Aerial Manipulator with a Compliant Arm for Bridge Inspection

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Abstract—This paper presents the design, development and testing of a 4-DoF aerial manipulator for bridge inspection, where the arm is placed at the upper part of the multirotor body. The manipulator joints are equipped with a compliant mechanism that allows the contact with the environment reducing the influence over the platform stability. The transmission mechanism consists of two pairs of springs and a potentiometer for measuring the angular deflection between the servo and the joint angular position, which allows the estimation of the contact forces. Experimental tests have been done with the aerial manipulator placing the end effector at different points in the lower part of a bridge girder, which is needed by bridge inspectors to measure girder’s deflections over time.

I. INTRODUCTION

In the last decade aerial robots are catching much interest in robotics research due to a wide variety of possible applications areas. More recently the development of Unmanned Aerial Systems (UAVs) equipped with robotics manipulators extends these applications since provides an improvement in the capability of interaction with natural environment. The inspections of power lines, manipulations of objects or building of platforms for rescue missions are good examples of the applications areas of these aerial manipulators.

The first research works focused in UAVs with a gripper for object grasping tasks and transporting loads [1] or for structure construction with a quadrotor team [2]. In [3], a manipulation system for a ducted-fan UAV is presented. This ducted fan is capable of interacting with the environments and can be used for industrial inspection tasks. The dynamical characteristics of a quadrotor with a custom-made manipulator for remote inspection by contact are showed in [4]. Examples of aerial vehicles with multi-link manipulators have been also developed. Robotics arms with more degrees of freedom can give an improvement of the manipulation capabilities. In [5] experimental results of an aerial manipulator composed by a helicopter and an industrial manipulator are presented. Similarly, a multirotor attached to a multi-link manipulator has been also presented in [6] and [7].

There have been several studies about dynamics and methodologies for controlling aerial platforms with robotics arms. In [8], the Lagrange dynamics of a quadrotor-manipulator system is presented and decoupled into the center of mass dynamics and the internal rotational dynamics of the UAV’s rotation and robotic arm configuration. In [9], a hybrid visual servoing with a hierarchical task-composition control framework is presented as a solution of the control problem for the aerial vehicle and the manipulator. An adaptive motion control laws using the method of virtual decomposition was proposed by [10].

An aerial manipulation system presents complex dynamics due to the modification of the system center of mass and the mass distribution when the arm is carrying out a manipulation task. This dynamic coupling hinder the stabilization and control of the system. Therefore, it is advisable to design lightweight arms to help the minimization of the influence of the manipulator over the aerial vehicle [11]. Furthermore, the interaction with the environment would produce contact forces that affect to the UAV stabilization [12]. Therefore, a compliant manipulator can be highly desirable due to provide protection against shocks and impacts. In [13], a design and experimental compliant lightweight robotic arm equipped with a compliant finger module for aerial inspection and manipulation in contact is presented. The development of UAVs attached with compliant robotic arms increase the possibilities of the aerial manipulation applications. One of these applications is the bridge inspection. The use of an aerial manipulation system for the bridge inspection task was presented in [14].

![Figure 1. Aerial manipulator for bridge inspection](image)

At present, bridge inspection is done through visual...
observations by inspectors. To accomplish the task, inspectors access to bridge components through equipment (ladders, rigging and scaffolds) and vehicular lifts (manlifts, bucket trucks and under-bridge inspection vehicles). They must work at high altitude and therefore, it becomes potentially dangerous for the inspectors. An aerial manipulator system can provide a solution for accomplish the inspection without human intervention, for that the arm can be equipped with sensors to measure structural cracks, voids in concrete or loss of reinforcing steel bar (rebar) cross section, deflections, etc.

This paper presents the design of a lightweight compliant manipulator for bridge inspection by contact. The robotic arm is attached to the top of a multirotor thus the manipulator can perform the inspection tasks using a sensor or tool placed at the end effector when the aerial vehicle is flying below a bridge. An altitude-force controller is also proposed and tested experimentally.

The paper is organized as follows: the next section describes the compliant robotic arm design. The kinematic and dynamic model is presented in Section III. This model is simplified for the development of an altitude-force control strategy as are described in section IV. Finally, experiments with the aerial manipulator designed inspecting a bridge are shown in Section V. Conclusions section is also included.

II. COMPLIANT ARM DESIGN

The design of an arm robot for aerial manipulation should take into account the payload of the aerial vehicle. Therefore, the high weight and mass distribution of most commercial robots manipulators make them not suitable for aerial manipulation applications. Low weight should be the first specification of the manipulator. This characteristic combined with an optimization of the arm’s inertia terms can reduce the influence of the robotic manipulator over the stability of the aerial platform. These constraints demand the use of materials with low mass density, such as aluminum and carbon fiber or 3D-printers materials as PLA or ABS.

In the last years the 3D-printers have achieved a great popularity and have become a powerful tool in the design and development of prototypes in several fields of engineering. The most affordable 3D printers on the market work with PLA or ABS. These materials have a low mass density and an acceptable resistant to impact. All of that make them an excellent election for the design and development of an aerial manipulator prototype. Furthermore, the use of a 3D-printer makes easier the repairs in case of UAV’s crashes or damages due to strong impacts.

The most used actuators for this kind of prototypes are smart servos as Herkulex or Dynamixel servos. These devices provide a high torque to weight ratio with accurate position control and present a compact solution that simplifies the mechanical design. Nevertheless, they have not a real torque control option and consequently, this complicates the implementation of different torque based control techniques present in the bibliography. On the other hand, the manipulator arm must interact with the environment hence the actuators will have a strong exposure to impacts and overloads. Thus it is highly convenient to endow the actuators of a passive compliance mechanism. It should absorb the impact energy in order to protect the servos and guarantee the platform stability. Using springs as elastic material in the compliance mechanism is possible to estimate the contact force through the measure of the deflection of these springs, making what is known as Series Elastic Actuators. Next subsection presents the implementation of a robust and compact mechanism placed between the actuators and the arm’s links designed for this goal.

