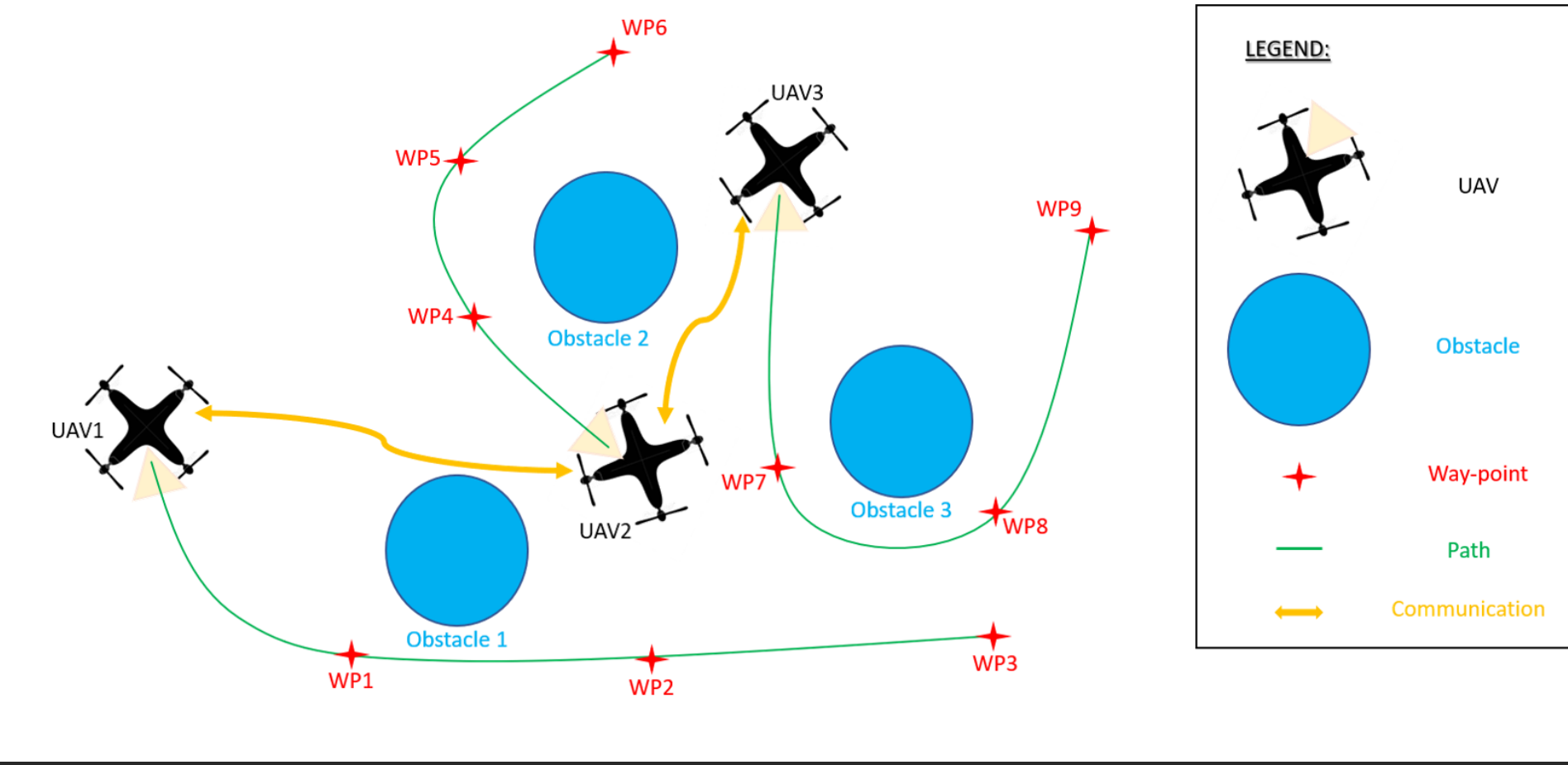
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Context

Unmanned Aerial Vehicles (UAVs) technology starts to support the agricultural domain in monitoring the land for checking and countering the presence of parasites that can damage the crop.

