2017 NSF CYBER-PHYSICAL SYSTEMS PRINCIPAL INVESTIGATORS' MEETING

CPS: Small: Cyber-Physical Communication for Cooperative Human-Robot Mobility

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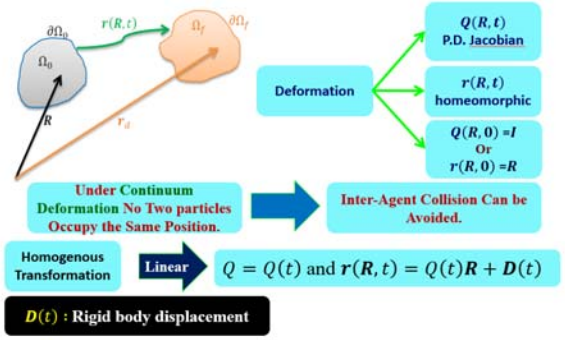
Objectives

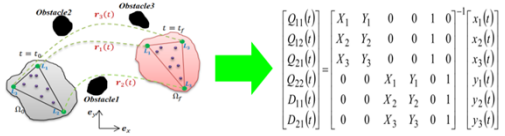
This project studies continuum deformation safety and liveness conditions and continuum deformation optimization of a Multiple Quadcopter System (MQS) flying with and without payload. We study the following research problems:

- ✓Safety formal verification
- ✓Cooperative aerial lift and manipulation
- ✓Human cyber-physical heads-up interface
- ✓Experimental evaluation and validation

Continuum Deformation Coordination



Element of Q and D based on Leaders' Positions

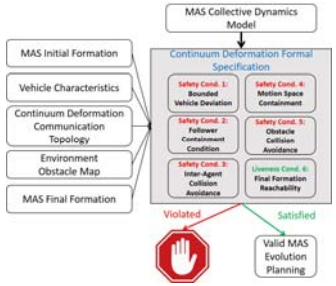


$$\begin{bmatrix} Q_{11}(t) \\ Q_{12}(t) \\ Q_{21}(t) \\ Q_{22}(t) \\ D_{11}(t) \\ D_{21}(t) \end{bmatrix} = \begin{bmatrix} X_1 & Y_1 & 0 & 0 & 1 & 0 \\ X_2 & Y_2 & 0 & 0 & 1 & 0 \\ X_3 & Y_3 & 0 & 0 & 1 & 0 \\ 0 & 0 & X_1 & Y_1 & 0 & 1 \\ 0 & 0 & X_2 & Y_2 & 0 & 1 \\ 0 & 0 & X_3 & Y_3 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ y_1(t) \\ y_2(t) \\ y_3(t) \end{bmatrix}$$

Project number: NSF CNS 1739525, The University of Michigan. **Contacts**: E. M. Atkins and H. Rastgoftar.

Continuum Deformation Safety Specification

- ✓Developed continuum deformation safety and liveness conditions.
- ✓Constructed Linear Temporal Logic (LTL) formulae to check validity of inter-agent and obstacle collision avoidance as well as agent and motion-space containment.



Cond. 1: $\bigwedge_{i\in\mathcal{V}} \square\left(\|\mathbf{r}_i-\mathbf{r}_i^{\mathrm{HT}}\|_2^2 \le \delta^2\right)$

Cond. 2: $\bigwedge_{i\in\mathcal{V}_c} \square\left(\Omega\left(\mathbf{r}_1^{\mathrm{HT}},\cdots,\mathbf{r}_{d+1}^{\mathrm{HT}},\mathbf{r}_i\right)\ge 0\right)$

Cond. 3: $\bigwedge_{i,j\in\mathcal{V},\ i\neq j} \square\left(\|\mathbf{r}_i-\mathbf{r}_j\|_2^2 \ge (2\epsilon)^2\right)$

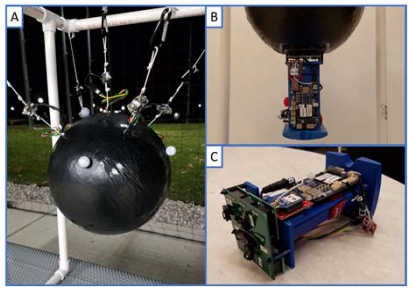
Cond. 4: $\bigwedge_{i\in\mathcal{V}} \square\left(\bigwedge_{k=1}^{m_O} \neg\left(\Omega\left(\mathbf{o}_{k,1},\cdots,\mathbf{o}_{k,m_B},\mathbf{r}_i\right)\ge 0\right)\right)$

Cond. 5: $\bigwedge_{i\in\mathcal{V}} \square\left(\bigwedge_{k=1}^{m_O} \neg\left(\Omega\left(\mathbf{o}_{k,1},\cdots,\mathbf{o}_{k,m_B},\mathbf{r}_i\right)\ge 0\right)\right)$

Cond. 6: $\Diamond\square \bigwedge_{i\in\mathcal{V}} \left(\|\mathbf{r}_i-\mathbf{r}_i^f\|_2^2 \le \varepsilon^2\right)$

Instrumented Payload

A) Instrumented payload on test rig
B) Payload insert partially removed
C) Payload insert with self-contained electronics



Sensor Specifications:

- 5 Inline Load Cell Tension Sensors
- 9-axis IMU
- 6DOF Pose via Motion Capture

Additional Specifications

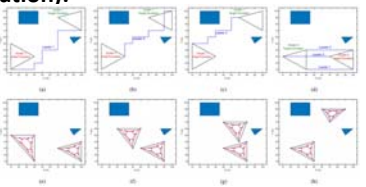
- Mass = 1.015kg
- WiFi connectivity to Vehicles
- Smooth surface for low drag

Features

- Real-time data collection and streaming to vehicles
- Ground truth for tension force estimation
- Supports user force input identification

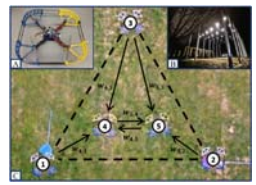
Transport Mode (Optimization):

(a-c) Optimal paths for leaders guiding cluster 1.
(d) Optimal paths for leaders guiding cluster 2.
(e-h) Cluster formations at t = 60s, t = 120s, t = 180s, and t = 240s



Experimental Evaluation – Formation Control

A) Custom quadrotor
B) M-Air netted Facility,
C) Mid-flight, overhead snapshot in M-Air with three leaders (1,2,3) and two followers (4,5) flying with continuum deformation.

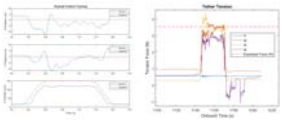


Experimental Evaluation – Formation Control w/ Payload

- 4 Quadrotors & a Payload
- Formation guidance (to-date)
- Successfully carried payload and collected data

Take-Off

Hover



Conclusion

- ✓This work applies a scalable continuum deformation paradigm to an application in which multiple quadcopters carry a single payload.
- ✓The human interacts with the team through a novel cyber-physical interface with combination of phone and haptic (pushing) guidance inputs.
- ✓Theoretical advances assure collision-free scalable coordination during cooperative transport with minimum computation overhead.
- ✓Initial experiments have validated continuum deformation with five quadrotors in free-flight. Recent experiments validate cooperative payload transport with comprehensive data collection for haptic inputs.
- ✓This project has provided education opportunity to high school and undergraduate students, e.g., construction and test of a tensegrity tether.