Design and Implementation of Rotor Aerial Manipulator System*

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Abstract—With the development of rotor aerial robot, it has been widely used as a stabilized flying platform to achieve observation, communication relay and so on by equipping corresponding equipment, which are always called passive tasks. However, many applications need rotor aerial robots to possess more active capability, such as grasp, carry and assemble. Thus, the demand for an aerial manipulation system gradually appears, and becomes a hot research issue in recent years. Aerial manipulator system, usually composed of rotor aerial robot and the manipulator, is a new type of robot system with active operating capability. Compared with the mobile manipulator based on the ground and underwater mobile robot which is now widely applied, the aerial manipulation has larger working range and better flexibility obviously. Unfortunately, the new aerial manipulation system also brings new challenges, such as strong dynamics coupling, the modeling and stabilization problem, etc. which may affect its further application. Thus, in our work, an actual physical aerial manipulator system is designed and implemented for its system and application research. Based on the system, the preliminary modeling and control was researched and also an experiment for grasping and carry application is conducted. The conclusions of these researches will help us to realize and improve the system in the future.

I. INTRODUCTION

Rotor aerial robots (RAR) have played an important role in anti-terrorist, disaster assistance, reconnaissance and surveillance for civil and military applications during past decades. They have lots of distinctive features, including low altitude flight and stable hover which are the basis of the above applications. Generally, the applications of RAR focused on some passive tasks like information collection, communication relay, etc. With the task and environment getting more and more complex, many applications need RAR to possess more active capabilities such as grasp, carry and assemble. Especially, traditional mobile manipulators composed of manipulator and ground, underwater even space robots have been verified and successfully used in many applications. Inspired by this, rotor aerial manipulator system (RAMS) composed of a RAR and a manipulator becomes a research trend that has recently received great attention. Obviously, this combination will greatly increase the utility of both the manipulator and the UAV in 3-D space including operation in the air.

Compared with conventional aerial robots, the RAMS shows a lot of advantages. a) It can rapidly capture the aerial or ground target, making sampling in environment monitoring and unmanned scientific investigation possible [1]. b) It is able to enter into complex scenarios, such as earthquake field and fire scene, to perform installation and reposition of measurement device [2]. c) Multiple aerial manipulation robots can take the initiative to fulfill cooperative transportation task of heavy load, at the same time lowering transport costs [3]. These features above show that the RAMS will have perfect application prospect.

The control of RAMS faced many challenges and difficulties due to the introduction of operation device. Firstly, RAR system kinetic mechanism is rely on the aerodynamics produced by high-speed revolution of propellers, which results in the obvious nonlinear characteristics, strong coupling, under-actuated feature and high sensitivity to perturbations [4]. The RAMS dynamic complexity further increases owing to the operating mechanism, making system modeling and controller design much more difficult. Besides, this operating device will contact with the external environment when in aerial operation. Thus, rotor dynamic parameters will change as the result of closely approaching object, and the operated target position can also be effected by rotating propellers. Furthermore, since continuous contact with environment exists in the whole operation process, the flight characteristics of RAR may change a lot. Therefore, considering these problems above, the existing control methods can hardly be used in the RAMS [5].

Although plenty of challenges exist in this new robot field, more and more attention has been paid to the development of RAR capable of physically interacting with objects in external environment in recent years. Meanwhile, many aerial manipulating robots have emerged and effectively fulfilled some aerial manipulation tasks. Yale aerial robot is composed of an unmanned helicopter and a compliant gripper [6], which can pick up objects on the ground. Drexel Autonomous Systems Lab presents a quadrotor-manipulator vehicle called MM-UAV [7] and is used to open or close the valve in dangerous situation. Seoul National University shows an aerial robot successfully operating an unknown drawer which is a quadrorter equipped with a multi Degree-Of-Freedom (DOF) manipulator [8]. DLR and University of Seville in ARCAS FP7 European Project have also performed a lot of grasping and transportation demonstration experiments with different aerial manipulation robot systems to demonstrate the practical applications [9-10].