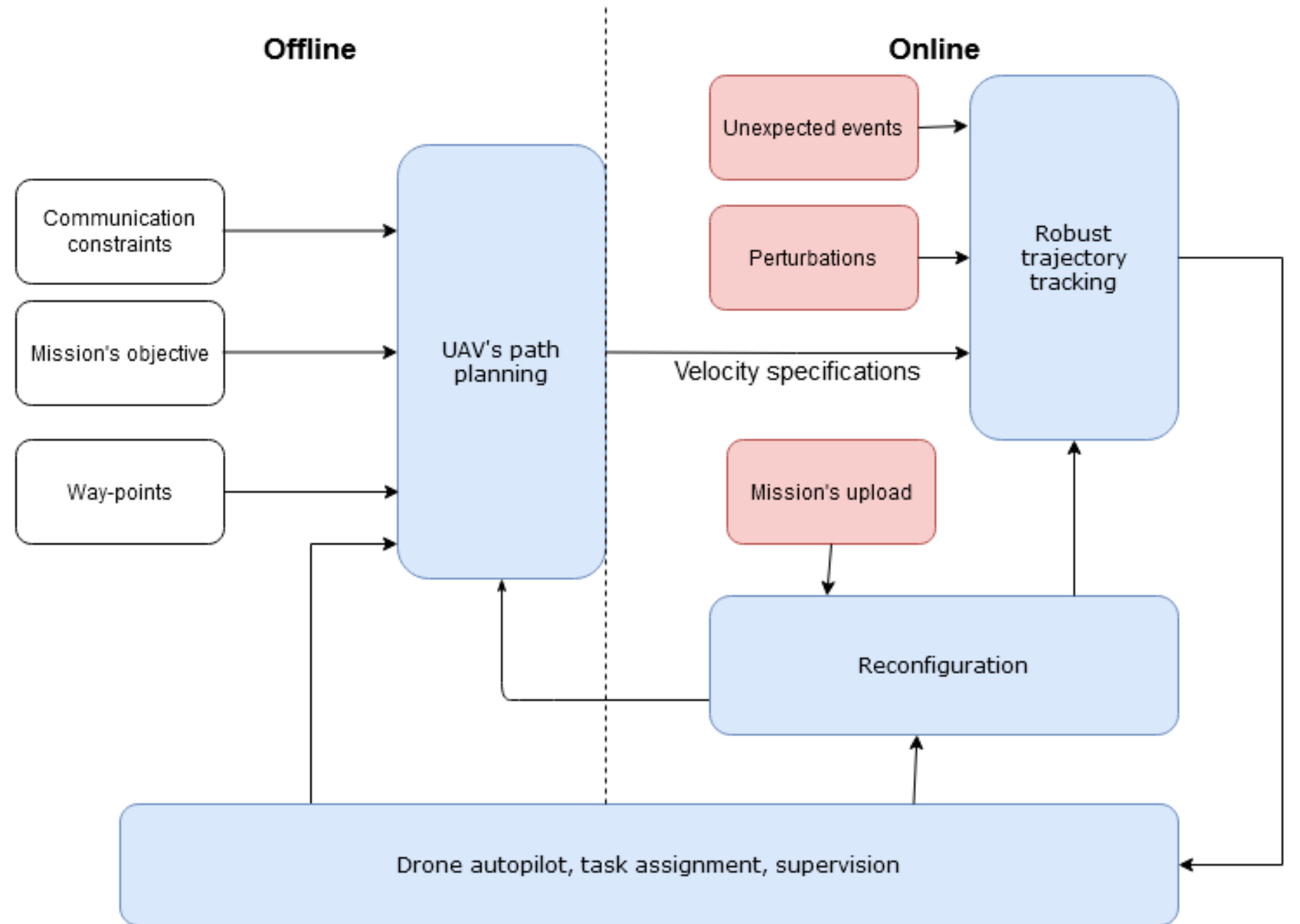


To properly manage a UAVs team, equipped with multiple sensors and actuators, it is necessary to test these technologies and design *reliable coordination strategies able to efficiently manage the team.*



Motion planning strategy

The motion planning scheme we adopt is decomposed into offline optimal trajectories generation and online tracking.



Exploit the properties of B-spline curves

We consider the parametrization of the trajectories with B-spline curves, $z(t) = \mathbf{P}\mathbf{B}_{d,\xi}(t), \forall t \in [t_0, t_N]$, with \mathbf{P} the position matrix of the control points with appropriate dimension, $\mathbf{B}_{d,\xi}(t)$ the basis function and $\xi = \{\tau_1 \leq \tau_2 \leq \dots \leq \tau_m\}$ a knot sequence. If $m \geq d + 2$, we can define B-splines of degree d over the knot sequence [3].

