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To cite this version:

Vincent Marguet, Bogdan Gheorghe, Ionela Prodan, Florin Stoican. Reliable motion planning and coordination for a team of aerial drones. Journée des doctorants 2022, Jun 2022, Grenoble, France. hal-03701687

HAL Id: hal-03701687

https://hal.univ-grenoble-alpes.fr/hal-03701687

Submitted on 22 Jun 2022

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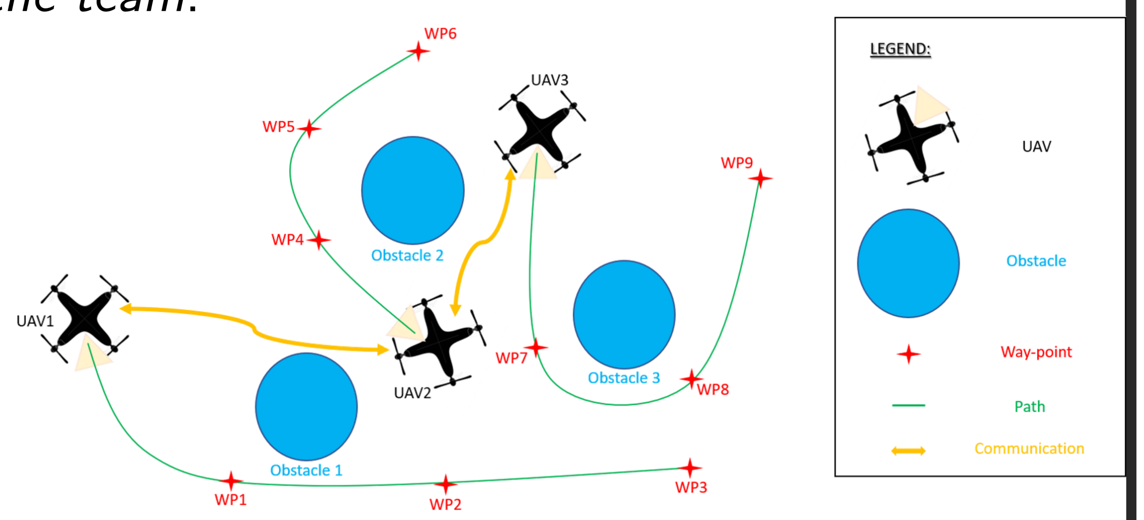
Reliable motion planning and coordination for a team of aerial drones

Vincent Marguet[1], Bogdan Gheorghe[1,2], Ionela Prodan[1], Florin Stoican[2]
[1] Univ. Grenoble Alpes, Grenoble INP†, LCIS, F-26000, Valence, France
†Institute of Engineering and Management Univ. Grenoble Alpes
[2] Department of Automatic Control and Systems Engineering, UPB, Bucharest, Romania
{vincent.marguet, ionela.prodan}@lcis.grenoble-inp.fr

