Control of an aerial robot with multi-link arm for assembly tasks

A.E. Jimenez-Cano, J. Martin, G. Heredia, A. Ollero*  
Robotics, Vision and Control Group  
School of Engineering, University of Seville  
Seville, Spain  
guiller@cartuja.us.es

R. Cano  
(*) Centre for Advanced Aerospace Technology (CATEC)  
La Rinconada (Seville), Spain

Abstract— This paper deals with aerial manipulators consisting of an unmanned aerial vehicle equipped with a robotic multi-link arm. The paper presents methods for the control of the aerial platform taking into account the motion of the arm. It shows how a Variable Parameter Integral Backstepping controller outperforms the results obtained by using PID controllers. The paper presents a quadrotor with a new arm designed for assembly tasks and the implementation of the proposed control methods. The experiments with this quadrotor with the arm also confirm the better performance of the Variable Parameter Integral Backstepping controller when comparing with PID controllers.

Index Terms—Aerial robotics, aerial manipulation, quadrotor nonlinear control

I. INTRODUCTION

Mobile manipulation has received a lot of attention in the last ten years [1]. The main objective is the execution of complex manipulation tasks in unstructured and dynamic environments. Mobile manipulator systems provide the added advantage of mobility offered by the platform and dexterity offered by the manipulator. Use of such systems allows for a variety of new applications both in terms of manufacturing as well as service robotics to assist people in everyday situations. However, most research on mobile manipulation has been limited to ground platforms. The use of aerial mobile manipulators would open a new bunch of applications, such as the inspection and maintenance of aerial power lines, the building of platforms for the evacuation of people in rescue operations or the construction in inaccessible sites.

Unmanned Aerial Vehicles (UAVs) of different sizes have been used in applications such as exploration, detection, precise localization, monitoring and measuring the evolution of natural disasters. However, in most of these applications the aerial robots are mainly considered as platforms for environment sensing. Then, the aerial robots do not modify the state of the environment and there are no physical interactions between the UAV and the environment. Furthermore, the interactions between the UAVs are essentially information exchanges, without physical couplings between them.

Recently there has been growing interest towards the development of aerial robots capable of physically interacting with objects in the environment, although most of the work has been devoted to object grasping applications. Several quadrotors and helicopters with gripping mechanisms in the belly have been developed [2][3]. Teams of these quadrotors have been used for construction of cubic structures with magnetic joints [4], and to build architectural structures with bricks [5]. In [6] modeling and control of a manipulating UAV is studied. Also an aerial robot with a small arm has been developed for remote inspection by contact of industrial plants [7].

Fig. 1. QARM1 quadrotor with 3-link manipulator arm, developed by University of Seville and CATEC.

The ARCAS FP7 European Project [8] is developing a cooperative free-flying robot system for assembly and structure construction. The ARCAS system will use aerial vehicles (helicopters and quadrotors) with multi-link manipulators for assembly tasks. Compared to the previously published work, the use of multi-link manipulators has several advantages over the grasping mechanisms used in most developed systems. The arm allows for greater flexibility in the kind of tasks that can be done, not only grasping objects but also manipulating them, as for example mounting pieces, fastener installation, inspection by contact,
etc. Furthermore, the extra degrees of freedom of the arm can be used to compensate the oscillations and perturbations that are always present in aerial vehicles, to stabilize the position of the tool and to accommodate the effect of contact forces and torques in the assembly tasks. This paper presents the design and control structure of a quadrotor prototype with a specially built light multi-link manipulator (Fig. 1).

A problem that arises in these applications is that the dynamic behavior of the vehicle changes due to the modification of the aerial vehicle mass center and mass distribution by grasping and manipulating objects, and by contact forces that may appear when interacting with the environment. This effect is usually not taken into account explicitly and left to the integral term in the feedback controller for correction. The paper [9] presents stability limits within which the changing mass-inertia parameters of the system will not destabilize quadrotors and helicopters with standard PID controllers. On the other hand, [10] studies the effect of grasping objects at a point displaced from its center of mass and develops a controller that takes it into account explicitly.

This paper addresses the design and control of quadrotors with multi-link manipulator arms. Next section presents the control approach that has been followed. The dynamic model of the quadrotor with a variable center of mass and inertia is presented in section III, while section IV presents the Variable Parameter Integral Backstepping controller. Section V shows the simulation experiments that have been done, and section VI the outdoor experiments performed with the QARM1 prototype. Finally, the Conclusions and References are also included.