Properties of B-splines:

1) Local support:

$$B_{i,d,\xi}(t) = 0, \forall t \notin [\tau_i; \tau_{i+d+1}]$$

2) Global partition of unity:

$$\sum_{i=1}^n B_{i,d,\xi}(t) = 1, \forall t \in [\tau_{d+1}; \tau_{n+1}]$$

3) Global convexity:

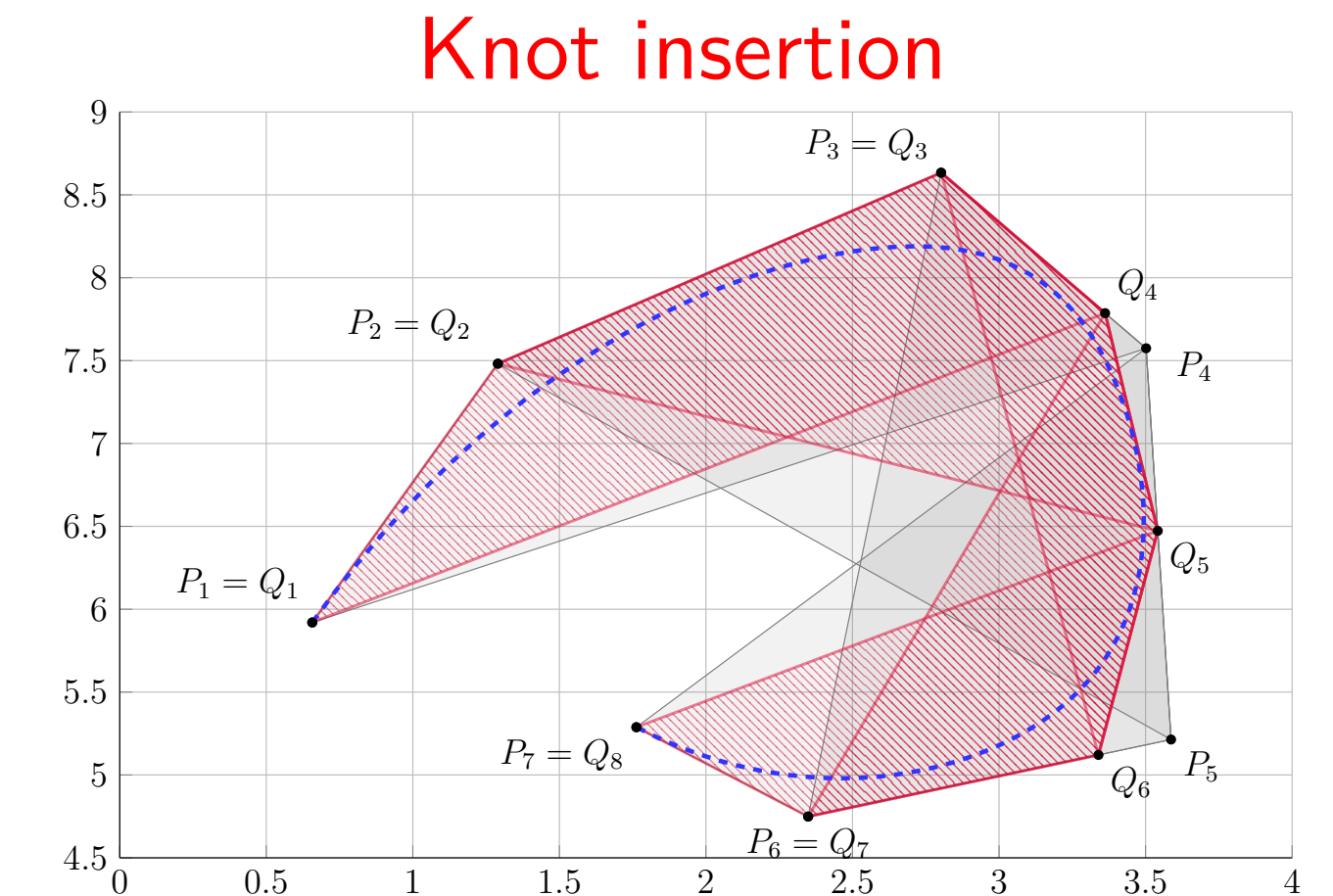
$$z(t) = \sum_{i=1}^n P_i B_{i,d,\xi}(t), \forall t \in [\tau_{d+1}; \tau_{n+1}]$$

4) Smoothness:

