Implementation of distributed consensus with guaranteed real-time communication on an outdoor testbed

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Motivation

- Several applications that require cooperation among flying robots

[1] Joshi et. al. Implementation of distributed consensus on an outdoor testbed, ECC '16

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- Practical implementation: outdoors, decentralized

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Quadrotors[1] can be approximated as double integrators, driven to consensus only using exchange of position data

Communication: Synchronized, no data collisions, guaranteed real-time

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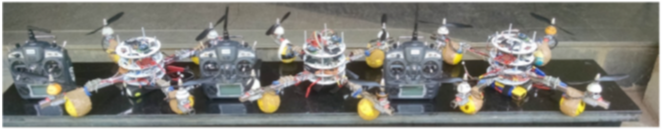
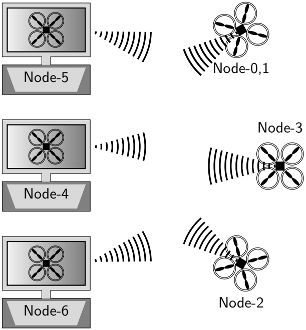
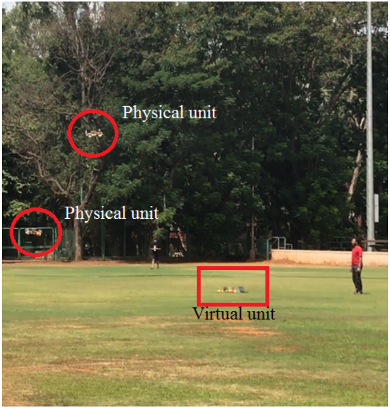
Testbed




Node-5
Node-0,1
Node-3
Node-4
Node-6
Node-2


Physical unit
Physical unit
Virtual unit

Hardware Architecture

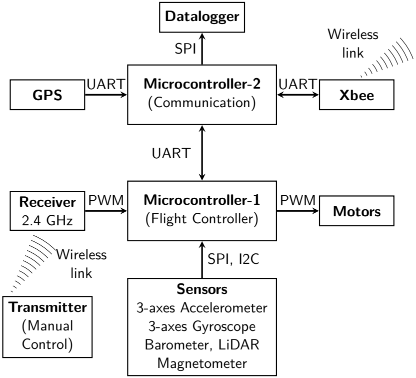


Figure: Physical unit

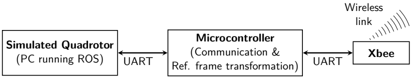
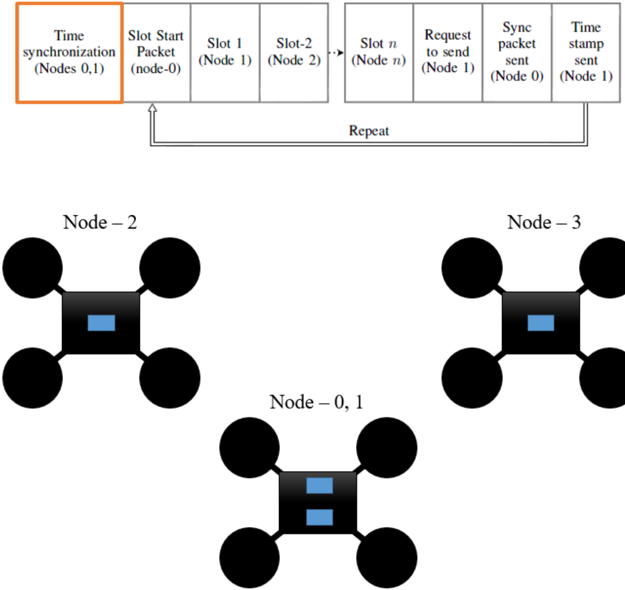