II. CONTROL APPROACH
The full dynamic model of a quadrotor with a n-link manipulator arm is very complex since it includes the coupled dynamics of the quadrotor aerial vehicle and the manipulator. Then, the model based controller needed to compute jointly the control actions of the aerial platform and the arm is also complex and difficult to implement in the on-board hardware. To make the problem more tractable and develop a control strategy that can be implemented onboard we have considered the control scheme in Fig. 2.

The quadrotor controller block is the responsible for attitude and position control of the quadrotor. The arm joints variables are used in this controller to compensate for the motion of the arm. For control design purposes, the quadrotor model is considered as a standard quadrotor plus an articulated body, which causes the center of mass to be displaced from the geometric Z axis of the quadrotor and modifies the inertia, and both of them are dependent on the arm joint angles. On the other hand, the arm controller block takes as inputs the state coordinates of the quadrotor, and it commands the motors of the arm to try to compensate for the motion of its base (quadrotor), so that the Tool Center Point (TCP) or end effector of the manipulator (gripper shown in Fig. 1) maintains the desired position (to grab and release objects), or follows a predefined trajectory.

This paper concentrates on the quadrotor attitude controller which is responsible for stabilizing quadrotor attitude angles, taking care of the variable position of the center of mass and the inertia matrix, which vary when the manipulator arm moves. Next section describes the dynamic model of a quadrotor with a multi-link manipulator, which is needed to design the attitude controller. Section IV presents the Variable Parameter Integral Backstepping controller which is used to control quadrotor attitude.

The position controller uses an Integral Backstepping algorithm, and the arm controller use a standard PID-based scheme.

III. DYNAMIC MODEL OF A QUADROTOR WITH A MULTI-LINK MANIPULATOR
Dynamic models of quadrotors usually consider that the mass distribution is symmetrical leading to simplified model equations [11]. Mass distribution of a quadrotor with a multi-link manipulator arm is no longer symmetrical and varies with the movement of the arm. The effect is twofold: there is a displacement of the center of mass, which in general will be off the z body axis of the quadrotor, and also the inertia matrix changes when the arm joints move. Consider a quadrotor with a manipulator arm with n links attached to its lower part, being \( y = [y_1, ..., y_n] \) the coordinates of the links. If the dynamics of the arm is neglected, the Newton-Euler general dynamic equations of the quadrotor at the center of mass in body coordinates can be expressed as:

\[
\dot{m}V + \Omega \times (mV) = F_{prop} + F_{aero} + F_{grav} \\
I(\gamma)\ddot{\Omega} + \Omega \times (I(\gamma)\dot{\Omega}) = \tau_{prop} + \tau_{aero} + \tau_{arm}(y)
\]  (1)  (2)

where \( V \) is the linear speed and \( \Omega \) is the angular speed, both in body frame coordinates. \( F \) and \( \tau \) are respectively the external forces and torques applied to the quadrotor (subindex grav is for gravity, aero is for aerodynamic and prop is for propulsive), while \( m \) is the mass of the system. The term \( \tau_{arm}(y) \) is the torque generated by the total propulsive force being applied at the quadrotor geometric center which is displaced from the center of mass. The inertia matrix \( I(\gamma) \) is calculated with respect to the center of mass, which depends on the angular positions of the arm links.
Note that the inertia matrix can no longer be approximately diagonal and that the inertia cross-products will be present. If the aerodynamic forces are neglected, the equations for the three rotational degrees of freedom result in:

\[
\begin{align*}
\dot{\phi} &= \dot{\theta} \dot{\psi} a_1 + (\dot{\phi} \dot{\psi} - \dot{\theta}) a_2 - (\dot{\phi} \dot{\theta} + \dot{\psi}) a_3 + \\
&\quad + (\dot{\phi}^2 - \dot{\theta}^2) a_4 + \theta a_5 \Omega_r + d_1 U_2 + T_{arm1}(y) \\
\dot{\theta} &= \dot{\psi} b_1 - (\dot{\phi} \dot{\psi} - \dot{\theta}) b_2 + (\dot{\phi}^2 - \dot{\theta}^2) b_3 + \\
&\quad + (\dot{\phi} \dot{\psi} - \dot{\theta}) b_4 - \phi b_5 \Omega_r + d_2 U_3 + T_{arm2}(y) \\
\dot{\psi} &= \dot{\phi} c_1 + (\dot{\phi}^2 - \dot{\theta}^2) c_2 + (\dot{\phi} \dot{\psi} - \dot{\phi}) c_3 - \\
&\quad - (\dot{\phi} \dot{\psi} + \dot{\theta}) c_4 + d_3 U_4
\end{align*}
\]