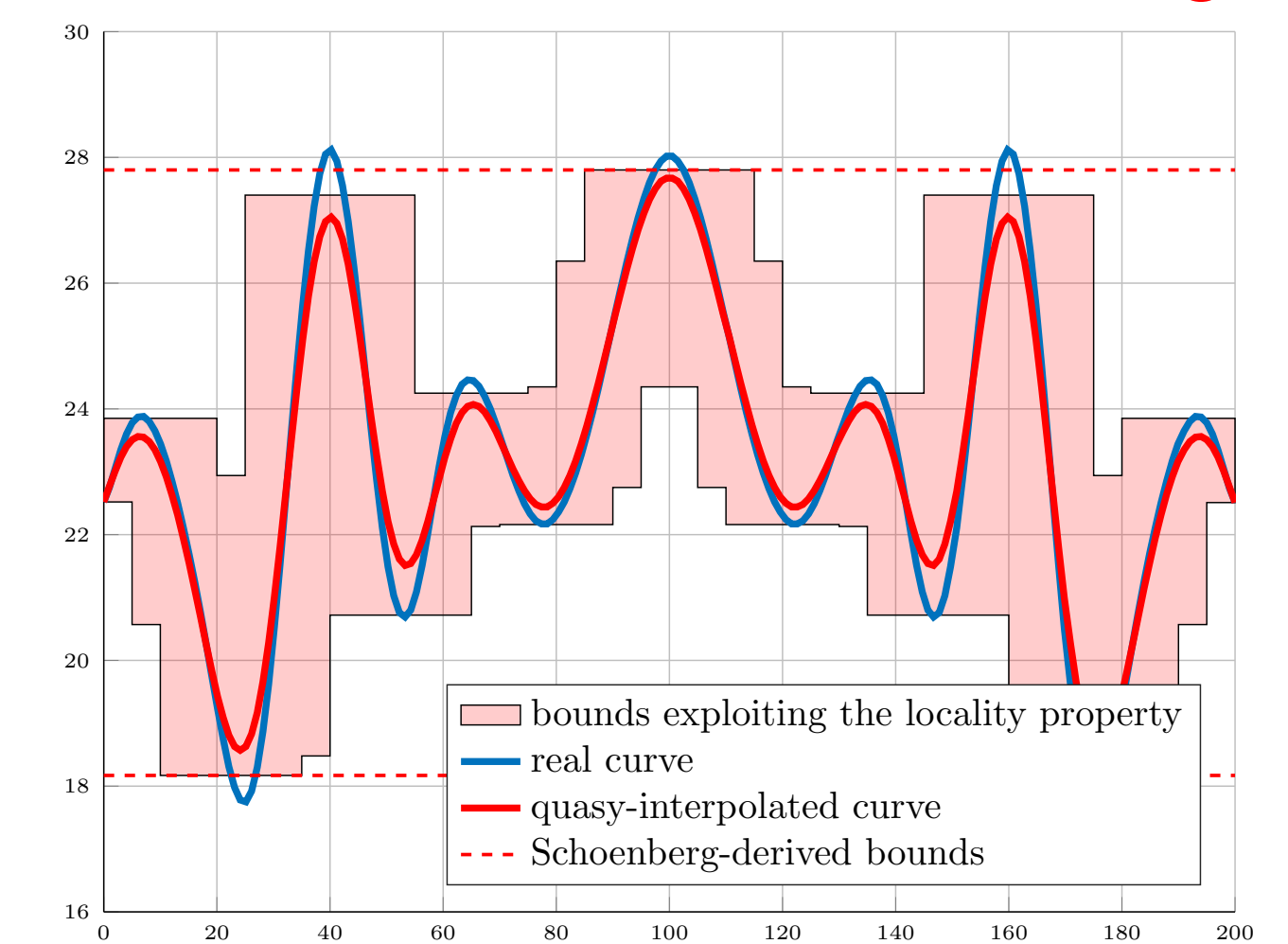
$$B_{i,d,\xi}(\tau_l) \in \mathcal{C}^{d-\mu_l} \text{ at } \tau_l \in \xi \text{ with multiplicity } \mu_l \text{ and } \mathcal{C}^\infty \text{ otherwise.}$$

5) Convexity property:

The curve lies within the union of convex hull defined by subsets of consecutive control points.