Figure: Virtual unit

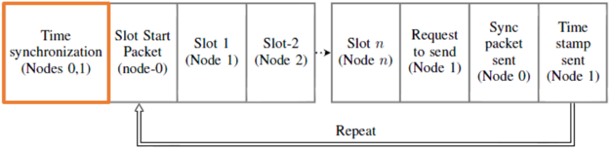
Communication Protocol

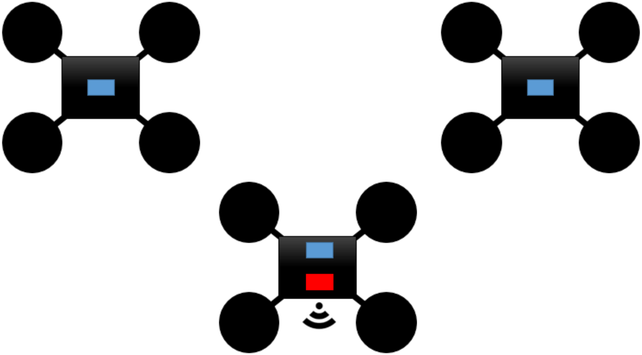
- Synchronized data transfer
- Real-time, no data collisions
- Fully airborne. No need of ground station
- Robust: can handle link breakage with synchronizing node

Time synchronization



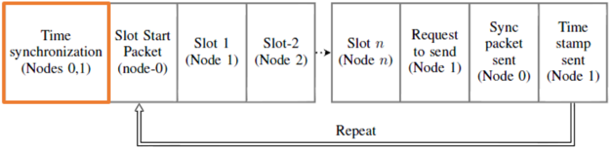
Time synchronization

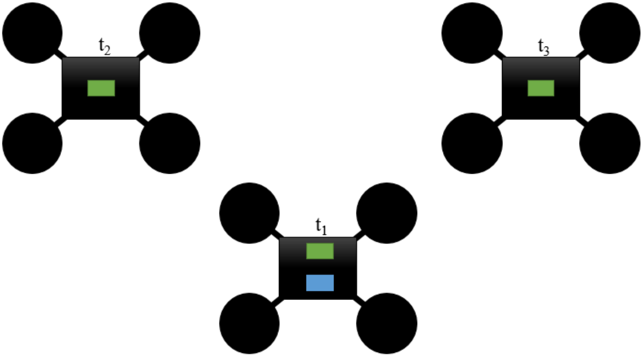




Synchronization packet

Time synchronization





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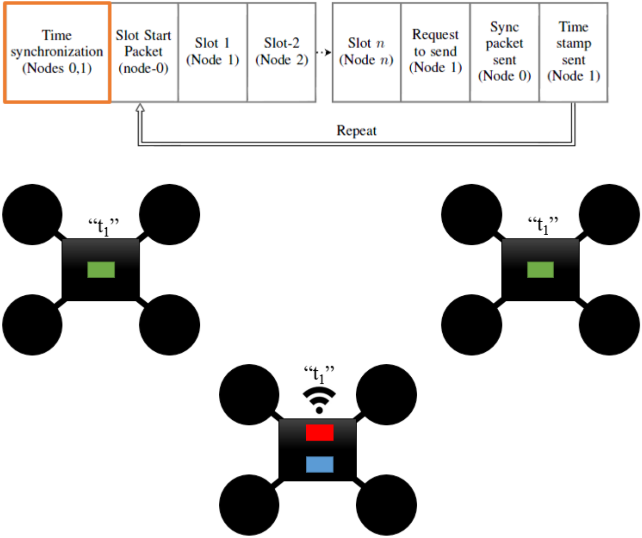
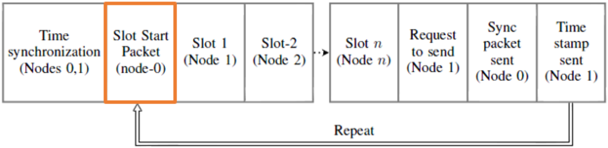
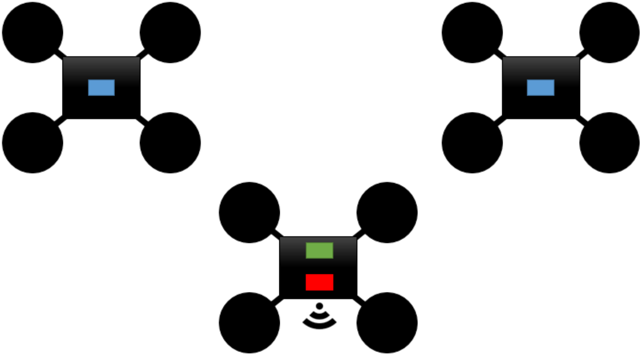