where \(\phi, \theta, \psi\) are the roll, pitch, and yaw attitude angles respectively and the parameters \(a(y) = [a_1, a_2, a_3, a_4, a_5]\), \(b(y) = [b_1, b_2, b_3, b_4, b_5]\), \(c(y) = [c_1, c_2, c_3, c_4]\) and \(d(y) = [d_1, d_2, d_3]\) vary with the position of the arm because they are obtained from the inertia matrix \(I(y)\) of the system as follows:

\[
\begin{align*}
a_1 &= \begin{pmatrix} l_{xy} - l_{xz} \\ l_{xx} - l_{yy} \end{pmatrix} \quad b_1 = \begin{pmatrix} l_{xy} \\ l_{yy} \end{pmatrix} \\
a_2 &= \begin{pmatrix} l_{xy} \\ l_{xx} \end{pmatrix} \quad b_2 = \begin{pmatrix} l_{xy} \\ l_{yy} \end{pmatrix} \\
a_3 &= \begin{pmatrix} l_{xz} \\ l_{xx} \end{pmatrix} \quad b_3 = \begin{pmatrix} l_{xz} \\ l_{yy} \end{pmatrix} \\
a_4 &= \begin{pmatrix} l_{yz} \\ l_{xx} \end{pmatrix} \quad b_4 = \begin{pmatrix} l_{yz} \\ l_{yy} \end{pmatrix} \\
a_5 &= \begin{pmatrix} l_r \\ l_{xx} \end{pmatrix} \quad b_5 = \begin{pmatrix} l_r \\ l_{yy} \end{pmatrix}
\end{align*}
\]

In the above expressions \(l\) is the distance from the rotors to the geometric center of the quadrotor and \(l_r\) is the rotor inertia. The control inputs are written according to the angular velocities of the four rotors (\(\Omega_i\)) as follows:

\[
\begin{align*}
U_1 &= K_p (\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\
U_2 &= K_d (\Omega_1^2 - \Omega_2^2) \\
U_3 &= K_d (\Omega_3^2 - \Omega_1^2) \\
U_4 &= K_d (\Omega_2^2 + \Omega_3^2 - \Omega_1^2 - \Omega_2^2)
\end{align*}
\]

where \(K_p\) is the thrust factor and \(K_d\) the drag factor.

IV. VARIABLE PARAMETER INTEGRAL BACKSTEPPING CONTROLLER

There are many control techniques that have been used for quadrotor control. Among them, PID is one of the most popular in practical applications since it is easy to implement and tune. However, PDIs are not able to cope well with the variable center of mass and inertia of our system.

The controller that we have implemented is the Variable Parameter Integral Backstepping (VPIB). It is based on a nonlinear backstepping controller with an integral term [11], which is well suited for the cascaded structure of the quadrotor dynamics, guarantees asymptotic stability and has robustness to some uncertainties, while the integral action cancels the steady state errors. Furthermore, as will be shown in the next subsection, the inertia moments appear explicitly in the controller parameters, giving it the ability to adapt to substantial changes in the inertia moments of the quadrotor when the arm moves. The proposed controller also includes a feedforward term to compensate the \(T_{arm}(y)\) torque, generated by the displacement of the center of mass from the quadrotor geometry center.

A. Attitude control

The quadrotor attitude controller is very important since it is in the inner control loop and will maintain the desired quadrotor orientation. Since quadrotors are underactuated systems, the position control loop is built on top of the attitude control loop, generating desired attitude references that are passed to the inner loop.

This subsection will describe the derivation of the roll VPIB controller. The design process of the VPIB controller is similar for the other two attitude angles. Consider the tracking error \(e_1 = \phi_d - \phi\), where \(\phi_d\) is the desired roll angle, and its dynamics:

\[
\frac{de_1}{dt} = \phi_d - \omega_x
\]

Then a virtual control over the angular speed \(\omega_x\) will be formulated, which is not a control input. Therefore, the desired angular speed can be defined as follows:

\[
\omega_{xd} = k_1 e_1 + \dot{\phi}_d + \lambda_1 \dot{\chi}_1
\]

with \(k_1\) and \(\lambda_1\) positive constants and \(\dot{\chi}_1 = \int_0^t e_1(r)dr\) the integral of the roll tracking error. Next, the angular velocity tracking error \(e_2\) and its dynamics can be defined by:

\[
\frac{de_2}{dt} = k_1 (\phi_d - \omega_x) + \dot{\phi}_d + \lambda_1 e_1 - \dot{\phi}
\]

