A Hierarchical Learning Control Framework for an Aerial Manipulation System

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Abstract. A hierarchical learning control framework for an aerial manipulation system is proposed. Firstly, the mechanical design of aerial manipulation system is introduced and analyzed, and the kinematics and the dynamics based on Newton-Euler equation are modeled. Secondly, the framework of hierarchical learning for this system is presented, in which flight platform and manipulator are controlled by different controller respectively. The RBF (Radial Basis Function) neural networks are employed to estimate parameters and control. The Simulation and experiment demonstrate that the methods proposed effective and advanced.

1. Introduction

Recently, unmanned aerial vehicles (UAV) of multi-rotors (such as quadrotor, hexrotor) have been deeply investigated and applied in many fields due to their advantages with flexibility and efficiency[1]. The traditional UAVs were equipped with actuators, however, which can be applied in some passive tasks, such as aerial photo and supervise etc[2]. Aerial manipulators (AM), which consist of aircrafts of multi-rotors and manipulators, can make up this problem and can be used in many active tasks, including aerial assembling, rescue etc. Hence, there is the tendency from traditional UAVs to aerial manipulation system.

The design, modeling and control for AM are a series of challenging problems because of their complexities. These include the following profiles: 1) structural complexity. Aerial manipulator belongs to a kind of combined system, and there exist important impact to the whole system from the interactions between subsystems. Simultaneously, it is sensitive for aerial platforms to load, hence the structure and parameters of manipulator equipped affect the loading capability and working flexibility of the system. 2) Non-holonomy and underactuation, the typical aerial platforms, such as quadrotor and octarotor etc, belong to non-holonomic system and are underactuated, which lead to the difficulty to control. 3) Dynamical interaction, the forces and torques derived from manipulator motion and interaction with environment make great impact to system stability, some parameters values of which are hard to estimate, which is difficult to design of controllers. And the perturbances from interior and exterior impact the precision of manipulator motion. From the above, design and control of AM are challenging problems and hot research topics.

Recently, there have been various types of AMs, which cover different aerial platform including helicopter[3], quadrotor[4], hexrotor[5] etc, and different manipulators including single joint, multi-joint[6], delta[7] and two-arm[8] etc. In comparison to delta, cascade manipulators have larger work space and better flexibility. However, there exist problems of balance among flexibility, complexity and loading capability for the choosing degree of freedom (DoF)[9]. Now, the non-holonomic and underactuated system are used for aerial platform, which restricts the precisions and flexibilities of manipulators. In [10], a redundant arm of 7 DoF is used to boost system flexibility, enhancing the difficulty of cooperation between subsystems and reducing load simultaneously. In [11] and [12], two
types of holonomic aerial platforms are presented. The core idea of these is that the thrust forces are converted from parallel to non-parallel.

For method to modeling for kinematics and dynamics of AMs are classical. In comparison to quaternion, Euler angle is more natural and easier to express in form of rotation matrix used regularly in robotics, which are used in AM kinematics more frequently. And New-Euler is more fit than Lagrange to dynamics modelling of cascade system.

In the last years, the main research work focus on trajectory of end-effector tracking[10] and interaction force control[13]. There have been many control methods for the problems as mentioned above, among which PID controller is used in wide range[14], but parameter adjustment of PID remains still to restrict adaptivity. To address to this problem backstepping controller have been proposed in aerial platform, however, which can arises “Differential Blast” in multi-dimensional situation, and are not fit to multivariable system as a consequence.

In this paper, a hierarchical learning control framework for AM is proposed. The system researched consists of a traditional quadrotor and a manipulator with 4 joints, which are controlled by different methods respectively. An estimation and learning control methods based on RBF neural networks are proposed.

2. Description of Mechanical Structure
To combine the power to volume ratio, the terminal load and the operational flexibility available, in this article, we choose the AM which use quadrotor and 4-DOF manipulation as our research object, see figure 1.

The research system in this paper consist of quadrotor’s platform and 4-DOF manipulation, using the carbon fiber as body material of quadrotor, and using the technology of 3D printing to support design of manipulator. We use Dynamixel AX-12A digital steering servo motor. The core of controller of the quadrotor and manipulator are STM32-M4 types.

