Sequential Manipulation Planning for Over-Actuated Unmanned Aerial Manipulators

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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

thrust generator 2
thrust generator 3
thrust generator 4
thrust generator 1
link 1
link 2

- 4×quadcopter
- 4×carbon fiber tubes
- Raspberry Pi Zero 2W
- Dynamixel U2D2 USB converter
- 700mAh 5V lithium battery

3-DoF manipulator with a 1-DoF gripper, actuated by 4×Dynamixel XC330-M228-T, connected by 3D-printed connector

6-DoF virtual base
UAM original trans

versatile grippers that can be kitted with different accessories

- Crazyflie 2.1 control board
- Crazyflie BigQuad deck
- 4×Emax RS1108 brushless motor
- power distribution board
- 4×BLHeli electronic speed controller
- 4×Emax AVAN Mini 3-inch propeller
- 11.1V 45C 1000mAh battery

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)

(a) Original Structure   (b) Kinematic Inversion   (c) VKC Construction

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

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

Task constraints
$$\|f_{\text{task}}(\boldsymbol{x}_T) - \mathcal{G}_{\text{goal}}\|_2^2 \leq \xi_{\text{goal}}$$

Safety constraints
$$\boldsymbol{x}_{\min} \leq \boldsymbol{x}_t \leq \boldsymbol{x}_{\max}, \quad \forall t = 1, 2, \ldots, T$$
$$\|\delta \boldsymbol{x}_t\|_\infty \leq \dot{\boldsymbol{x}}_{\max}, \|\delta \dot{\boldsymbol{x}}_t\|_\infty \leq \ddot{\boldsymbol{x}}_{\max}, \quad \forall t = 2, 3, \ldots, T-1$$
$$\sum_{i=1}^{N_{\text{link}}} \sum_{j=1}^{N_{\text{obj}}} |\text{dist}_{\text{safe}} - f_{\text{dist}}(L_i, O_j)|^+ \leq \xi_{\text{dist}},$$
$$\sum_{i=1}^{N_{\text{link}}} \sum_{j=1}^{N_{\text{link}}} |\text{dist}_{\text{safe}} - f_{\text{dist}}(L_i, L_j)|^+ \leq \xi_{\text{dist}},$$

(a) Physical Abstraction
(b) Constructed VKC

Dynamics & Control

planner and high-level controller at remote PC (100 HZ)
UAM onboard controller (500 Hz)

position controller, feedback linearization controller, control allocation, attitude controller, trajectory planner, dynamics controller
flying vehicle quadcopter controller
4-DoF manipulator motor torque controller

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

$$\boldsymbol{e}_p = \boldsymbol{p}^r - \boldsymbol{p}, \quad \boldsymbol{e}_v = \boldsymbol{v}^r - \boldsymbol{v},$$
$$\boldsymbol{e}_\theta = \frac{1}{2}[\boldsymbol{R}(\boldsymbol{\theta})^T\boldsymbol{R}(\boldsymbol{\theta}^r) - \boldsymbol{R}(\boldsymbol{\theta}^r)^T\boldsymbol{R}(\boldsymbol{\theta})]_\vee$$
$$\boldsymbol{e}_\omega = \boldsymbol{R}(\boldsymbol{\theta})^T\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}^r - \boldsymbol{\omega},$$

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

Trajectory Tracking (Feedback linearization+PID)
$$\boldsymbol{u}^d = \begin{bmatrix} m\,{}^W_B\boldsymbol{R}^T & 0 \\ 0 & {}^B\boldsymbol{J}(\boldsymbol{q}_M) \end{bmatrix}\left(\begin{bmatrix} \boldsymbol{u}_v \\ \boldsymbol{u}_\omega \end{bmatrix} - \begin{bmatrix} g\hat{\boldsymbol{z}} \\ {}^B\boldsymbol{\tau}_g(\boldsymbol{q}_M) - {}^B\boldsymbol{\omega} \times {}^B\boldsymbol{J}(\boldsymbol{q}_M){}^B\boldsymbol{\omega} \end{bmatrix}\right)$$
$$\boldsymbol{u}_v = \dot{\boldsymbol{v}}^r + K_{v1}\boldsymbol{e}_v + K_{v2}\boldsymbol{e}_p + K_{v3}\int \boldsymbol{e}_p\,dt$$
$$\boldsymbol{u}_\omega = \dot{\boldsymbol{\omega}}^r + K_{\omega1}\boldsymbol{e}_\omega + K_{\omega2}\boldsymbol{e}_\theta + K_{\omega3}\int \boldsymbol{e}_\theta\,d$$

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
$$\boldsymbol{u}^d \Rightarrow \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{T}$$

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

Flying vehicle reference trajectory
End-effector reference trajectory

Experiment Tasks