Using (6) and (7) the roll tracking error dynamics equation (5) can be rewritten as:

\[
\frac{de_2}{dt} = -k_1 e_1 - \lambda_1 \dot{\chi}_1 + e_2
\]

Now, \(\dot{\phi}\) in (7) can be replaced by its expression in the rotational model (3), and the control input \(U_2\) appears explicitly:

\[
\frac{de_2}{dt} = k_1 (\phi_d - \omega_x) + \phi_d + \lambda_1 e_1 - \dot{\theta} \dot{\psi} a_1 - (\dot{\phi} \dot{\psi} - \dot{\theta}) a_2 + \\
\quad + (\dot{\phi} \dot{\psi} + \dot{\theta}) a_3 - (\dot{\phi}^2 - \dot{\theta}^2) a_4 - \theta a_5 \Omega_r - d_1 U_2
\]
\[
\frac{de_2}{dt} = k_1(-k_1 e_1 - \lambda_1 x_1 + e_2) + \dot{\theta}_d + \lambda_3 e_1 - \theta \psi a_4 - (\phi \psi - \tilde{\theta}) a_2 + (\theta \dot{\phi} + \psi \dot{\theta}) a_3 - (\dot{\psi}^2 - \theta^2) a_4 - \dot{\theta} a_5 \Omega_r -
\]

Finally the control input \( U_2 \) can be calculated as:

\[
U_2 = \frac{1}{d_4}[(1 - k_3^2 + \lambda_3) e_1 + (k_3 + k_4) e_2 - k_3 \lambda_3 x_1 + \dot{\phi}_d - \dot{\theta} \psi a_4 - (\phi \psi - \tilde{\theta}) a_2 + (\theta \dot{\phi} + \psi \dot{\theta}) a_3 - (\dot{\psi}^2 - \theta^2) a_4 - \dot{\theta} a_5 \Omega_r]
\]

where \( k_2 \) is a positive constant which determines the convergence speed of the angular speed loop. Similarly, the following pitch and yaw control signals can be derived:

\[
U_3 = \frac{1}{d_2}[(1 - k_5^2 + \lambda_5) e_5 + (k_5 + k_6) e_6 - k_5 \lambda_5 x_5 + \dot{\theta}_d - \phi \psi b_1 + (\psi \dot{\theta} + \dot{\phi}) b_2 - (\dot{\psi}^2 - \theta^2) b_3 - (\theta \dot{\phi} - \psi \dot{\theta}) b_4 + \phi b_5 \Omega_r]
\]

\[
U_4 = \frac{1}{d_3}[(1 - k_7^2 + \lambda_7) e_7 + (k_7 + k_8) e_8 - k_7 \lambda_7 x_7 + \dot{\psi}_d - \dot{\phi} c_1 - (\theta^2 - \dot{\psi}^2) c_2 - (\theta \dot{\psi} - \dot{\phi}) c_3 + (\phi \dot{\psi} + \dot{\phi}) c_4]
\]

with \((k_3, k_4, k_5, k_6, \lambda_2, \lambda_3) > 0, \) and \((\chi_2, \chi_3)\) the integral position tracking errors of pitch and yaw angles respectively.

V. SIMULATION EXPERIMENTS

Extensive simulation tests have been performed with the proposed controller. The simulator implements the full dynamic model of the quadrotor with the manipulator arm. The noise characteristics of the sensors have also been included in the simulator, to make it more realistic. The attitude sensors are updated at 50 Hz and have a standard deviation of 1.2 degrees. The position sensors have been assumed to have a standard deviation of 0.04 m and updated at 10 Hz, which could be typical if vision sensors are used.

The first batch of simulations was intended to test the performance of the VPIB attitude controller. For comparison purposes a standard nested PID controller, which does not take into account explicitly the movement of the arm, has been also simulated. The roll, pitch and yaw attitude angles of the quadrotor are shown in Fig. 3. for the VPIB controller and Fig. 4. for the PID controller.

The simulation experiments have three parts: in the first 5 seconds the quadrotor stabilizes the flight and puts the arm pointing down. Then in the second part (from 5 to 10 s.) the arm is raised until it is totally extended horizontally. In the last 5 seconds of the simulation the quadrotor tries to maintain hover with the arm extended (worst case situation). It can be seen from the simulations that the VPIB performs much better than the PID in stabilizing the attitude angles when the arm is moving.