Context

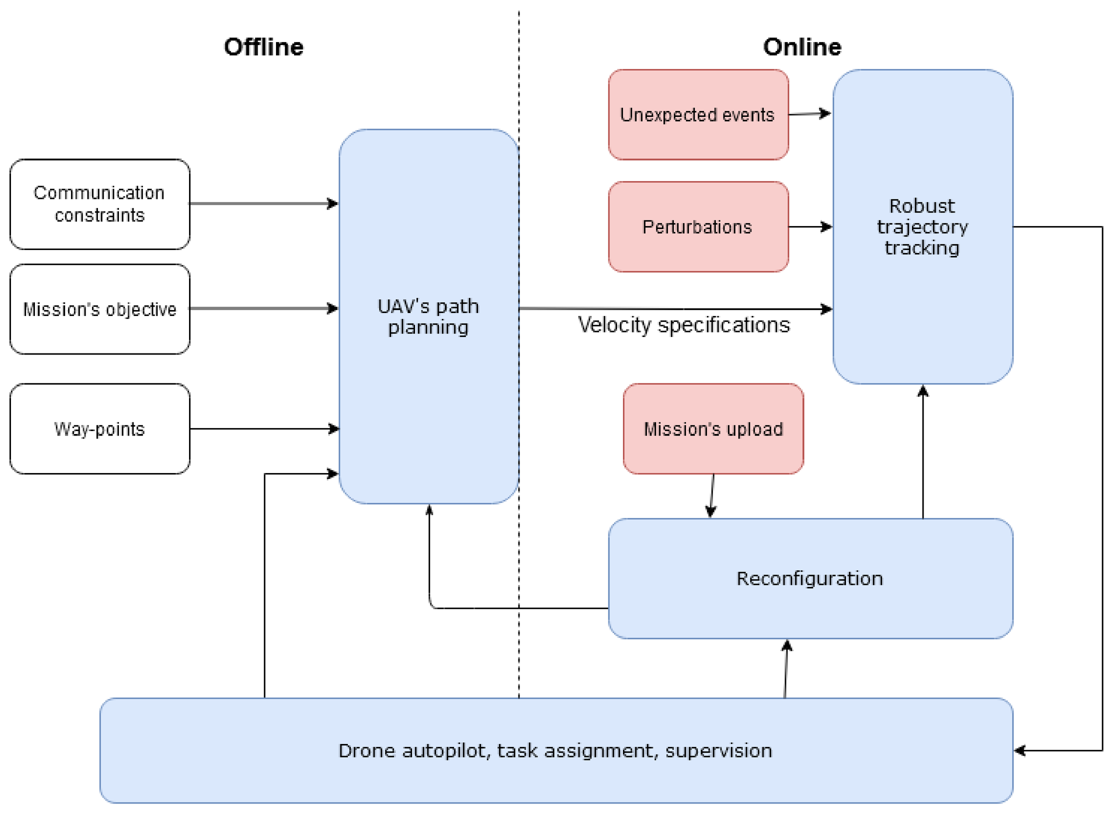
Unmanned Aerial Vehicles (UAVs) technology starts to support the agricultural domain in monitoring the land for checking and countering the presence of parasites that can damage the crop.

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 $\xi = \{\tau_1 \leq \tau_2 \leq \ldots \leq \tau_m\}$ 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:
$B_{i,d,\xi}(t) = 0,\ \forall t \notin [\tau_i; \tau_{i+d+1})$

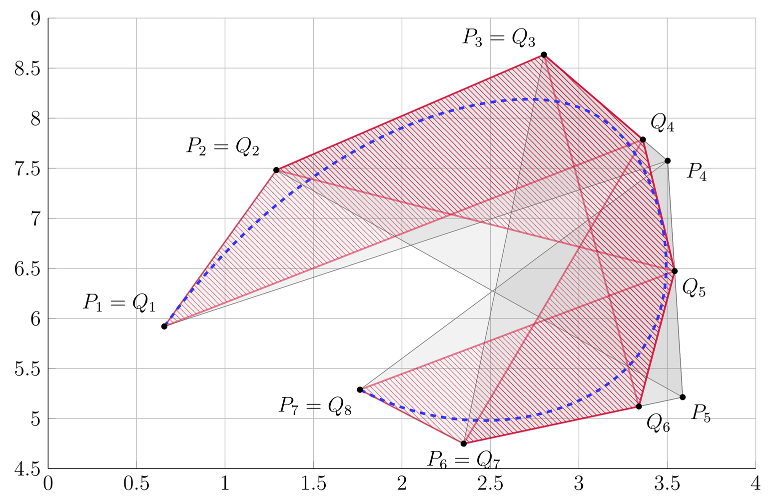
2) Global partition of unity:
$\sum_{i=1}^{n} B_{i,d,\xi}(t) = 1,\ \forall t \in [\tau_{d+1}; \tau_{n+1})$

