Robust Control Framework for Retractable Tether Multirotor UAVs (RTMUAV)

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Project Objectives and Goals

- System model and control framework for RTMUAV
  - MUAV and Payload
  - Cable dynamics
  - Slack-to-taut and taut-to-slack impulsive behavior of the tethered UAV dynamics
  - Robust geometric controller

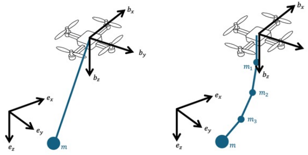

Figure 1. Diagram representing modeling of quadrotor [1]

Background

- Multirotor unmanned aerial vehicles (MUAVs)
  - Compact; agile; highly adaptable
  - Tethered MUAVs
    - Tether can reach difficult to access areas
- Applications of TMUAV:
  - Payload transportation
  - Environmental monitoring
  - Search and rescue
  - Sensor deployment
  - Benefits over:
    - Gripper arm
    - Ground-linked
- Geometric Controller
  - Removes the singularities of local coordinates
  - Allows for global convergence of the UAV and payload
- Literature
  - Control framework for TMUAV/RTMUAV
  - Exponential stability
  - Lack of slack and taut transitions
  - Simple cable model

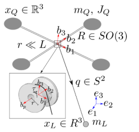

Figure 2. Diagram representing pulley system with UAV [3]

Numerical Equations

$$\dot{x}_Q = v_Q \tag{17}$$

$$\dot{x}_L = v_L \tag{18}$$

$$\dot{v}_L = -\frac{T}{m_L} q - g e_3 \tag{19}$$

$$\dot{v}_Q = \frac{f}{m_Q} R e_3 + \frac{T + m_c g}{m_Q} q - g e_3 \tag{20}$$

$$\dot{q} = \omega \times q \tag{21}$$

$$\dot{\omega} = -\frac{1}{m_Q L} \left(q \times (f R e_3)\right) \tag{22}$$

$$\dot{R} = R\hat{\Omega} \tag{23}$$

$$\dot{\Omega} = J_Q^{-1} \left(M - \tau e_p - \Omega \times J_Q \Omega\right) \tag{24}$$

$$\ddot{L} = \frac{r}{J_P + m_c r^2} \left(\tau - (T + m_c g) r\right) \tag{25}$$

$$T_{\mathrm{t}} = k_c (d - L) + c_c (\dot{d} - \dot{L}) \tag{26}$$

$$T_{\mathrm{s}} = 0 \tag{27}$$

Modeling Constraints

- Tether Modeling
  - Cable modeled with mass
  - Retractable system with pulley inertia
  - Modeled as spring damper system when taut for tension computation
  - State switch determined by comparing the distance between the UAV and payload with the tether length

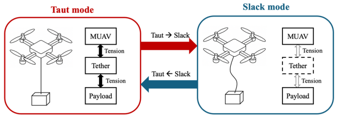

Figure 3. Diagram depicting differences between taut and slack [1]

- Ground Condition Modeled
  - UAV and payload cannot go below ground
  - Ground modeled as spring damper system with high values
- Three Phase Simulation
  1. **UAV lifts off** the ground and **hovers** above the payload
  2. UAV **deploys tether** and it attaches to the payload
  3. **Payload is lifted** off the ground through the **retracting** of the tether

Data and Results

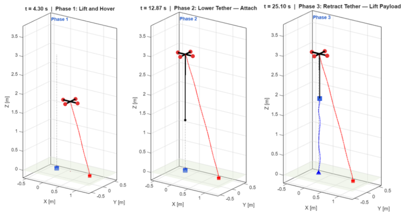

Figure 4. Diagram depicting the three phases of the RTMUAV mission as it occurs in the simulation.

- Vibrations noticed in UAV and payload position
  - Stability analysis required
  - Oscillations during flight
- In flight tether length

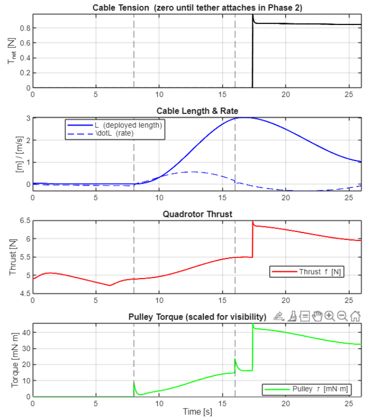

Figure 5. Graphs showing cable tension, length, UAV thrust, and pulley torque over the 3 phases of the simulation

- Phase 1 → 2 (~8 s)
  - Pully torque appear
  - Cable length starts increasing
- Phase 2 → 3 (~16 s)
  - Discrete jump in torque and thrust due to increased mass
  - Tension, thrust and torque stabilized

Ongoing Study

- UAV completed all three phases
- Oscillation errors in Y component
  - Discontinuities in derivates or integrals

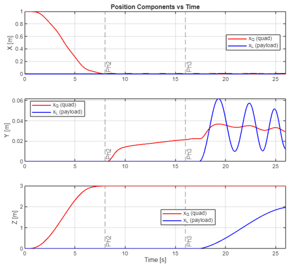

Figure 6. Plot depicting the positions of UAV and payload in x, y, and z.

- Slack to taut modeling
  - Testing random jerks or forces onto payload to force slack state and state transitions
  - Non-minimal jerk trajectories
    - Forcing trajectories onto system which require slack to taut state transitions

Future Studies

- Modeling of tether as multiple links
  - Easier to monitor slack vs taut
  - Different tensions for both UAV and payload
- Create 2 axis testbed for the UAV and tethered payload to verify tension measurement and state transitions
- Study the effect of the aerodynamics of payload with different tether configurations and payload shapes

References

[1] Handrick, D., Eckenrode, M., & Lee, J. (2025). Review of Tethered Unmanned Aerial Vehicles: Building Versatile and Robust Tethered Multirotor UAV System. Dynamics, 5(2), 17. https://doi.org/10.3390/dynamics5020017

[2] Sreenath, K., Taeyoung Lee, & Kumar, V. (2013). Geometric control and differential flatness of a quadrotor UAV with a cable-suspended load. 52nd IEEE Conference on Decision and Control. https://doi.org/10.1109/cdc.2013.6760219

[3] Zeng, J., Kotaru, P., & Sreenath, K. (2019). Geometric control and differential flatness of a quadrotor UAV with load suspended from a Pulley. 2019 American Control Conference (ACC), 2420–2427. https://doi.org/10.23919/acc.2019.8815173

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This work is supported by the Magellan Mini-Grant

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