Mechanical Design of a 6-DOF Aerial Manipulator for assembling bar structures using UAVs

R. Cano*, C. Pérez* F. Pruaño* A. Ollero** G. Heredia**

*Centre for Advanced Aerospace Technologies, Seville, Spain (e-mail: {rcano,cperez,fjpruano.ext}@catec.aero).
**University of Seville, Seville, Spain (e-mail: {aollero,guiller}@us.es).

Abstract: The aim of this paper is to show a methodology to perform the mechanical design of a 6-DOF lightweight manipulator for assembling bar structures using a rotary-wing UAV. The architecture of the aerial manipulator is based on a comprehensive performance analysis, a manipulability study of the different options and a previous evaluation of the required motorization. The manipulator design consists of a base attached to the UAV landing gear, a robotic arm that supports 6-DOF, and a gripper-style end effector specifically developed for grasping bars as a result of this study. An analytical expression of the manipulator kinematic model is obtained.

1. INTRODUCTION

In the last years, a significant progress has been made in research and development of Unmanned Aerial Vehicles (UAVs) involving physical contact and interaction tasks with the environment, such as cargo transport, load deployment, sampling, aerial grasping or even aerial manipulation mainly using rotary-wing platforms.

Initially, low capacity UAVs incorporated fixed claws under the platform (Mellinger et al. (2011); Pounds et al. (2011)), allowing the system to carry lightweight and small size objects. However, the uncertainty in the positioning maneuver during hovering, inherent to rotary wing platforms, and the reduced motion of claws made an autonomous accurate grasping difficult. To face this problem, solutions with either magnetic devices (Lindsey et al. (2011)) or by using poorly articulated claws (Doyle et al. (2011)) were proposed. Although this last option had the additional advantage of extending the range of applications of the robotic system, also implied a significant increase in on-board weight, which was difficult to afford by conventional UAVs. With the recent release of new high power aerial platforms, weight restrictions have ceased to be so critical. This fact has led to the use of multi-jointed manipulators (Jimenez-Cano et al. (2013); Kondak (2013); Danko (2013)).

The FP7 European Commission project ARCAS (FP7-287617) has recently proposed the development of a robotic aerial system for the cooperative assembly of bar structures. In this context, a lightweight manipulator with 6 Degrees Of Freedom (DOF), on-board a rotary-wing UAV, has been considered for indoor experiments. The mechanical design of this manipulator is the subject of this paper. In the next section, design requirements are reviewed. Section 3 and 4 respectively show the mechanical architecture and the design of the robotic manipulator. Finally, section 5 presents the kinematic model, being the last section for conclusions.

2. REQUIREMENTS

The three basic functions required for an aerial manipulator intended for assembling bar structures are the capture, including the manipulator approach to the bar and the grasping by the end effector; the transport, that involves the displacement of the load from the storage place to the construction site; and the assembling of the bar, whose purpose is to install it at the assigned location within the structure. These functions will be executed in a cyclic manner during the construction process, so that once a bar has been captured, transported, and finally assembled, the aerial manipulator returns back to the storage place to capture a new one and to repeat the process. The successful achievement of these capabilities is conditioned by the fulfillment of several design requirements. Some of these requirements are generic, typical of any manipulator, and others are specific, due to the particularity of being on-board a rotary-wing UAV. The later are reviewed below.

Weight and length of the manipulator. The UAV maximum payload is usually very limited, being this capacity drastically reduced when the mass of the load is far from the Center Of Gravity (COG) of the platform. Moreover, loads with a highly off-centre mass make the platform stabilization difficult and seriously undermine its maneuverability. Therefore, the weight of the manipulator should be a key feature during the design process. Regarding the length of the manipulator, it should be long enough to provide a suitable workspace. For the UAV used in the experiments, the manipulator weight will be lower than 1.5 Kg and a minimum length (fully extended) of 500 mm will be considered. This length will not only allow to handle the bar below the aerial platform without risk of collision with their propellers, but also to have it at the same height.