![Figure 1. The mechanical structure of AM researched](image)

3 System Modeling

3.1 Kinematic Modeling
The coordinate system of inertia for reference ,the inherent coordinate system of flight platform and the coordinate system of actuator which at the end of the mechanical arm are respectively expressed as \( \{W\} \), \( \{B\} \) and \( \{E\} \). If Euler angles are used to represent the posture, the positional matrix of \( \{B\} \) with respect to that of \( \{W\} \) could be expressed as (1):

\[
_{b}^{w}T = \begin{pmatrix} R_{xyz}(\psi, \phi, \gamma) & _{b}^{w}P \_\text{BORG} \\ 0 & 1 \end{pmatrix}
\]  

(1)

In this matrix, \(_{b}^{w}P\_\text{BORG}\) is the position vector of the coordinate system origin of \( \{B\} \) with respect to \( \{W\} \). \( R_{xyz} \) is the corresponding Rotation matrix of x-y-z Euler angles.

The transformation matrix of \( \{B\} \) relative to \( \{W\} \) can be obtained by the standard D-H method:

\[
_{b}^{w}T = \prod_{i=1}^{N} A(\theta_i)
\]  

(2)
in which, \( N \) is the joint number of the manipulator, \( \mathbf{A}(\theta) \) is the transformation matrix of the coordinate system of the \( i \)th joint relative to the coordinate system of the \( i-1 \)th joint (the 0th joint defined as the coordinate system of \( \{B\} \)), \( \theta_i \) is the angle variables of the \( i \)th joint. We can use the D-H parameter method to determine the transformational matrix of joint’s coordinate system.

\( \mathbf{V}_E \), the linear velocity of the coordinate system of \( \{E\} \) relative to \( \{B\} \), has a kind of relationship with angular velocity \( \dot{\mathbf{q}} \) of joints. It can be expressed as follows:

\[
\mathbf{V}_E = \mathbf{J}_V(q) \dot{q}
\]

(3)

where \( \mathbf{J}_V(q) \) is Jacobian matrix.

\( \mathbf{Q} \) has a kind of velocity relationship with different coordinate systems, it can be expressed as follows:

\[
\mathbf{V}_Q = \mathbf{A}_B^A \mathbf{V}_B + \mathbf{A}_B^A \mathbf{R} \mathbf{V}_Q + \mathbf{A}_B^A \mathbf{Q}_B \mathbf{R}^A \mathbf{Q}
\]

(4)

In this formula, \( \mathbf{A}_B^A \) is the velocity of the origin of the \( \{B\} \) coordinate system under the \( \{A\} \) coordinate, and \( \mathbf{R}_B^A \) is the Rotation matrix of coordinate systems which between \( \{A\} \) and \( \{B\} \). \( \mathbf{V}_Q \) is the relative velocity of \( \mathbf{Q} \) which under the coordinate system of \( \{B\} \), \( \mathbf{Q}_B \) is the Inertial Tensor Matrix of airframe. \( \mathbf{G}_B \) is the propulsion, \( \mathbf{M} \) is the coefficient of lift and \( \mathbf{F}_A \) is the functional vector based on the variables of joint angle, angular velocities and angular accelerations. \( \mathbf{r} \) is the vector belong to the effect point of lift which relative to the origin of coordinate system of \( \{B\} \).

The postures and velocities of the end-effector relative to the aerial platform frame are determined according to the equation above.

3.2 Dynamics Modeling

We can use the Newton-Euler Equation to establish the dynamic equation model of the multi-propeller platform:

\[
\begin{cases}
\mathbf{m}_p \ddot{\mathbf{v}}^p + \mathbf{\Omega}_p \times \mathbf{v}^p = \sum_{i=0}^{N} \mathbf{F}_i^p + \mathbf{G}_B^p \\
\mathbf{I}_p \ddot{\mathbf{\Omega}}^p + \mathbf{\Omega}_p \times \mathbf{\Omega}_p = \sum_{i=0}^{N} \mathbf{\Omega}_i \times \mathbf{r}_i^p + \mathbf{M}(\Omega^p, \Omega^p, \Omega^p, \Omega^p)
\end{cases}
\]

(5)

where \( \mathbf{m}_p \) is the quality of airframe, \( \mathbf{I}_p \) is the Inertial Tensor Matrix of airframe, \( \mathbf{F}_p \) is the propulsion, relative to the coordinate system of airframe, produced by rotors. \( \mathbf{G}_B^p \) is used to express the gravity of the aerial platform which under the coordinate system of airframe. \( \mathbf{F}_A \) is used to express the force, from the manipulation to the aerial platform ,under the coordinate system of airframe. Meanwhile, \( \mathbf{r} \) is the vector belong to the effect point of lift which relative to the origin of coordinate system. \( \tau^R \) is the reverse torque under the coordinate system of airframe which produced by rotors. \( \mathbf{M} \) is the torque under the coordinate system of airframe which manipulation send to aerial platform .