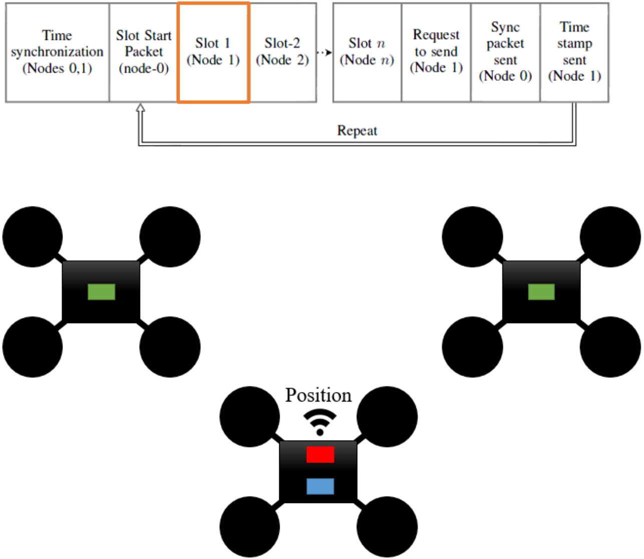
Slot allotment



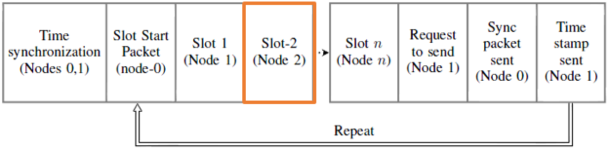


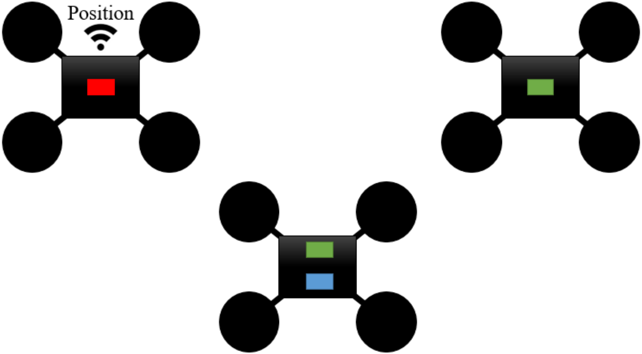
Slot allotment complete

Data transfer



Data transfer





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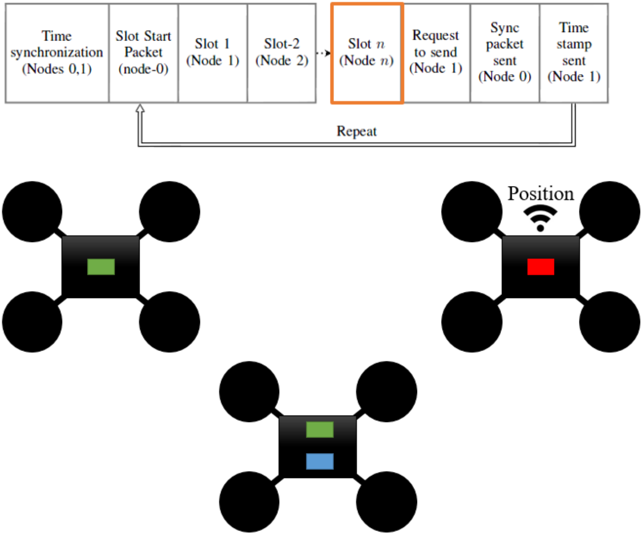
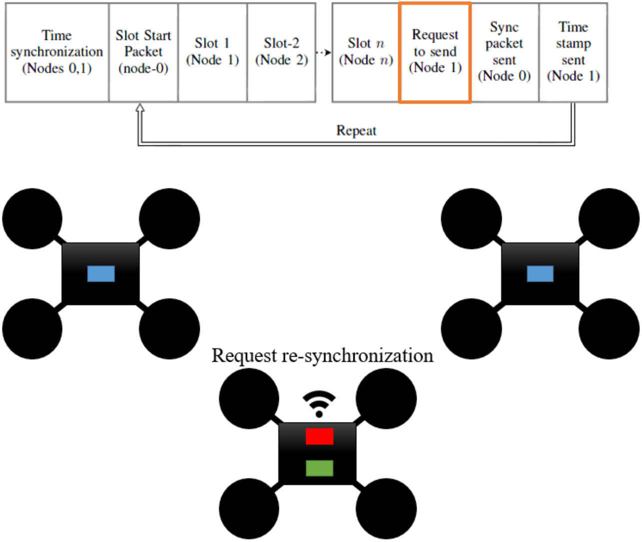