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Generally, the RAMS in present research consists of two main parts: the RFR body and the operating mechanism. The RAR platform including helicopter, multirotor, coaxial rotorcraft [11] or ducted-fan aerial vehicle [12]. Then, the operating devices can be classified into two groups: single-DOF grippers [6] and multi-DOF manipulator system [13,12]. Nevertheless, the most widely-used type of RAMS at present is the multirotor aircraft with a multi-DOF robot arm installed below its base. This is mainly due to the simple symmetrical structure of multirotor, relative lower coupling and facilitating to controller design. The multi-DOF manipulator contributes RAMS to acquire much more flexibility and operation space when performing aerial tasks [13].

For the RAMS research, the group in Shenyang Institute of Automation, Chinese Academy of Science (SIA, CAS) have done lots of work, including dynamics modeling, system estimation and controller design [14]. Meanwhile, an actual physical RAMS has been built as seen in Fig.1. It consists of a hex-rotor aerial robot and a five-DOF manipulator, which is presented in Section II. Based on this platform, rotor parameter identification is introduced in Section III. Then, flight experiment and dynamic grasping demonstration are showed and analyzed in next section. Conclusion and future work are given in the last.

![Figure 1. RAMS in SIA CAS.](image)

## II. ROTOR AERIAL MANIPULATOR SYSTEM

### A. Hex-Rotor Aerial Robot

#### Structure

The hex-rotor vehicle frame is made of carbon fiber with six arms symmetrically distributed shown in Fig.1. Its basic structure parameters are provided in TABLE I. And the E800 motors and the corresponding matching Electronic Speed Controllers (ESC) and propellers are from DJI, Shenzhen.

| Parameter                  | Value   |
|----------------------------|---------|
| Tip-to-tip wingspan        | 113 cm  |
| Arm length                 | 40 cm   |
| Propeller                  | 33 cm   |
| Frame height               | 40 cm   |
| Total mass                 | 3.6 kg  |
| 6 cells Li-po battery      | 0.7 kg  |

### Hex-Rotor Aerial Robot Control System

The hex-rotor aerial robot system consists of four sub-systems, including the flight control sub-system, sensor sub-system, communication sub-system, and ground station sub-system.

The employed autopilot is the Pixhawk open-source flight controller. Pixhawk runs a very efficient real-time operating system, which provides a POSIX-style environment [15]. Besides, it mainly includes Mission Management, Flight Management, MAVLink, Flight States Estimation, Trajectory Control, Position Control, Attitude Control, etc. The software structure diagram for Pixhawk autopilot is shown in Fig.2.

![Figure 2. Software structure diagram for pixhawk autopilot.](image)

The sensor sub-system includes gyroscope, accelerometer, magnetometer, barometer and GPS. In addition, to improve location precision outdoors, Differential GPS system can also be applied on this system. A DGPS navigation solution module and the corresponding application program interface are developed by SIA group to provide the autopilot with DGPS data when necessary.

Then, the ground station is installed in mobile workstation, and connected to the onboard flight controller with 915 MHz wireless digital transmission module. It is mainly used to monitor the flight states data of RAR, receive operational information from manipulator, complete global path planning, and switch to automatic flight mode or manual control flight mode. The autopilot on RAR can also be used to record the experimental data throughout the flight operation process, which facilitates off-line data analysis.

### B. Five-DOF Manipulator System

#### Manipulator System

As the operating device of RAMS, a commercial 5-DOF manipulator, PhantomX Pincher AX-12 Robot Arm, is attached below the vehicle base. It is composed of five
AX-12A Dynamixel actuators and a parallel gripper at the end, connected by rugged ABS links, with vertical reach of 35 cm and horizontal reach of 31 cm, and weights 550 g. The robot arm is controlled by a 16MHz AVR microcontroller automatically, and also can be remotely controlled with handle by 2.4GHz XBee wireless module.

- **Six Axis Force/Torque Sensor**

  When the RAMS is in hover operation, the manipulator will be driven to obtain a desired end-effector pose. If the aerial manipulation task is to grasp a fast moving object, then the arm joints need to move rapidly. In this circumstance, relative larger forces, such as Coriolis and centrifugal force, will be act on the connected base as well as the RAR body simultaneously. The same phenomenon also appears in the operation in touch with external environment [16]. Hence, an additional six-axis force sensor is installed between the manipulator base and the RAR body to measure these time-varying forces, shown in Fig.3. Six axis force/torque sensor, also called as six axis loadcell, measures six components of forces and torques. The device used on RAMS is SRI-M3701B, and its main parameters is shown in TABLE II. Additionally, the six-axis force sensor data can be collected and transformed by data processing board, and then recorded by autopilot for off-line analysis.

  | Parameter | Value |
  |-----------|-------|
  | Mass      | 10 g  |
  | Diameter  | 15 mm |
  | Height    | 14 mm |
  | FX, FY    | 100 N |
  | FZ        | 200 N |
  | MX, MY, MZ| 1 Nm  |

C. Overall System

So far the overall hardware and software system for aerial manipulator have been presented, and the hardware structure is shown in Fig. 3.

