Communications-aware trajectory planning formulations

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Half-day Tutorial Session at ICUAS 2026 (09:00 – 13:00), 15th June 2026
Room Calypso A – Divani Corfu Palace

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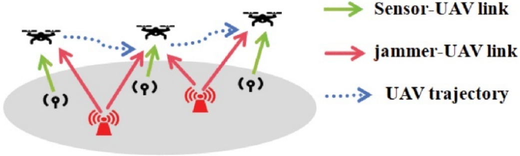
Communication-aware Robotics

What is Communication-aware Robotics?

Communication-aware Robotics is an **interdisciplinary** field that studies how the motion, position, and/or orientation of transceivers, mounted on robots, affect the communication. Some typical problems addressed are trajectory planning and positioning.



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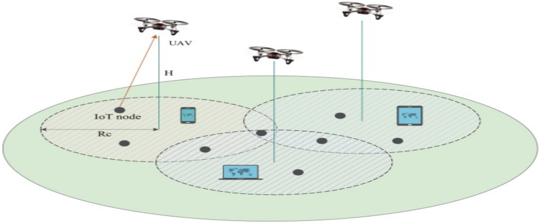

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Oversimplification

What is a model? What are its elements?

Modeling means describing something in terms of certain aspects of interest, such as:

- **Object representation**. What?
- **Model input**. Which ones?
- **Range of validity**. When?
- **Input-to-Object relation**. How?

$\longrightarrow$

$$\begin{aligned} \dot{\mathbf{x}} &= f(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} &= h(\mathbf{x}) \end{aligned}$$

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OVERSIMPLIFICATION OCCURS WHEN A MODEL IS USED OUTSIDE ITS RANGE OF VALIDITY.

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Oversimplification

When Robotics Oversimplifies Communication

- Inefficient energy usage.
- Infeasible or unsafe trajectories.
- Degraded system performance.

When Communications Oversimplifies Robotics

- Unrealistic assumptions on connectivity.
- Unexpected communication losses.

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INTERDISCIPLINARY APPROACHES ARE ESSENTIAL TO AVOID OVERSIMPLIFYING EITHER ROBOTICS OR COMMUNICATION ASPECTS.

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Interdisciplinary approaches are essential to avoid oversimplifying either robotics or communication aspects.

However, **overly complex models** are not the solution either.

Communication-Aware Trajectory Planning

Problem Formulation

The Communications-aware Trajectory Planning (CaTP) problem for a single robot can be structured as:

$$
\begin{aligned}
\underset{\mathcal{C},\mathcal{T}}{\text{minimize}} \quad & J(\mathcal{C},\mathcal{T}) \\
\text{s.t.} \quad & \text{Motion model,} \\
& \text{Channel model,} \\
& \text{Trajectory constraints,} \\
& \text{Communication constraints.}
\end{aligned}
$$

where:

- $\mathcal{C}$: communication-related optimization variables,
- $\mathcal{T}$: trajectory variables of the robot.

Energy-Efficient Trajectories (Unconstrained)

Convex Combination

$$\underset{\mathbf{u}}{\text{minimize}} \quad \vartheta\, E_{\text{mo}}(\mathbf{u}, 0, \mathcal{T}) + (1-\vartheta)\, f_{\text{com}}(\mathbf{u}, 0, \mathcal{T})$$

- $\vartheta \in [0,1]$: trade-off parameter;
- E_{mo}: motion energy;
- f_{com}: communication cost function.

Energy-Communication Efficiency

$$\underset{\mathbf{u}}{\text{maximize}} \quad \frac{g_{\text{com}}(\mathbf{u}, 0, \mathcal{T})}{E_{\text{mo}}(\mathbf{u}, 0, \mathcal{T})}$$

Alternative definitions of the communication utility:

$$g_{\text{com}} = -f_{\text{com}} \qquad \text{(negated cost)} \qquad g_{\text{com}} = f_{\text{com}}{}^{-1} \qquad \text{(inverse cost)}$$

Both formulations combine robotic energy and communication performance objectives.