Compact configuration of the manipulator. If the storage place, where the bars are collected, is far from the
construction site, it will be useful that the aerial manipulator could take a compact configuration during bar transportation. This will prevent accidental impacts with obstacles and will reduce the aerodynamic drag of the whole structure. This compact configuration may also be adopted by the manipulator when it is not in use, improving the controllability of the aerial platform and facilitating the access to tight places.

Uncertainty in the positioning of the platform. When the rotary-wing UAV hovers, it is not completely stable, but there are small oscillations around the control reference of all DOF. These oscillations, mostly caused by electro-mechanical asymmetries and turbulences in the air stream entering the platform rotors, may cause difficulties in the end effector positioning. Manipulator dynamic is usually faster than the aerial platform and therefore it is able to compensate quicker this kind of disturbances. However, the manipulator dynamic is strongly coupled with the aerial platform (Jimenez-Cano et al. (2013); Kondak et al. (2013)) and it would be necessary to find a compromise between the manipulator speed and the reaction forces at the platform.

Disturbances caused by displacements of the manipulator COG. When the manipulator configuration changes, the position of its COG varies, generating a reaction torque at the platform. In rotary wing UAVs, this torque produces an inclination of the propellers plane, which also induces a displacement of the entire aerial platform. This disturbance is particularly evident in those cases in which combined mass of the manipulator and its load is significant in comparison with the mass of the UAV. On heavy platforms with lightweight manipulators and loads this disturbance is negligible. The UAV control system can be used to compensate the effect of this perturbation, being not strictly necessary to develop any other additional mechanism.

3. ARCHITECTURE

The manipulator architecture is based on a comprehensive performance analysis, a manipulability study of the different options and a previous evaluation of the required motorization.

2.1 Performance analysis

The identification process of the joints that need to be implemented in the manipulator is performed through the performance analysis during the bar capture, transport and assembly phases. Regarding the grasping, if the target bar is prepared every time with a similar position and orientation, manipulator joints will always adopt a similar configuration to capture it. If the bar is in a different placement each time, grasping maneuver could require more complex motions. In any case, these abilities will be much more critical in the assembly phase of the bar due to the high precision required and the presence of significant contact forces, so this task will be analyzed with more details.

To fulfill the requirement for a safe and efficient bar transportation using a compact manipulator configuration, the implementation of two pitch-type joints is proposed: one at the base of the manipulator, to allow it to retract under the platform; and another approximately at the midpoint to fold the manipulator onto itself maximizing the length reduction.

In the assembly process of the bar shown in Fig. 1, the aerial platform starts by positioning near the construction site (1), maintaining a safety distance that allows a manipulation free of obstacles. Then, the manipulator is configured to reach the target bar orientation (2). Once the platform stabilizes, the manipulator is slowly placed at the same height of the final assembly location and in front of it (3), keeping enough clearance to avoid collisions due to the platform oscillations. Then, the manipulator extends within the vertical plane, moving the end effector by a straight line without changing the bar orientation, in order to place it just over the assembly location (4). Finally, when the platform stabilizes again, the end effector performs a vertical linear motion to insert the bar (5).

In general, the precise linear movements of the bar, both horizontal and vertical, should be performed with the manipulator DOF instead of using the aerial platform, more difficult to control. Then, it has been decided to include three pitch-type joints to allow these linear movements without orientation changing. In addition to this, a very often maneuver is the rotation of the bar in the end effector plane just to orient it. A roll-type joint can be used for this purpose, but it is recommended to locate it close to the end effector, at the end of the kinematic chain, to avoid moving also other joints when the rotation is performed. Furthermore, joint configurations that lead the manipulator out of the vertical plane generate disturbances due to the displacement of the manipulator COG that are difficult to compensate by the control system [6]. However, as small oscillations of the platform in the lateral direction are unavoidable, it is also required the presence of a yaw-type joint that allows to correct the perturbations.

It is well known that the minimum number of DOF to achieve any position and orientation within the workspace is 6. More DOF would allow multiple solutions, which could be very beneficial in case of environments with many obstacles. However, the use of more DOF results in a larger weight and control complexity. Then, it was decided to use only six. Nevertheless, the aerial platform used in experiments already
has 4-DOF, so theoretically some of the six manipulator DOF could even be replaced by some of the four platform DOF. Since the aerial platform dynamic is slower than the manipulator one, some manipulation tasks would be difficult to perform.