Let \( \omega \) be the velocity of rotor. \( \mathbf{F}_p^R \) and \( \tau^R \) are all proportional to the square of \( \omega \) [15]:

\[
\begin{align*}
\mathbf{F}_p^R &= k_{\omega i} \omega^2 \\
\tau^R &= k_{\omega i} \omega^2
\end{align*}
\]

(6)

where, \( k_{\omega i} \) is the coefficient of lift and \( k_{\omega i} \) is the coefficient of torque.

We can use the recursive Newton-Euler method to establish the dynamic model of manipulation [16].

\[
\begin{cases}
\dot{\mathbf{v}}_{\omega i} = \mathbf{R}_{\omega i} \dot{\mathbf{v}}_{\omega i} + \mathbf{\dot{\omega}}_{\omega i} \times \mathbf{\omega}_{\omega i} \\
\dot{\mathbf{r}}_{\omega i} = \mathbf{R}_{\omega i} \dot{\mathbf{r}}_{\omega i} + \mathbf{\dot{\omega}}_{\omega i} \times \mathbf{\omega}_{\omega i} \\
\dot{\mathbf{q}}_{\omega i} = \mathbf{R}(\omega_{\omega i} \times \mathbf{P}_{\omega i}) \mathbf{q}_{\omega i} \times \mathbf{P}_{\omega i} + \mathbf{\dot{\omega}}_{\omega i} \times \mathbf{\dot{\omega}}_{\omega i} \\
\dot{\mathbf{F}}_{\omega i} = \mathbf{m}_{\omega i} \dot{\mathbf{v}}_{\omega i} \\
\dot{\mathbf{\tau}}_{\omega i} = \mathbf{m}_{\omega i} \dot{\mathbf{v}}_{\omega i} + \mathbf{\dot{\omega}}_{\omega i} \times \mathbf{\omega}_{\omega i} \times \mathbf{I}_{\omega i} \dot{\mathbf{v}}_{\omega i}
\end{cases}
\]

(7)
and the angular velocity and acceleration in body frame.\(\omega\) and \(\dot{\omega}\) are the resultant force and torque in body frame. \(\tau\) is the acceleration of center of mass in body frame. \(\dot{\nu}\) is the acceleration of center of mass in body frame. \(\dot{\nu}\) is the acceleration of center of mass in body frame.\(\nu\) is the resultant force and torque in body frame.

4. Hierarchical Learning Control

Aerial platform and manipulator are controlled by different controllers respectively. The learning algorithms are used to estimate parameters and build controllers.

Dynamic characteristics of aerial platform can be affected by manipulation operation except for the rotor rotation. Due to the specified tasks of manipulator and its limited degrees of freedom, it’s difficult for manipulator to offer control output under the condition of executing task trajectory. Thus the torque of the manipulator to the aerial platform is regarded as disturbance and the platform position is controlled by the rotor output in the paper. The \(N\) rotors generate propulsion force and the thrust vector of the propulsion force relative to the body coordinate system constitutes a matrix and the matrix is denoted by \(e^F \in \mathbb{R}^{3 \times N}\). The magnitude of the thrust force is approximately proportional to the rotor speed \(\omega\) and the relationship is shown as:

\[
f = k_{rf}\omega^2
\]

The propulsion force generated by the \(i\) th rotor relative to the body coordinate system can be calculated:

\[
F_{i}^b = e^F k_{ri}\omega_i^2
\]

Relative to the body coordinate system, the resultant of the propulsive forces can be obtained:

\[
F^b = \sum_{i=1}^{N} F_i = \sum_{i=1}^{N} e^F k_{ri}\omega_i^2 = k_{r} e^F \omega
\]

where \(\omega = [\omega_1^2, \omega_2^2, ..., \omega_N^2]^T\).