The aircraft autopilot integrates several avionics sensors on one circuit board, such as accelerometer, gyroscope and barometer. Thus, the autopilot is placed at the center of frame in order to acquire accurate position attitude and velocity information of the RAR. The force sensor data transformation board and robot arm controller are located above the plane of these propellers for further flexibility and larger operation space of manipulator. Then, the power battery is fixed at the position above the robot arm, making the center of gravity locating near the symmetrical center of the whole structure.

In general, RAMS contains two parts: the onboard part and the ground part. The connect bridge between them is wireless communicating module, shown in Fig.4. The aerial part is to stabilize the RAR, perform manipulation task in the air, collect and transmit information to ground, etc. And the core component is the Pixhawk autopilot, for it provides the real time flight state information, records various kinds of information of RAMS including RAR data, manipulator data, force sensor data and even the external environment information. As to the ground part, ground station and its operator are of importance in secure and effective aerial manipulation. Operators need to send commands to the aerial manipulator, do operation on ground station, switch to manual control in case of emergency, etc.

![RAMS functional diagram block](image-url)

### III. PARAMETER IDENTIFICATION OF SINGLE ROTOR MODEL

In order to obtain the accurate aerodynamics parameters, in the first a ground experiment is designed for the modelling of single rotor as shown in Fig.5. A motor with a propeller is fixed on the top of a long straight pole, and the six-axis force sensor is installed between motor base and the top, where the ground effect can be neglected. Then, the motor is driven by ESC and Remote Control (RC), and the flight controller records the Pulse Width Modulation (PWM) signal, and corresponding force/torque data.
As an effect of rotation, there is a generated force called the aerodynamic force $F$ or the lift force and there is a generated moment called the aerodynamic moment $M$ [17], as
\begin{align}
F &= \frac{1}{2} \rho A C_T r^2 \Omega^2, \\
M &= \frac{1}{2} \rho A C_D r^2 \Omega^2,
\end{align}
where $\rho$ is air density, $A$ is blade area, $C_T$, $C_D$ are aerodynamic coefficients, $r$ is radius of blade, and $\Omega$ is angular velocity of rotor. All these parameters above can be seen as constants, except for $\Omega$. And rotor velocity $\Omega$ is relevant with battery voltage and PWM signal.

The mathematical relationship between PWM signal and aerodynamic force is shown as a second order transfer function [18]. Using low-pass filter to filtrate high-frequency noises in acquired data, then the transfer function can be identified by System Identification Module in Matlab, as
\begin{equation}
F(s) = \frac{0.006674s + 0.07417}{s^2 + 448.2s + 3136}.
\end{equation}
The proportion between aerodynamic force $F$ and moment $M$ is
\begin{equation}
K = \frac{M}{F} = 0.0179.
\end{equation}
To verify the validity of this identified model, realistic PWM data is taken as input, and corresponding aerodynamic force $F$ and moment $M$ can be obtained from transfer functions. The realistic measured force and moment from six-axis force sensor, as well as the calculated ones, are shown in Fig.6, where the sampling frequency is 50 Hz. Results show that identified models are effective.

The single rotor model is one of the important part of the whole RAMS dynamic model. In the further work, the single motor model will be applied for the system modelling research.

IV. FLIGHT EXPERIMENT AND DYNAMIC GRASPING DEMONSTRATION

A. Outdoor Flight Experiment

The influence of the manipulator movement on the RAR is a key problem of the RAMS. In this experiment, the state change of RAMS before and during the movement is researched.