Re-synchronization



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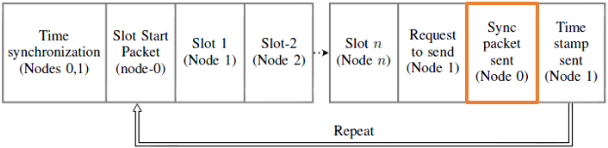
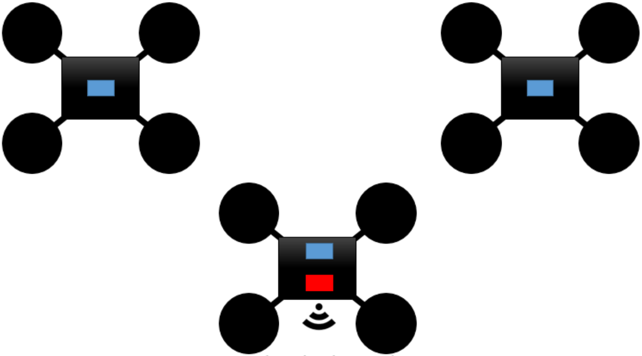
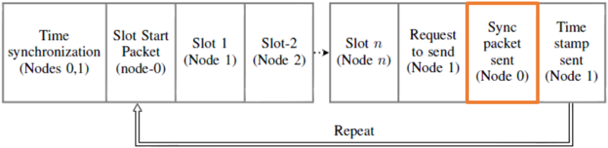
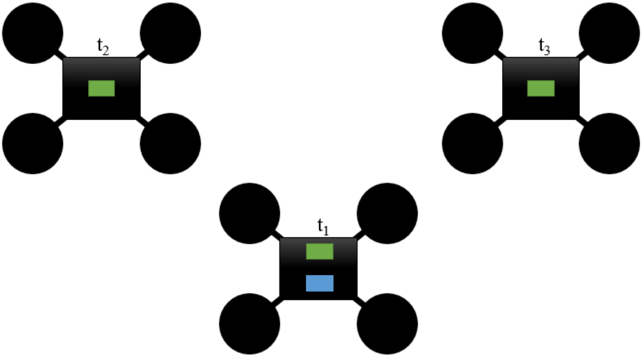