Approximation based on the Schoenberg operator



Offline trajectory generation Solve the constrained optimization problem [1]:

$$\min_P \sum_{l=1}^{n_{drones}} \int_{t_0}^{t_N} \|\dot{z}_l(t)\| dt = \min_P \sum_{l=1}^{n_{drones}} \sum_{i=1}^{n+1} \sum_{j=1}^{n+1} \int_{t_0}^{t_N} (P_{l,i} M_1)^T B_{i,d-1}(t) B_{j,d-1}(t) (P_{l,j} M_1) dt$$

$$\text{s.t.} \begin{cases} \text{initial positions} \\ \text{waypoint passing: } \forall k \in \{0; N\}, P_1 B_d(t_k) = w_k \\ \text{communication maintenance with the previous agent } l-1: \\ A_{comm}(P_l - P_{l-1}) \cdot B_d(t) < b_{comm} \quad \forall l \in \{2, n_{drones}\} \\ \text{communication maintenance with the ground station:} \\ A_{comm}(P_{n_{drones}} - Position_{base}) \cdot B_d(t) < b_{comm} \end{cases}$$

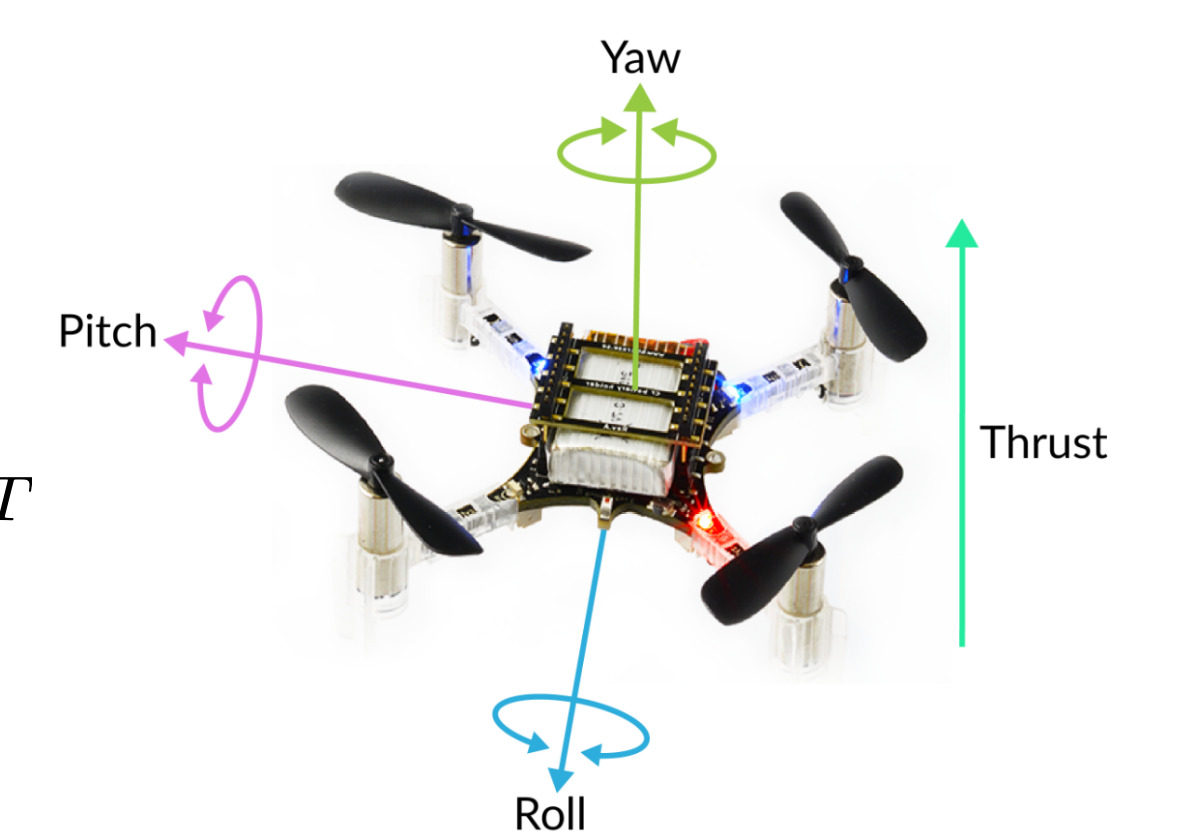
Control of the Crazyflie

Consider the dynamical model of a quadcopter [2]:

$$\dot{x}(t) = Ax(t) + h_\psi(t), \text{ with } A = \begin{bmatrix} 0_{3 \times 3} & I_3 \\ 0_{3 \times 3} & 0_{3 \times 3} \end{bmatrix},$$

the state $x = [\xi v]^T = [x y z v_x v_y v_z]^T$, the input $u = [T \phi \theta]^T$ and

$$h_\psi = \begin{bmatrix} 0_{1 \times 3} & T(c\phi s\theta c\psi + s\phi s\psi) & T(c\phi s\theta s\psi - s\phi c\psi) & -g + Tc\phi c\theta \end{bmatrix}^T$$