Finally, although the inverse kinematics model of a manipulator can be calculated for any simple 6-DOF chain integrated by rotation joints, it is not always possible to obtain it analytically. Numerical methods are a common alternative, but they are usually slower and often lead to problems of convergence, so they are not recommended for real-time applications with high sampling time. Since the solution of the problem may not be unique, the analytical expression has the additional advantage of being able to include simple programming strategies to choose the most suitable solution among all possible. Therefore, in order to obtain an analytic expression of the inverse kinematics, a mathematical method developed by Pieper (1968) is used for its calculation. This method requires as a condition that the axes of three consecutive joints intersect at a point or are parallel. To overcome this condition, it was decided that the manipulator joints 4, 5 and 6 are respectively roll-pitch-roll.

2.2 Manipulability study

The above performance analysis gives rise to one main architecture with regards to the choice and order of the DOF. However, it provides two major solutions in terms of the DOF location. For the first solution, the DOF distribution from the base of the manipulator to the end effector is yaw-pitch/pitch-roll-pitch-roll. An elongated structure (designed by “r”) would be located between the first and the second pitch-type joints to gain some extra length. For the second solution, the DOF distribution is yaw-pitch-pitch/roll-pitch-roll and the elongated structure would be between the second pitch-type joint and the following roll-type one. In this section, the degree of manipulability of both sequences is examined to choose the most favorable. Specifically, it is analyzed the dexterity of the manipulator to move the end effector in arbitrary directions with equal ease, since this ability is crucial to reduce the uncertainty in the positioning of the aerial platform when it hovers.

One of the most representative manipulability index of a manipulator with a given configuration \([\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]\) is the volume \(V\) of the manipulability ellipsoid (Yoshikawa (1990)). The measures of \(V\), corresponding to a manipulator configurations sweeping in the range of the expected position during the insertion of the bar, are shown in Fig. 2. In particular, pitch-type joints are analyzed at the intervals \(\theta_2 = \left[ -\frac{\pi}{2}, 0 \right] \), \(\theta_3 = [0, \pi] \), \(\theta_4 = -(\theta_3 + \theta_2)\), while the rest of joints are fixed to \(\theta_1 = \theta_5 = \theta_6 = 0\). Reference lengths of 5 cm for each link and 20 cm for the elongated structure are considered.

The higher manipulability volume is reached by the sequence yaw-pitch/pitch-roll-pitch-roll, so this one will be chosen for the manipulator design. It is obtained for the configuration shown in Fig. 3. Since around this optimal configuration is possible to move the end effector very fast in any direction and far enough from the workspace boundary, it will be considered as a base position to perform precise maneuvers, such as the insertion of the bar. By contrast, a singular configuration with the manipulator fully extended would not be advisable, since any disturbance of the aerial platform may require a not reachable end effector position.

![Fig. 2. Manipulability ellipsoid volume for considered sequences. The maximum volume obtained for yaw-pitch/pitch-roll-pitch-roll sequence (in blue) is 0.0362 m³, while for yaw-pitch-pitch/roll-pitch-roll (in red) is 0.0224 m³.](image)

![Fig. 3. Manipulator configuration for the maximum volume of the manipulability ellipsoid. Joint coordinates pitch-type (in red) are \(\theta_2 = -0.7714\) rad, \(\theta_3 = 1.3002\) rad and \(\theta_4 = -0.5288\) rad. The intersection between the ellipsoid and the plane \(y = 0\) is an ellipse shown on scale 1:4.](image)
2.3 Motorization pre-evaluation

The motorization for driving the manipulator joints is selected by ensuring that the expected maximum torques, provided by the manipulator dynamic model, are always reachable. Although this model is initially unknown, a previous simplified evaluation can be made in order to have a useful first approach to face the design process.