Let the force point vector of the \(i\) th rotor relative to the body coordinate system be represented by \(r_i\), the torques of rotors \(\tau\) relative to the body coordinate system are divided into two parts. The first part is derived from thrust forces. The second part are the counter torques produced by rotation of the rotor. Thus their relational expression can be represented:

\[
\tau_i = r_i \times F_i + (-1)^{i-1} k_{oc} e^F \omega_i^2
\]

On the basis of the equation (2), (12) can be rewritten as:

\[
\tau = r \times F + k_{oc} e^F \omega = S(r, k_{oc}, e^F) \omega
\]

where

\[
S(r, k_{oc}, e^F) = \begin{bmatrix}
-k_{oc}, & -k_{oc}, & k_{oc}, \\
k_{oc}, & -k_{oc}, & -k_{oc}, \\
-k_{oc}, & k_{oc}, & -k_{oc}
\end{bmatrix}
\]

The torque generated by the rotor in the body coordinate system can be expressed:

\[
\tau = M_{oc}\omega
\]

in which \(m_{oc} = S(r, k_{oc}, e^F)\).

According to the equation (2) and the formula (4), the generalized force generated by the input speed of the rotor can be obtained:

\[
\begin{bmatrix}
\tau^b \\
F^b
\end{bmatrix} = \begin{bmatrix}
k_{oc} e^F \\
M_{oc}
\end{bmatrix} \omega
\]

Seen as (16), the transform matrix of the rotor speed \(\omega\) to the generalized force is the singular matrix, and therefore this system is not decoupled completely.

In response to the coupling of system and the limit of rotors’ lift, we can use behavioral scheduling technique to dispose the captive sub-goal by specific behaviors which handled in a single control cycle.
We hypothesize that the current Euler angle is $\xi^C$ and the targeted Euler angle is $\xi^T$, so the corresponding rotational matrix are called $^C R$ and $^T R$.

According to the transformation of coordinate system, we can get the transformational matrix which used to express how the current coordinate system $\{C\}$ transforms to the desired coordinate system $\{T\}$:

$$ ^T \! R = ^C R^{-1} \! ^T R $$

where $\hat{w} = S_\omega (w)$ is used to express the matrix which attached by taking the unit vector $w$ as the axis and rotating the angle of $\theta$. So we can express the deviation of posture control by the rotation angle $\xi^T \theta$ and the equivalent spin axis $\xi^T \hat{w}$ which is corresponding to $^C \! R$. And we can the following:

$$ \xi^T \theta = \cos \left( \frac{\omega^T (\xi^C R - I)}{2} \right) $$

where $\omega^T = \xi^T \hat{w}$

$$ \xi^T \hat{w} = \frac{1}{2 \sin \theta} \begin{pmatrix} \tau_{x3} - \tau_{x1} \\ \tau_{y2} - \tau_{y3} \\ \tau_{z1} - \tau_{z3} \end{pmatrix} $$

According to the equation (5), we can use $\tau^b$ as the input of posture control. From the equation (19), we can know that the velocity of rotor can be controlled by $\tau^b_x$ and $\tau^b_y$ independently. The other control tasks of aerial platforms are all at the basis of the pitch-roll control task.

The RBF neural networks with Gaussian kernel functions are used to estimate parameters and to control.

5. Simulations and Experiments

A pitch-roll control task, with stochastic perturbation whose magnitudes are distributed in 0-1.8Nm, is simulated to compare the performances of three methods, including a good parameters of PID, PID with states estimation (PID-Est), and learning control with estimation (LC-Est). The simulation results are shown in figure 2, which show that learning control with estimation has advantages in dynamic and static state performances over other methods.

![Figure 2](image.jpg)

**Figure 2.** Methods comparison for pitch-roll control with perturbation

![Figure 3](image.jpg)

**Figure 3.** Testing of manipulator

We make indoor experiment to test the performance of manipulator, shown as figure 3, in which it demonstrated that manipulator can run in stable when switch states of configuration.

6. Conclusions

In this paper, a control framework of the aerial manipulation system is proposed based on learning. On account of the analysis for the controlled system, we propose a set of parameter estimation and learning control methods based on RBF network. Simulation and experimental results demonstrate
that the control framework proposed can boost the performance of the AM effectively, in comparison to PID control.

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