Online trajectory tracking Design a nonlinear predictive controller:

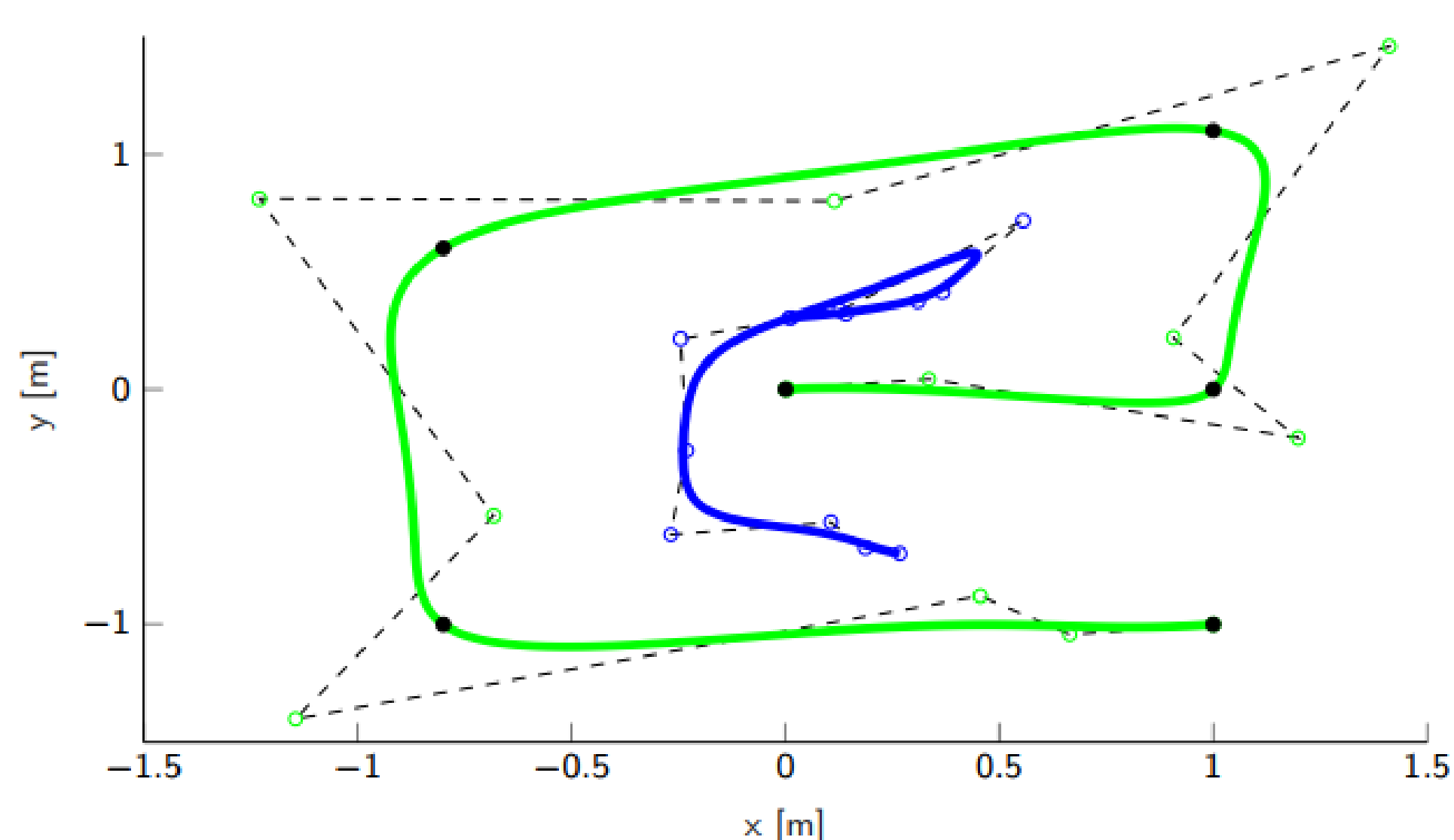
$$u^* = \min_u \sum_{s=0}^{N_{pred}-1} \left(\|\xi(k+s) - z(k+s)\|_Q^2 + \|u(k+s) - u_{eq}\|_R^2 \right) + \|\xi(k+N_{pred}) - z(k+s)\|_P^2$$

with the reference $z(k)$, the equilibrium input value $u_{eq} = [g \ 0 \ 0]^T$ and the prediction horizon N_{pred} .