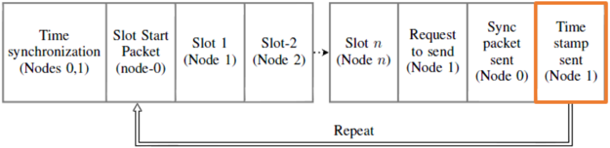
Synchronization packet

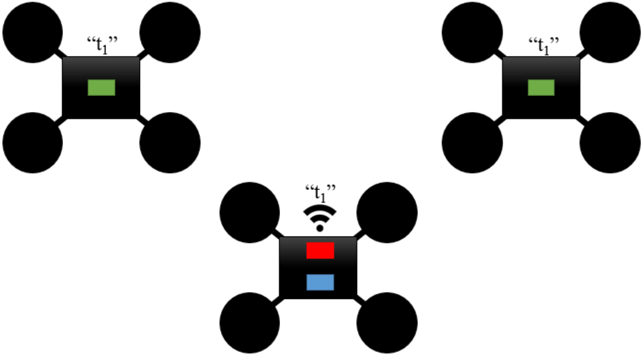
Re-synchronization





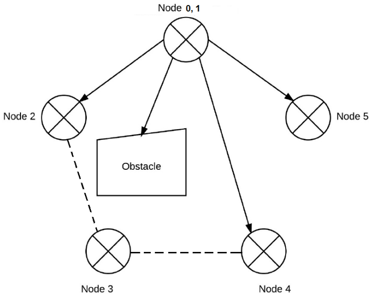
Re-synchronization





Addressing contingencies

- Link break with Node-0,1
- Link break with all nodes



Communication Protocol

Indoor environment

- Area: 10 m $\times$ 10 m
- Duration: 300 s
- Average efficiency: 98.11%

Table: Efficiency (%) of data reception of six nodes: indoor

Node	1	2	3	4	5	6
1	-	95.64	99.75	99.88	99.50	96.02
2	97.66	-	91.82	100.00	99.50	96.02
3	99.41	96.85	-	98.82	99.38	95.90
4	99.53	98.67	99.87	-	100.00	96.52
5	98.36	98.67	98.49	99.88	-	92.55
6	99.41	96.25	99.62	99.88	99.38	-

Communication Protocol

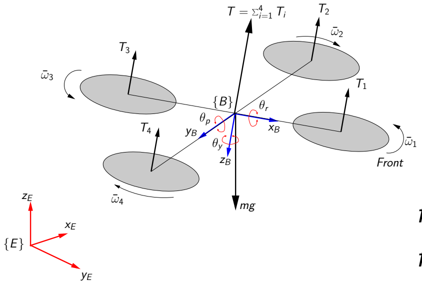
Outdoor environment

- Area: 55 m $\times$ 46 m
- Duration: 300 s
- Average efficiency: 90.25%

Table: Efficiency (%) of data reception of six nodes: outdoor

Node	1	2	3	4	5	6
1	-	92.49	91.20	94.24	89.22	90.77
2	91.18	-	93.88	89.22	88.34	91.39
3	84.24	91.49	-	92.84	87.09	92.02
4	86.09	89.87	91.07	-	89.61	92.76
5	89.30	91.99	92.69	90.86	-	91.76
6	86.66	91.36	87.39	91.47	85.21	-

Quadrotors as double integrators



- Control inputs:
  - Roll, θ_r
  - Pitch, θ_p
  - Yaw, θ_y
  - Thrust, T

$$f_x = T \sin\theta_p \approx T\theta_p$$
$$f_y = T \sin\theta_r \cos\theta_p \approx T\theta_r$$

for small θ_p and θ_r

If we can vary θ_p and θ_r independently and instantaneously, then motion in the $x_E y_E-$ plane can be modelled as a double integrator.

Consensus law

Consider a team of n quadrotors. For each quadrotor i at time t:

- Position: $\mathbf{p}_i^E(t) = \begin{bmatrix} p_x^E(t) & p_y^E(t) \end{bmatrix}^T \in \mathbb{R}^2$
- Velocity: $\mathbf{v}_i^E(t) = \begin{bmatrix} v_x^E(t) & v_y^E(t) \end{bmatrix}^T \in \mathbb{R}^2$
- Consensus: $\|\mathbf{p}_i^E(t) - \mathbf{p}_j^E(t)\| \to 0$ and $\mathbf{v}_i^E \to 0$ as $t \to \infty$, for all $\mathbf{p}_i^E(0)$ and $\mathbf{v}_i^E(0)$ and all $i, j = 1, \ldots, n$.