Extensive tests have also been done to test position control with compensation of the motion of the arm. In this case, three different configurations have been tested. The first one is the standard nested PID controller that does not consider the movement of the arm for the attitude control loop, which also implements PID for position control. The second is the VPIB controller for the attitude and an Integral Backstepping controller for position. And the last case is the same that the previous one, but including the arm controller that tries to compensate for the oscillations of the quadrotor.

To illustrate the controller performance, Fig. 1. shows the position of the TCP of the manipulator arm in the vertical plane (X-Z), which is the most interesting for object manipulation. Fig. 1. shows typical results of the excursions of the TCP when the aerial robot is trying to maintain it in a fixed position for the three controllers discussed in the previous paragraph (remember that the simulator includes...
sensor noise errors and update rate). Shaded polygons have been plotted covering the envelope of the TCP positions (red for the PID controller, blue for the VPIB controller and green for the VPIB with arm compensation). Maximum TCP deviations are typically within +/- 10 cm for the PID controller, within +/-5 cm for the VPIB controller and within +/- 1.5 cm for the VPIB with arm compensation.

Fig. 5. TCP of the arm in the vertical plane with the VPIB controller

These simulations show that the VPIB outperforms significantly the standard PID controller for position control. Furthermore, the movement of the arm to compensate for the oscillations of the quadrotor is able to reduce the position error of the TCP, making the proposed controller a promising solution for precise object manipulation applications.

VI. OUTDOOR EXPERIMENTS

A. Design and construction of a quadrotor with a 3-link manipulator arm.

The experimental tests have been done outdoors with the QARM1 aerial robot, which is a quadrotor with a 3-link light manipulator arm developed by GRVC at University of Seville and CATEC (see Fig. 1.).

The quadrotor has a standard configuration with four electric motors with fixed-pitch propellers in the ends of two crossbars. The quadrotor gross weight is 980 g. including batteries, controller and sensors. It has a three-link manipulator arm attached at the center of its belly between the two skids. The manipulator weights 400 g., and the payload is around 200 g.

The QARM1 has a controller board based on the Arduocopter design [12] with a 16 MHz ATMega2560 microcontroller, and a sensor board with MEMS three-axis accelerometers and gyros, and a single frequency GPS receiver.

The manipulator arm has been specially designed and built for this purpose, given the payload limitations of the quadrotor. The main design criteria that have been considered are to minimize the displacement of the center of gravity and the total arm weight, and maximize the load to weight ratio. The different parts of the arm have been built from polymer powder by Rapid Manufacturing.

B. Attitude control experiments

Several tests have been performed outdoor with the QARM1 to test the proposed VPIB controller. The experiments consisted in moving the arm while the quadrotor was in flight to test the stabilization performance of the controller. The arm was moved several times from a position in which is pointing down and the arm extended horizontally (see Fig. 8.).

The tests were performed first with the standard nested PID controller which does not consider the effects of the
arm, and then using the VPIB controller proposed in this paper. Typical results for the roll and pitch angles using the PID controller are shown in Fig. 9. Also roll and pitch attitude angles when the QARM1 is controlled by the VPIB controller are presented in Fig. 10.

The VPIB controller performed consistently better than the PID controller. With VPIB the attitude angles were more stable and the oscillations were reduced to less than a half compared to the standard PID.

More tests will be needed to study the VPIB controller performance. The MEMS sensors that are mounted now on the QARM1 are not very precise and are somewhat affected by the vibration of the motors. Furthermore, the position error of the single frequency GPS receiver did not allow testing neither the position controller nor the arm compensation with this sensor suite. A more precise sensor suite will be installed in the QARM1 in the future.

VII. CONCLUSIONS

Aerial robotics is evolving to include not only systems with sensing capabilities but also with the possibility to act on the environment, and particularly with manipulation capabilities. This paper deals with an Unmanned Aerial System with a robotic arm. Particularly, a quadrotor with a multi-link arm for assembly applications is presented. The paper has shown by simulation and outdoor experiments how a Variable Parameter Integral Backstepping controller can be used to control the aerial platform compensating the motion of the arm. It has been also shown that the proposed method outperforms the results that can be obtained with conventional PID controllers.

Future work will be devoted to the integration of the arm controller for assembly operations, including the assembly of structures as considered in the ARCAS project.

ACKNOWLEDGMENT

This work has been supported by the ARCAS Project, funded by the European Commission under the FP7 ICT Programme (ICT-2011-287617) and the CLEAR Project (DPI2011-28937-C02-01), funded by the Ministerio de Ciencia e Innovacion of the Spanish Government.

The authors would like to thank Victor Vega and Juan Braga for their unselfish help during the experiments.

REFERENCES