The movement of manipulator in this experiment is shown in Fig.7. All links of the robot arm are clustered together at beginning as seen in Fig.7-(a). When the trigger command is received from ground operator, the arm extends automatically until the pointing down pose shown in Fig.7-(d). Then, the arm will swing periodically at different speeds. Before the RAR is switched back to manual control, the robot arm will return to the original pose as (a) at first.
hovering position variances of RAMS before and during manipulation movement are provided in TABLE III. Numerical results show that all of these three position variances in manipulator movement process are larger than those before movement, which indicates that the influence of the manipulator movement cannot be ignored when designing the controller of the system and it can be considered as internal disturbance.

| Hovering Position of RAMS | Position Variance Before movement | During movement |
|---------------------------|-----------------------------------|-----------------|
| x                         | 0.0012                            | 0.0084          |
| y                         | 0.0020                            | 0.0038          |
| z                         | 4.2×10⁻⁴                          | 0.0021          |

B. Grasping Experiment

There are many tall buildings in modern cities, some of which often have dangerous objects on external surface, due to the effect of rain, wind or even human factors, as shown in Fig.9. It is usually difficult or dangerous for workers to deal with the situation. In this case, a RAMS may be the best choice to fulfill this task in consideration of its flexibility, high efficiency and safety. The indoor grasping experiment research is to demonstrate this application of RAMS and analyze the problem included and also verify the feasibility of our system.

![Dangerous Objects on Tall Building](image)

Indoor Positioning System

A motion capture system is used as the positioning system for solve the problem that GPS is invalid indoors, as shown in Fig.10. This system is OptiTrack vision-based localization system by NaturalPoint, and mainly consists of the following parts: eight Prime41 infrared cameras, a Gigabit switch, some motion capture markers, a workstation and the optical motion capture software Motive. Its effective capturing space is about 10 m long, 10 m wide and 5 m high, separated with safety net, large enough for flight experiment. The motion capture system running at 100Hz provides a real time positioning precision of submillimeter, with maximum time delay 5.3ms.

![Indoor Positioning System](image)

To transmit the position and attitude data to RAR obtained from indoor localization system, two steps are required to be completed by a mid-communication ground station system: firstly, receiving data from localization system; then, these processed data are transmitted to onboard flight controller using wireless module. Therefore, the main function of ground station system, shown in Fig.11, are real-time data acquisition and transmission, integration of rotorcraft control algorithm, sending control command timely, dynamic display of flight states, visual information processing, etc. Furthermore, it is written by Qt 4.8.5 and C++, and also has an Application Program Interface (API) providing for Matlab, where complex control, such as flight route planning and multiple RARs formation flight, can be fulfilled effectively.

Grasping Experiment

An 11 cm long and 2 cm in diameter tube is placed at a position of 110 cm above the ground, on which a visual marker is installed. Thus, the tube local position can be obtained as operating target position. Then, the RAMS with markers takes off and is automatically navigated to the position near the target, with the distance about 20 cm over the grasping position. Next, the manipulator is remotely controlled to adjust the end gripper pose to realize the
grasping of tube, while the RAMS is hovering with the help of onboard flight controller.

The whole operation process is displayed in Fig.12. The aerial manipulator reach the desired position, and is hovering in the air, getting ready for grasping, shown in Fig.12-(b). The grasping of tube is successfully completed by operator remote control, which can be seen in Fig.12-(c) and (d). Then, the RAMS returns with the captured tube and lands at last, as in Fig.12-(e) and (f).

C. Conclusion from Grasping Experiment

From the experiment, the following essential problems are found and should pay attention to in the future work, 

1) Grasping target recognition and localization. The target to be grasped should be recognized and localized firstly [19-21], which is required to supply necessary information for the planning of RAMS.

2) Planning of the gripper. Based on recognition and localization results above-mentioned, the gripper should approach the target with a feasible and optimal trajectory, which including the planning of RAMS and also manipulator.

3) Stable control of the RAMS. This problem may the key of the above two. The RAMS should realize the stable control to overcome the influence of movement and contact force during operation process of manipulator.

V. CONCLUSION AND FUTURE WORK

A RAMS consisting of a hex-rotor aerial robot and a five-DOF manipulator is designed and implemented in this work, including the control system development and verification. Based on this platform, the preliminary modelling identification is discussed. Besides, a grasping application experiment is conducted for analyzing the problem include. To achieve the goal of automatic grasping in outdoor environment, future work will focus on the overall system dynamics modeling, stability control, and aerial autonomous mission planning. Besides, based on multiple aerial manipulator platforms, cooperative operation and cooperative transportation are also significant.

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