The manipulator dynamic model can be written in the general form:

\[ \tau = M(\theta)\dot{\theta} + G(\theta) + V(\theta, \dot{\theta}) + F(\dot{\theta}) + \tau_c, \]

where \( \tau \) is the external torque vector, \( M(\theta) \) is the mass matrix, \( G(\theta) \) is the gravity terms vector, \( V(\theta, \dot{\theta}) \) considers centrifugal and Coriolis effects, \( F(\dot{\theta}) \) includes friction terms and \( \tau_c \) represents the torques generated by contact forces during bar installation, being \( \theta \) the manipulator joint coordinates vector. Friction effects are usually quite difficult to model, but in some cases are negligible compared to the other terms. Coriolis and centrifugal effects are relatively small since the speeds involved are small, while the inertia term is relevant in cases in which high mass needed to accelerate at a great distance from axis of articulation.

The proposed pre-evaluation of the motorization considers motors able to provide maximum torques \( \tau_{max} \) that satisfy

\[ \tau_{max} \geq I_0 a_{\text{ref}} + G(\theta^*) + \tau_c, \]

where \( \theta^* \) is the most unfavorable configuration of the manipulator with regard to gravitational effects; \( I_0 \) is a vector of approximated mass inertia moments; and \( a_{\text{ref}} \) is a vector of angular accelerations of each joint that is calculated to compensate the aerial platform oscillations caused by the turbulences in the air stream entering the platform rotors. The mass inertia moments vector \( I_0 \) is estimated assuming a manipulator structural mass of 150 g uniformly distributed, as well as an end effector mass of 200 g and a bar mass of 100 g. The concentrated mass of each motor is also considered. The maximum torques required at each joint for the horizontally extended configuration of the manipulator is shown in Table 1. Robotis-Dynamixel DC servo motors are selected for being small and lightweight, and having a geometry that facilitates the installation.

The manipulator consists of three components, shown in Fig. 4: a fixed base, a multi-joint arm and an end effector specifically developed for grasping bars. Structural materials used are commercial Carbon Fiber Reinforced Plastic (CFRP) and aluminum. Fasteners such as screws, nuts and washers are mostly aluminium made ones in order to save weight. The base reaches an approximate mass of 650 g, while moving components, the arm and the end effector, represent a combined mass of 750 g. Then, the total mass of the manipulator is 1.4 kg, below the limit imposed as a requirement due to the payload limitation of aerial platforms. The manipulator total length, when it is completely extended, is 450 mm from the first joint of the arm to the end effector. The position of the arm clamping point on the base is displaced about 100 mm from the center of the latter, so that planned initial length of 500 mm has been reduced.

### Table 1. Previous assessment of manipulator motorization.

<table>
<thead>
<tr>
<th>Art.</th>
<th>Type</th>
<th>( I_0 a_{\text{ref}} ) (Kg cm)</th>
<th>( G(\theta^*) ) (Kg cm)</th>
<th>( \tau_c ) (Kg cm)</th>
<th>( \tau_{\text{total}} ) (Kg cm)</th>
<th>( \tau_{\text{max}} ) (Kg cm)</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>ROLL</td>
<td>-</td>
<td>-</td>
<td>6.25</td>
<td>6.25</td>
<td>8</td>
<td>AX18A</td>
</tr>
<tr>
<td>5</td>
<td>PITCH</td>
<td>0.29</td>
<td>3.20</td>
<td>-</td>
<td>3.48</td>
<td>8</td>
<td>AX18A</td>
</tr>
<tr>
<td>4</td>
<td>ROLL</td>
<td>-</td>
<td>-</td>
<td>6.25</td>
<td>6.25</td>
<td>8</td>
<td>AX18A</td>
</tr>
<tr>
<td>3</td>
<td>PITCH</td>
<td>0.67</td>
<td>7.67</td>
<td>-</td>
<td>8.34</td>
<td>10</td>
<td>MX28T</td>
</tr>
<tr>
<td>2</td>
<td>PITCH</td>
<td>2.09</td>
<td>23.36</td>
<td>-</td>
<td>25.45</td>
<td>30</td>
<td>MX106T</td>
</tr>
<tr>
<td>1</td>
<td>YAW</td>
<td>-</td>
<td>11.25</td>
<td>11.25</td>
<td>17</td>
<td>MX64T</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Base

The base is an auxiliary fixed component that supports the mobile parts of the manipulator, as shown in Fig. 5. The main element of the base is a plate made of CFRP, where the rest of elements are installed on. It is attached to the UAV landing gear by four CFRP fittings and has both longitudinal and transverse stiffeners that provide a great rigidity. The arm is screwed at the front of the plate and some reinforcements are also placed close to the clamping point.