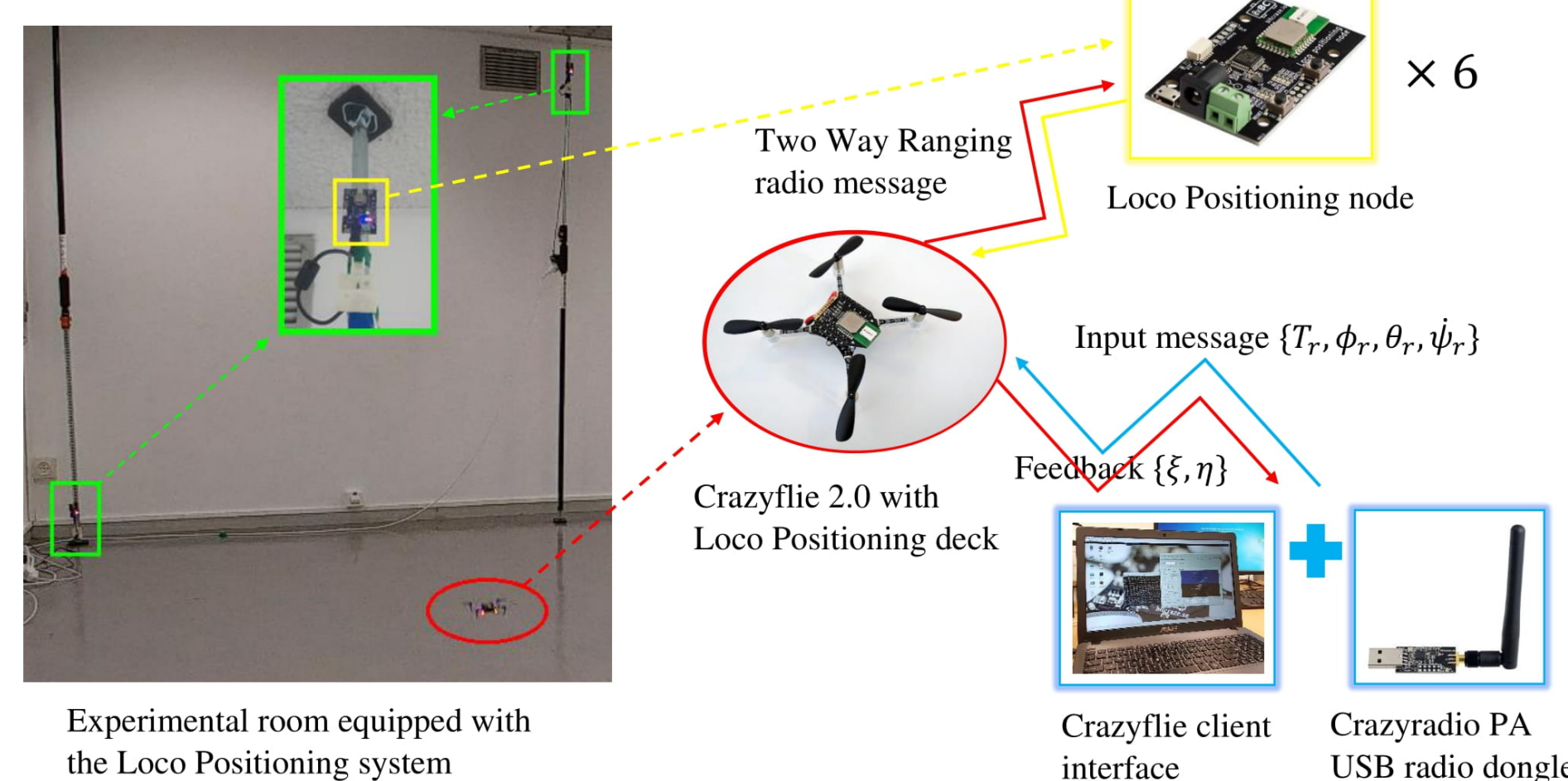
Experimental setup and tests at the Esisarium platform

Scenario: Consider two drones which pass through a collection of waypoints while maintaining a communication range of 0.8m.