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

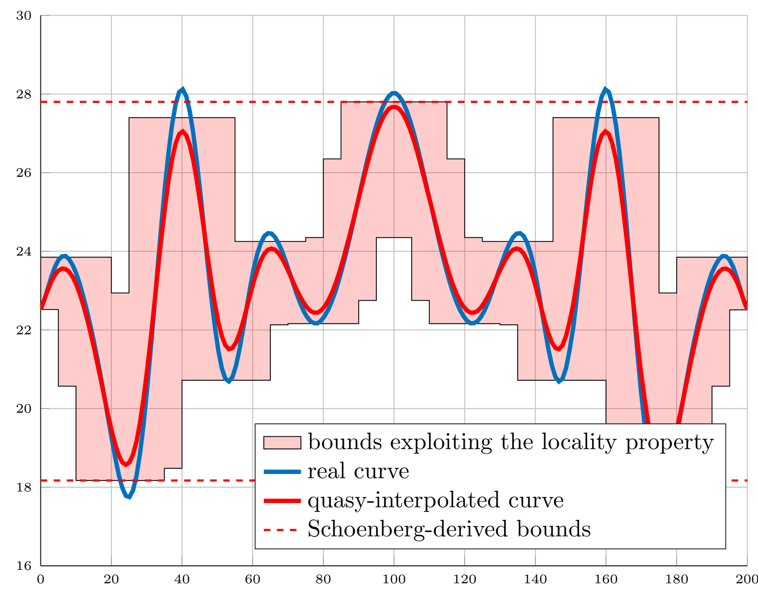
4) Smoothness:
$B_{i,d,\xi}(\tau_l) \in \mathcal{C}^{d-\mu_l}$ at $\tau_l \in \xi$ with multiplicity μ_l and $\mathcal{C}^{\infty}$ otherwise.

5) Convexity property:
The curve lies within the union of convex hull defined by subsets of consecutive control points.

Knot insertion



Approximation based on the Schoenberg operator



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

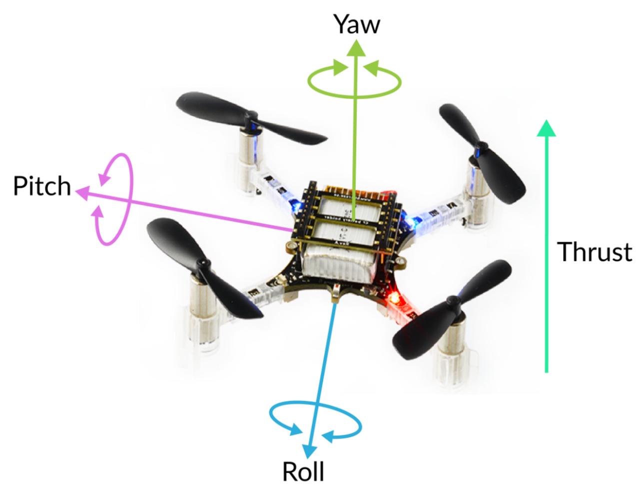
$$\min_{P} \sum_{l=1}^{n_{drones}} \int_{t_0}^{t_N} ||\dot{z}_l(t)||dt = \min_{\mathbf{P}} \sum_{l=1}^{n_{drones}} \sum_{i=1}^{n+1} \sum_{j=1}^{n+1} \int_{t_0}^{t_N} (P_{l,i}M_1)^T B_{i,d-1}(t) B_{j,d-1}(t)(P_{l,j}M_1)dt$$

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

Control of the Crazyflie

Consider the dynamical model of a quadcopter [2]:

$\dot{x}(t) = Ax(t) + h_{\psi}(t)$, with $A = \begin{bmatrix} 0_{3x3} & I_3 \\ 0_{3x3} & 0_{3x3} \end{bmatrix}$,
the state $x = [\xi\ v]^T = [x\ y\ z\ v_x\ v_y\ v_z]^T$, the input $u = [T\ \phi\ \theta]$ and
$h_{\psi} = \begin{bmatrix} 0_{1x3} & T(c\phi\, s\theta\, c\psi + s\phi\, s\psi) & T(c\phi\, s\theta\, s\psi - s\phi\, c\psi) & -g + Tc\phi\, c\theta \end{bmatrix}^T$



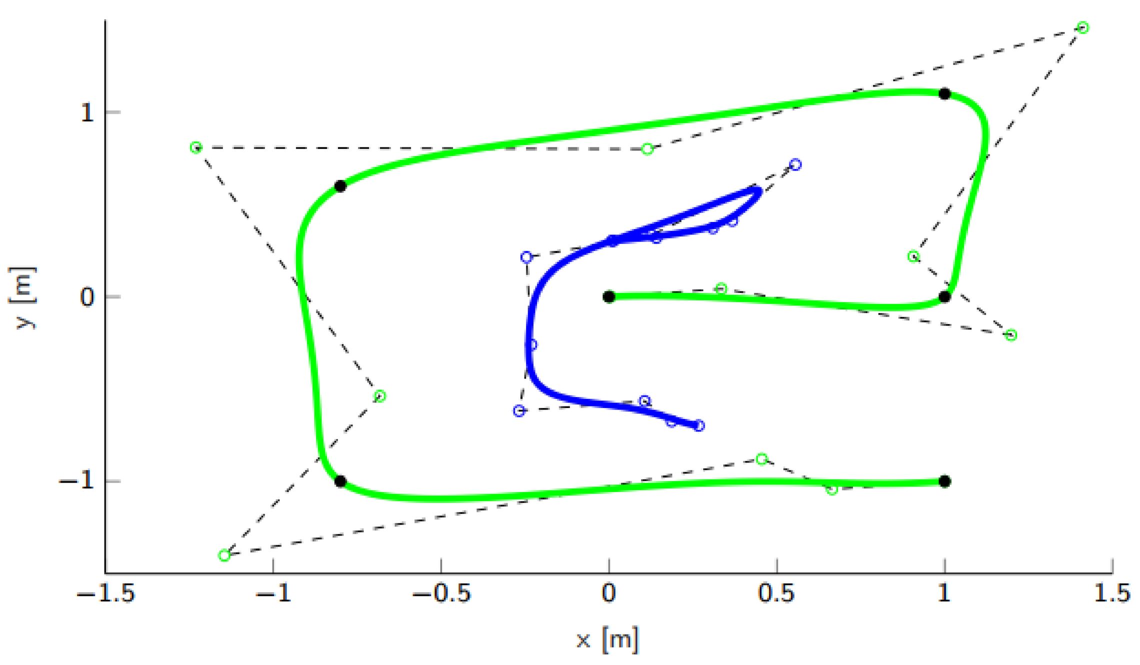
Online trajectory tracking Design a nonlinear predictive controller:

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

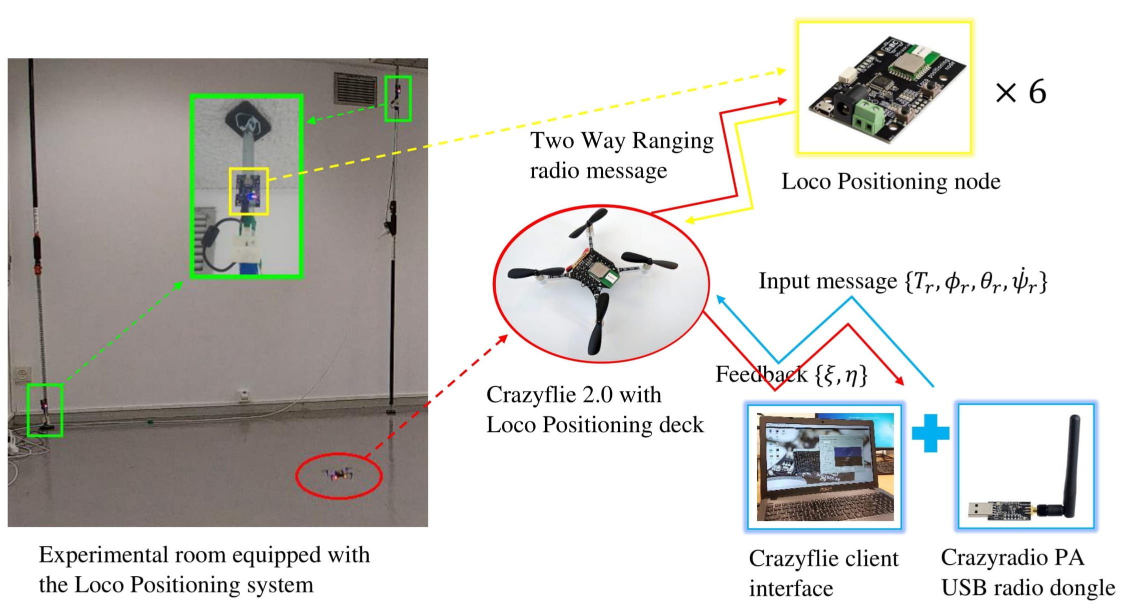
with the reference $z(k)$, the equilibrium input value $u_{eq} = [g\ 0\ 0]^{\top}$ and the prediction horizon N_{pred}.

Experimental setup and tests at the Esisarium platform

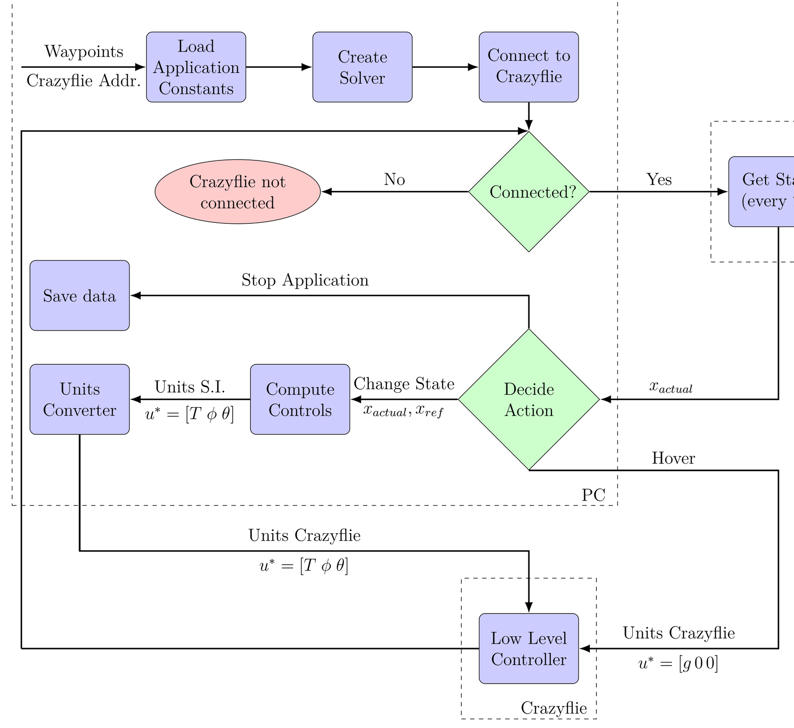
Scenario: Consider two drones which pass through a collection of waypoints while maintaining a communication range of 0.8m.
Implementation specifications: B-splines of order 5, $N_{pred} = 20$, sampling time for the controller of 0.1 [s], acquisition rate of the computed position and orientation of 34 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.

* This work is supported by the French National Research Agency in the framework of the « Investissements d'avenir » program « ANR-15-IDEX-02» and the LabEx PERSYVAL « ANR-11-LABX-0025-01».