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Energy-Efficient Trajectories: Constrained Formulations

Robotics Objective with Communication Constraint

$$\begin{aligned} \underset{\mathbf{u}}{\text{minimize}} \quad & E_{\text{mo}}(\mathbf{u}, 0, \mathcal{T}) \\ \text{s.t.} \quad & f_{\text{com}}(\mathbf{u}, 0, \mathcal{T}) \leq \bar{f} \end{aligned}$$

Optimization focuses on *motion energy*, while enforcing a lower bound on communication quality.

Communication Objective with Motion Constraint

$$\begin{aligned} \underset{\mathbf{u}}{\text{minimize}} \quad & f_{\text{com}}(\mathbf{u}, 0, \mathcal{T}) \\ \text{s.t.} \quad & E_{\text{mo}}(\mathbf{u}, 0, \mathcal{T}) \leq \bar{E} \end{aligned}$$

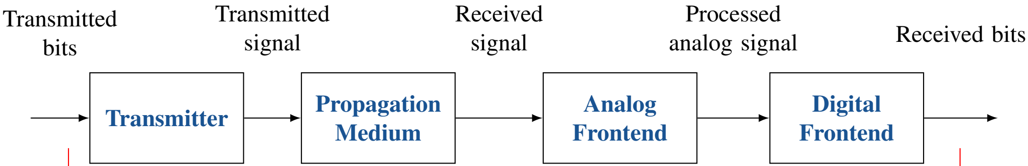
Optimization focuses on communication cost, while constraining the *robot's motion energy*.

Communication Constraints

Communication constraints can be categorized based on their nature:

Channel Model	**Physical Limitations**	**Performance Requirements**
Equality constraint	*Inequality constraint*	*Inequality constraint*
$L_P(\mathbf{p}_r(t), \mathbf{p}_t(t)) = \|\mathbf{p}_r(t) - \mathbf{p}_t(t)\|^2$ (Path loss)	$\|x(t)\| \leq P_{\max}$ (Tx power limit)	$\min_{t \in [0,T]} R(t) \geq R_{\text{des}}$ (Bit rate requirement)
Cannot be relaxed	**Cannot be relaxed**	**Can be relaxed**

Communication Constraints: Bits



Transmitter Constraint

Deterministic constraint:

$$\int_0^T r(t)\,\mathrm{d}t \geq N$$

Designer's constraint can be relaxed

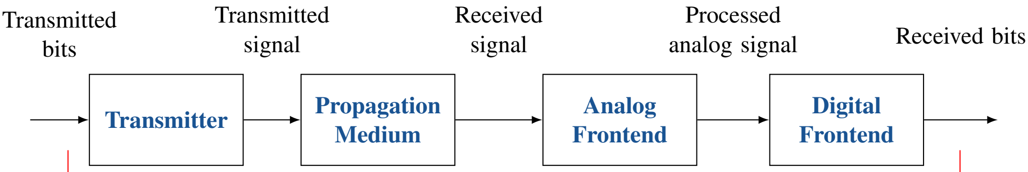
Receiver Constraint

Stochastic constraints:

$$\mathbb{E}\left[\int_0^T r_s(t)\,\mathrm{d}t\right] \geq N, \quad \Pr\left(\int_0^T r_s(t)\,\mathrm{d}t \geq N\right) \geq \eta$$

Designer's constraint can be relaxed

Communications Constraints: Power



Power Constraint

Deterministic constraint:

$$P(t) \leq P_{\max}$$

Receiver Constraint

Stochastic constraints:

$$\mathbb{E}\left[\frac{1}{T}\int_0^T P(t)\mathcal{H}^2(\mathbf{p}(t), \mathbf{q}(t), t)\mathrm{d}t\right] \geq P_{\min},$$

$$\Pr\left(P(t)\mathcal{H}^2(\mathbf{p}(t), \mathbf{q}(t), t) < P_{\min}\right) \leq \varepsilon, \ \forall t \in [0, T]$$

Designer's constraint can be relaxed

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Thank you

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