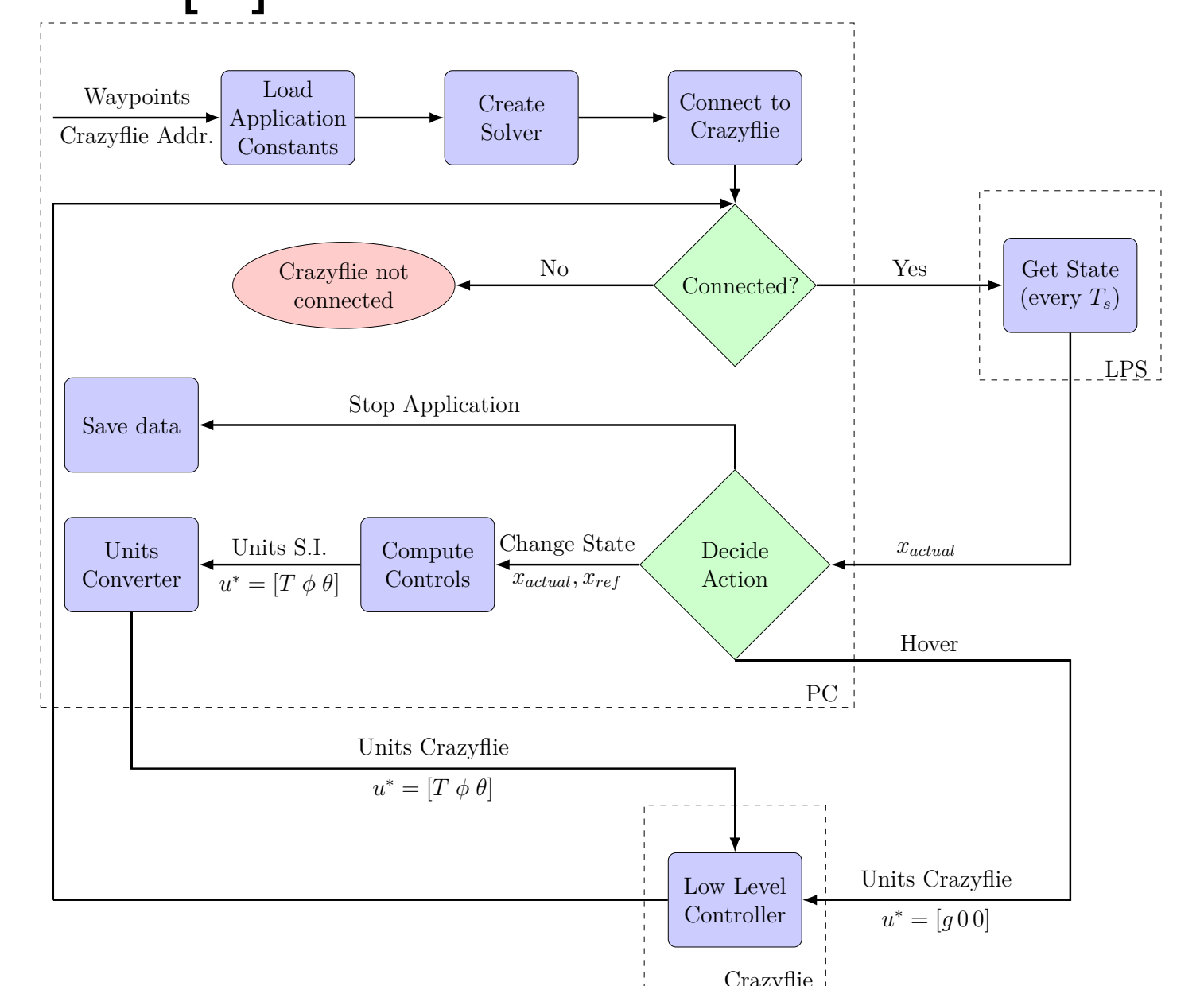
Implementation specifications: B-splines of order 5, $N_{pred} = 20$, sampling time for the controller of 0.1 [s], acquisition rate of the computed position and orientation of 34 Hz, mean computing time of the NMPC controller 55 [ms], initial thrust sent to the drones of 9.81 [N].



Actual motion of the two drones.



Loco Positioning and Lighthouse Systems



Flowchart for implementation

[1] Yoann Hervagault, Ionela Prodan, Laurent Lefevre: *Motion planning for USVs with communication guarantees: An experimental setup* 2019 18th European Control Conference (ECC). IEEE, 2019. p. 3984-3989.

[2] Ngoc Thinh Nguyen, Ionela Prodan: *Stabilizing a multicopter using an NMPC design with a relaxed terminal region* IFAC-PapersOnLine 54.6 (2021). p. 126-132.

[3] Florin Stoican, Alexandru Postolache, Ionela Prodan: *NURBS-based trajectory design for motion planning in a multi-obstacle environment* 2021 European Control Conference (ECC). IEEE, 2021. p. 2014-2019.