![Fig. 4. Manipulator components: base, arm and end effector.](image1)

![Fig. 5. Top view (left) and bottom view (right) of the manipulator base.](image2)
3.2 Arm

The arm is an articulated component that contains all the manipulator DOF. It includes a first section with two motorized joints, yaw-pitch, followed by an elongated structure in the shape of a "U", made in CFRP. There is a second section composed of a chain of four motors driving the remaining joints, pitch-roll-pitch-roll, as shown in Fig. 6.

![Fig. 6. Manipulator arm and DOF order.](image)

The "U" structure is formed by four rods embedded at their ends. A central stiffener curves the rods, originally straight. Rods prestressed in this manner make a highly stiff and lightweight structure. The design of the "U" structure allows the manipulator to adopt a compact configuration in situations that it is not used or while bar is being transported. The deployment process from the compact configuration to the base position is shown in Fig. 7. When the arm is retracted, the "U" structure can accommodate within the motors chain.

![Fig. 7. Arm deployment sequence: the manipulator goes from the compact configuration (1) to the base position (3) passing through (2).](image)

3.3 End effector

The manipulator end effector is gripper-style and has two claws designed for a robust hold by mechanical pressure. This architecture, particularly adapted to the bar used in experiments, cylindrical and 20 mm outer diameter, is shown in Fig. 8. Each claw is formed by two CFRP fingers, one upper and one lower. Upper fingers of both claws are connected for greater structural rigidity and they are directly driven by a single motor. Lower fingers, also connected, are moved simultaneously by this same motor through a gear transmission. The contact between the bar and each claw takes place in three points placed at 120° using rubber wheels. This envelope configuration, very resistant to disturbances, also helps during the bar gripping to its self-centering. Moreover, since the length of the bar is quite large, about 500 mm, in comparison with the end effector, the claws are designed spaced 80 mm to increase stability.

![Fig. 8. Manipulator end effector with the gripper in a closed position.](image)

5. KINEMATIC MODEL

The manipulator Direct Kinematic Model is obtained by using the well-known Denavit-Hartenberg (D-H) method. Coordinate frames associated to each DOF and the corresponding links are represented in Fig. 9, while D-H parameters are shown in Table 2. Craig convention (Ollero (2001)) is followed for mathematical developments.

![Fig. 9. Coordinates frames for DH method. Y-axis is not represented for simplicity. Vectors (Px,Py,Pz) and (ax,ay,az) describe the end-effector position and orientation respectively. Vector (nx,ny,nz) defines end effector rotation around Z6 axis.](image)

<table>
<thead>
<tr>
<th>Link</th>
<th>(a_{i-1})</th>
<th>(\alpha_{i-1})</th>
<th>(t_i)</th>
<th>(d_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(\theta_1)</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>(\pi/2)</td>
<td>-L2</td>
<td>(\theta_2)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>L3</td>
<td>(\theta_3 + \pi/2)</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>(\pi/2)</td>
<td>0</td>
<td>(\theta_4)</td>
<td>L4</td>
</tr>
<tr>
<td>5</td>
<td>(-\pi/2)</td>
<td>0</td>
<td>(\theta_5)</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>(\pi/2)</td>
<td>0</td>
<td>(\theta_6)</td>
<td>L6</td>
</tr>
</tbody>
</table>