Consensus law

- Information exchange modelled as undirected graph $\mathcal{G}_n := (\mathcal{V}, \mathcal{E})$ where $\mathcal{V} = \{1, ..., n\}$ is the set of nodes and $\mathcal{E} \subseteq (\mathcal{V} \times \mathcal{V})$ is the set of edges
- Node $\equiv$ quadrotor, edge $\equiv$ available communication channel
- Set of neighbours, $\mathcal{N}_i := \{j \in \mathcal{V} : (i, j) \in \mathcal{E}\}$.
- Adjacency matrix, $\mathcal{A}_n(\mathcal{G}_n) := [a_{ij}] \in \mathbb{R}^{n \times n}$
  - $a_{ij} = 1$, if communication link exists between agents i and j
  - $a_{ij} = 0$, otherwise

Consensus law

Theorem

Given a system

$$\dot{\mathbf{p}}^E = \mathbf{v}^E, \qquad \dot{\mathbf{v}}^E = \mathbf{f}^E \tag{1}$$

The control law [2]*,*

$$\mathbf{f}_i^E = \sum_{j \in \mathcal{N}_i} a_{ij}(\mathbf{p}_j^E - \mathbf{p}_i^E) - \beta \mathbf{v}_i^E, \qquad i = 1, \ldots, n$$

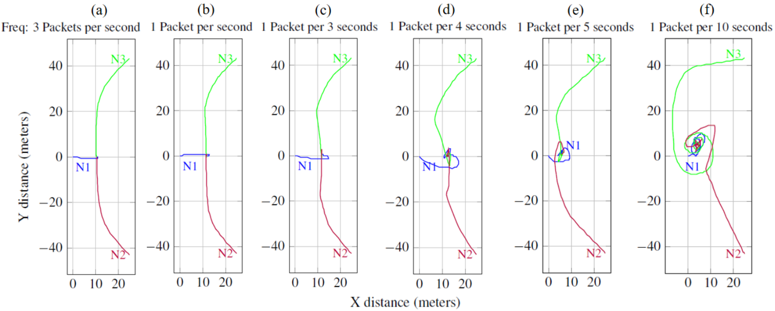
achieves consensus asymptotically iff $\mathcal{G}_n$ *is connected*

[2] Proof similar to W. Ren, R. Beard, Distributed consensus in multi-vehicle cooperative control, Springer, 2008

Consensus experiments

A GPS plot of physical and virtual agents reaching consensus

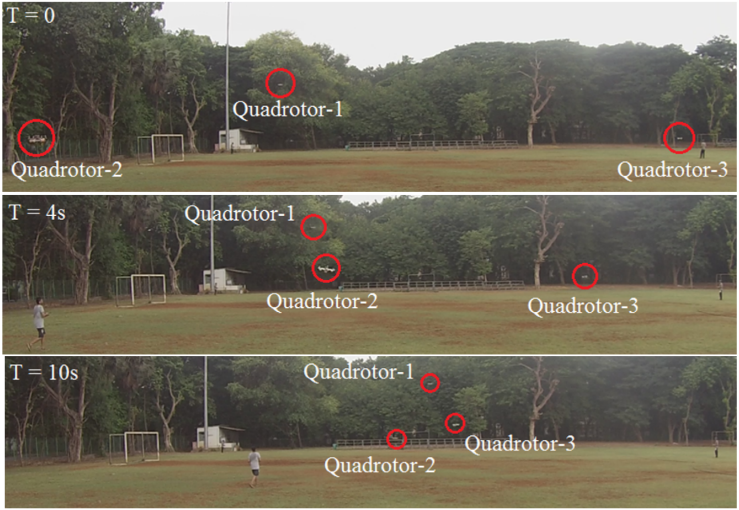
Consensus experiments



Effect of different data exchange rates on consensus performance

Conclusions

- Consensus achieved between agents using only exchange of position information.
- Real-time information exchange achieved using synchronized communication protocol with no data collisions.
- All computations are decentralized. No need of ground station.
- Effect of communication rate on consensus performance studied.



Thank you :)

Questions?