Sequential Manipulation Planning for Over-Actuated Unmanned Aerial Manipulators

Yao Su[1*], Jiarui Li[1,2*], Ziyuan Jiao[1*], Meng Wang[1], Chi Chu[1,3], Hang Li[1], Yixin Zhu[4], Hangxin Liu[1†]

[1] National Key Laboratory of General Artificial Intelligence, Beijing Institute for General Artificial Intelligence(BIGAI).
[2] Department of Advanced Manufacturing and Robotics, College of Engineering, Peking University.
[3] Department of Automation, Tsinghua University.
[4] Institute for Artificial Intelligence, Peking University.

* Equally Contribution. † Corresponding author.

Motivation

To date, UAMs are limited to tasks with **one-step** planning. To endow UAMs with **multi-step** sequential manipulation capability, UAM platform ought to: (i) coordinate the motions of its floating base and the manipulator that consists of a series of joints (ii) effectively produce varied motion patterns at different steps of a sequential task, especially when it interacts with objects with diverse kinematic structures.

Contribution

We tackle this issue with three contributions:

(i) a novel mechanical design of an over-actuated UAM
(ii) a virtual kinematic chain (VKC)-based motion planning framework
(iii) a hierarchical control architecture

Over-actuated UAM Platform

Flying Vehicle

(i) Two-DoF passive gimbal mechanism on each thrust generator
(ii) 12 DoF in high-level control over-actuated UAV
(iii) Omni-directional flight capability (vertical flight / flip over) full working space

Robotic Manipulator --- 3 DoF manipulator with parallel gripper

Sequential Aerial Manipulation Planning

Construct Virtual Kinematic Chain (VKC)

- **Kinematic inversion** reverses the kinematic model of an articulated object by converting the attachable link into the new root in the inverted kinematic mode
- **Virtual joint** defines the spatial transformation between two body frames and the joint type that constrains the relative motion between them
- **Virtual base** reflects the motion constraints imposed on the floating base

Task & Motion Planning on VKC

Trajectory optimization

$$\min_{\boldsymbol{x}_{1:T}} \sum_{t=1}^{T-1} \|\boldsymbol{W}_{\mathrm{v}}\delta\boldsymbol{x}_t\|_2^2 + \sum_{t=2}^{T-1} \|\boldsymbol{W}_{\mathrm{a}}\delta\dot{\boldsymbol{x}}_t\|_2^2$$

Physical constraints

$$h_{\mathrm{chain}}(\boldsymbol{x}_t) = 0,\ \forall t = 1, 2, \ldots, T$$

Task constraints

$$\left\|f_{\mathrm{task}}(\boldsymbol{x}_T) - \mathcal{G}_{\mathrm{goal}}\right\|_2^2 \leqslant \xi_{\mathrm{goal}}$$

Safety constraints

$$\boldsymbol{x}_{\min} \leqslant \boldsymbol{x}_t \leqslant \boldsymbol{x}_{\max}, \quad \forall t = 1, 2, \ldots, T$$

$$\|\delta\boldsymbol{x}_t\|_\infty \leqslant \dot{\boldsymbol{x}}_{\max}, \|\delta\dot{\boldsymbol{x}}_t\|_\infty \leqslant \ddot{\boldsymbol{x}}_{\max}, \quad \forall t = 2, 3, \ldots, T-1$$

$$\sum_{i=1}^{N_{\mathrm{link}}} \sum_{j=1}^{N_{\mathrm{obj}}} |\mathrm{dist}_{\mathrm{safe}} - f_{\mathrm{dist}}(L_i, O_j)|^+ \leqslant \xi_{\mathrm{dist}},$$

$$\sum_{i=1}^{N_{\mathrm{link}}} \sum_{j=1}^{N_{\mathrm{link}}} |\mathrm{dist}_{\mathrm{safe}} - f_{\mathrm{dist}}(L_i, L_j)|^+ \leqslant \xi_{\mathrm{dist}},$$

Dynamics & Control

Flying Vehicle Dynamics

$$\begin{bmatrix} m\boldsymbol{I}_3 & 0 \\ 0 & {}^B\boldsymbol{J}(\boldsymbol{q}_M) \end{bmatrix} \dot{\tilde{\boldsymbol{q}}}_B = \begin{bmatrix} {}^W_B\boldsymbol{R} & 0 \\ 0 & \boldsymbol{I}_3 \end{bmatrix} \boldsymbol{u} + \begin{bmatrix} mg\hat{\boldsymbol{z}} \\ {}^B\boldsymbol{\tau}_g(\boldsymbol{q}_M) - {}^B\boldsymbol{\omega} \times {}^B\boldsymbol{J}(\boldsymbol{q}_M)\,{}^B\boldsymbol{\omega} \end{bmatrix}$$