Table 2. D-H parameters. The origins of Frame 4 and Frame 5 are coincident for simplicity.
The model is given by the following equations (typical simplified notation is used for trigonometric functions, where \( \sin(\theta_i) = si \), \( \cos(\theta_i) = ci \) y \( \cos(\theta_1 + \theta_2) = \cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2) \)):

\[
P_x = s1s4s5L6 + c1((-s23c4s5 + c23c5)L6 + c23L4 + c2L3 - L2)
\]

(3)

\[
P_y = -c1s4s5L6 + s1((-s23c4s5 + c23c5)L6 + c23L4 + c2L3 - L2)
\]

(4)

\[
P_z = (c23c4s5 + s23c5)L6 + s23L4 + s2L3
\]

(5)

\[
a_x = (-c1s23c4 + s1s4)s5 + (c1c23)c5
\]

(6)

\[
a_y = (-s1s23c4 - c1s4)s5 + s1c23c5
\]

(7)

\[
a_z = c23s4s5 + s23c5
\]

(8)

\[
n_x = ((-c1s23c4 + s1s4)c5 - c1c23s5)c6 + (c1s23s4 + s1c4)s6
\]

(9)

\[
n_y = ((-s1s23c4 - c1s4)c5 - s1c23s5)c6 + (s1s23s4 - c1c4)s6
\]

(10)

\[
n_z = (c23c4s5 - s23s5)c6 - c23s4s6
\]

(11)

The manipulator Inverse Kinematic Model has been calculated following a specific development (Barrientos et al. (2007)) that uses Pieper method to achieve an analytical solution. This development allows a kinematic decoupling of the three first joint variables of the arm, \( \theta_1, \theta_2, \theta_3 \) obtained by purely geometrical methods, from the three later, \( \theta_4, \theta_5, \theta_6 \), calculated in a more systematic way from the homogeneous transform. The model is given by the following equations:

\[
\theta_1 = \arctg \left( \frac{P_y^*}{P_x^*} \right)
\]

(12)

\[
\theta_2 = \arctg \left( \frac{P_z^*}{\sqrt{(P_x^* + L2c1)^2 + (P_y^* + L2s1)^2}} \right)
\]

\[
-\arctg \left( \frac{L4s3}{(L3 + L4)c3} \right)
\]

(13)

\[
\theta_3 = \arctg \left( \frac{\sqrt{1 - \sin^2 \theta_2}}{\cos \theta_2} \right)
\]

(14)

\[
\theta_4 = \arctg \left( \frac{s1a_x - c1a_y}{-c1s23a_x - s1s23a_y + c23a_z} \right)
\]

(15)

\[
\theta_5 = \arccos (c1c23a_x - s1s23a_y + s23a_z)
\]

(16)

\[
\theta_6 = \arctg \left( \frac{c1c23a_x + s1c23a_y + s23a_y}{-c1s23a_x - s1s23a_y - s23a_z} \right)
\]

(17)

where

\[
P_x^* = P_x - L6a_x
\]

(18)

\[
P_y^* = P_y - L6a_y
\]

(19)

\[
P_z^* = P_z - L6a_z
\]

(20)

\[
CV = \frac{(P_x^* + L2c1)^2 + (P_y^* + L2s1)^2 + (P_z^*)^2 - L3^2 - L4^2}{2L3L4}
\]

(21)

\[
o_x = a_y n_z - a_z n_y
\]

(22)

\[
o_y = -a_x n_z + a_z n_x
\]

(23)

\[
o_z = a_x n_y - a_y n_x
\]

(24)

5. CONCLUSIONS

This paper presents a methodology to perform the mechanical design of a 6-DOF lightweight manipulator for assembling bar structures using a rotary-wing UAV. For a suitable choice of the number, type and order of the DOF, it has become clear the importance of conducting a thorough analysis of the expected manipulator performance. A manipulability study is also useful to maximize the manipulator dexterity, while a preliminary motor evaluation allows a first estimation of the weight and volume distribution to face the design process. A manipulator of this type developed for the ARCAS project is shown in Fig. 10. This robotic manipulator has been tested by teleoperation. In next months, an automatic control system will be developed to be integrated into the quadrotor controller to perform flight tests before the construction of bar structures.

Fig. 10. 6-DOF Aerial manipulator developed for ARCAS project.

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