Total wrench

$$\boldsymbol{u} = \begin{bmatrix} \sum_{i=1}^{4} {}^B_i\boldsymbol{R}\,T_i\hat{\boldsymbol{z}} \\ \sum_{i=1}^{4} (\boldsymbol{d}_i \times {}^B_i\boldsymbol{R}\,T_i\hat{\boldsymbol{z}}) \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_v(\boldsymbol{\alpha}, \boldsymbol{\beta}) \\ \boldsymbol{J}_\omega(\boldsymbol{\alpha}, \boldsymbol{\beta}) \end{bmatrix} \boldsymbol{T}$$

Trajectory Tracking (Feedback linearization+PID)

$$\boldsymbol{u}^d = \begin{bmatrix} m\,{}^W_B\boldsymbol{R}^{\mathrm{T}} & 0 \\ 0 & {}^B\boldsymbol{J}(\boldsymbol{q}_M) \end{bmatrix} \left(\begin{bmatrix} \boldsymbol{u}_v \\ \boldsymbol{u}_\omega \end{bmatrix} - \begin{bmatrix} g\hat{\boldsymbol{z}} \\ {}^B\boldsymbol{\tau}_g(\boldsymbol{q}_M) - {}^B\boldsymbol{\omega} \times {}^B\boldsymbol{J}(\boldsymbol{q}_M)\,{}^B\boldsymbol{\omega} \end{bmatrix} \right)$$

$$\boldsymbol{u}_v = \dot{\boldsymbol{v}}^r + K_{v1}\boldsymbol{e}_v + K_{v2}\boldsymbol{e}_p + K_{v3}\int \boldsymbol{e}_p\, dt$$

$$\boldsymbol{u}_\omega = \dot{\boldsymbol{\omega}}^r + K_{\omega 1}\boldsymbol{e}_\omega + K_{\omega 2}\boldsymbol{e}_\theta + K_{\omega 3}\int \boldsymbol{e}_\theta\, d$$

$$\boldsymbol{e}_p = \boldsymbol{p}^r - \boldsymbol{p}, \quad \boldsymbol{e}_v = \boldsymbol{v}^r - \boldsymbol{v},$$

$$\boldsymbol{e}_\theta = \frac{1}{2}[\boldsymbol{R}(\boldsymbol{\theta})^T\boldsymbol{R}(\boldsymbol{\theta}^r) - \boldsymbol{R}(\boldsymbol{\theta}^r)^T\boldsymbol{R}(\boldsymbol{\theta})]_\vee$$

$$\boldsymbol{e}_\omega = \boldsymbol{R}(\boldsymbol{\theta})^T\boldsymbol{R}(\boldsymbol{\theta}^r)\boldsymbol{\omega}^r - \boldsymbol{\omega},$$

Manipulator Dynamics

$$\boldsymbol{M}_M(\boldsymbol{q}_M)\ddot{\boldsymbol{q}}_M + \boldsymbol{C}_M(\boldsymbol{q}_M, \dot{\boldsymbol{q}}_M) + \boldsymbol{G}_M(\boldsymbol{q}_M) = \boldsymbol{\tau}_M + \boldsymbol{J}_{ext}\boldsymbol{F}_{ext}$$

Inverse Dynamics Controller:

$$\boldsymbol{\tau}_M = \boldsymbol{M}_M(\boldsymbol{q}_M)\ddot{\boldsymbol{q}}_M^d + \boldsymbol{C}_M(\boldsymbol{q}_M, \dot{\boldsymbol{q}}_M) + \boldsymbol{G}_M(\boldsymbol{q}_M)$$

$$\ddot{\boldsymbol{q}}_M^d = \ddot{\boldsymbol{q}}_M^r + K_{M1}\boldsymbol{e}_M + K_{M2}\dot{\boldsymbol{e}}_M + K_{M3}\int \boldsymbol{e}_M\, dt$$

$$\boldsymbol{e}_M = \boldsymbol{q}_M^r - \boldsymbol{q}_M,$$

Nullspace-based Control Allocation

$$u^d \Rightarrow \alpha, \beta, T$$

Low-level Quadcopter controller

$$\alpha_i, \beta_i, T_i \Rightarrow M_{ix}, M_{iy}, M_{iz}, T_i \Rightarrow \omega_{1-4}$$

Hierarchical Control Architecture

- Reference Trajectory from VKC
- 10/11 DoF
  (6DoF UAV, 4Dof arm, 1DoF obj)
- High-level controller on PC (100Hz)
- Low-level controller on UAM (500Hz)
- Wireless communication

Simulation Tasks

Experiment Tasks

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