A. Robotic Arm Design

Some of the tasks in bridge inspection that require direct contact with the bridge surfaces are the measurement of cracks and the measurement of the deflection of beams over time. To carry out these tasks with an UAV, the aerial manipulator should hold a desired position and force in a contact point during the time needed to attain sufficient accuracy by the sensor. Other task is monitoring the deterioration of the elastomeric bearings between the rafters and the pillars that usually have difficult access. Therefore a multi-link compliant robotic arm can be very useful for these tasks.

![Figure 2. Scheme of a 4-DoF robotic arm on a multirotor](image)

Figure 2 shows a scheme of the 4-DoF compliant arm developed. The actuators selected have been the Herkulex-DSR-0101 smart servos whose specifications can be found in [16]. The manipulator is formed by a shoulder yaw and pitch joints at the base, followed by an elbow and a wrist pitch joint. The center of mass of each link is placed within its
rotation axis, thus the kinematics are simplified. The compliant mechanism of each joint is shown in Figure 3. This mechanism consists of four symmetric springs which constant stiffness is 2 N/mm placed on part number 1. The part number 1 is linked to the servo. The part number 2 twists when a force is applied and thus the springs will compress. Depending on the rotation direction two springs are compressed. Thanks to the potentiometer placed on part number 3, the difference between both servo angle position and joint angle position can be measured. The potentiometers’ measurements are read by a BeagleBone Black embedded computer through the analog input ports. This device is in charge of controlling the servos. The control strategy of the manipulator arm is also implemented on this device and it is communicated by Ethernet with the Autopilot.

![Figure 3. Compliant mechanism.](image)

The specifications of the manipulator can be found on Table 1. As Table 1 shows, the compliant arm has an excellent relation between the maximum reach and weight. Obviously, the arm is designed to be equipped with low weight measurement sensors or cameras at the end-effector. Thus it has a low payload.

| Weight       | 0.4 [Kg] |
|--------------|----------|
| Arm reach    | 0.50 [m] |
| Joint Size   |          |
| L1 = 0.1 [m]|
| L2 = 0.2 [m]|
| L3 = 0.2 [m]|
| L4 = 0.1 [m]|
| Rotation Range|        |
| Shoulder yaw = ±150 [deg]|
| Shoulder pitch = ±90 [deg]|
| Elbow pitch = ±150 [deg]|
| Wrist pitch = ±150 [deg]|
| ±30 degrees  |

Table 1. Specifications of the manipulator arm.

III. Modelling

Let \( \xi = [p, \eta, q]^T \in \mathbb{R}^n \) be the generalized coordinates of the aerial vehicle and the robotic arm, where \( p = [x, y, z]^T \in \mathbb{R}^3 \) and \( \eta = [\vartheta, \varphi, \psi]^T \in \mathbb{R}^3 \) are the translation coordinates of the aerial platform center of mass in an inertial frame and the vehicle attitude by the classical roll, pitch, yaw Euler angles respectively. The \( k \)-link joint angles are represented by \( q = [q_1, \ldots, q_k]^T \in \mathbb{R}^k \). Then, considering the reduced flexible joint robot model presented in [17], the dynamics of an aerial vehicle equipped with a \( k \)-DoF compliant robotic arm can be described by:

\[
M(r)\ddot{\xi} + C(r, \dot{r})\dot{\xi} + g(\xi) = N(u, \theta, q) + \tau_{ext}
\]  
(1)

\[
B \ddot{\theta} + N(u, \theta, q) = \tau_m
\]  
(2)

Where \( r = [\eta, q]^T \in \mathbb{R}^{3+k} \) are the rotation coordinates of the system. The inertia matrix \( M(r) \in \mathbb{R}^{n \times n} \) must be symmetric and positive definite. The term \( C(r, \dot{r})\dot{\xi} \) represents Coriolis and centrifugal forces and complies with the property \( M(r) = C(r, \dot{r}) + C(r, \dot{r})^T \), which is skew-symmetric of \( M(r) - 2C(r, \dot{r}) \). The gravitational effects are given by \( g(\xi) \in \mathbb{R}^n \) and \( \tau_{ext} \) is the vector of external forces generated by the interaction with the environment. Matrix \( B \) is the inertial of servos’ shaft and frame and \( \tau_m \) is the torque generated by the motor. The vector \( N(u, \theta, q) \) is used to represent the forces and torques generated by the rotors over the aerial platform, \( u \in \mathbb{R}^6 \) and the torques given by the compliant joints:

\[
N(u, \theta, q) = \begin{bmatrix} I_{6 \times 6} & 0 \end{bmatrix} \begin{bmatrix} \theta - q \end{bmatrix}
\]  
(3)

Herein, \( K \in \mathbb{R}^{k \times k} \) is a diagonal matrix and represents the elastic constant terms of each joint and \( \theta = [\theta_1, \ldots, \theta_k]^T \in \mathbb{R}^k \) are the servos’ angular positions.

Then, the position of the end effector, \( p_{EE} = [x_{EE}, y_{EE}, z_{EE}]^T \), respect to an inertial frame can be expressed by the following equations:

\[
p_{EE} = p + \sum_{i=1}^{k} \left( \prod_{j=0}^{k-1} T_j \right) p_i
\]  
(4)

Herein \( T_i \in SO(3) \) are the kinematic transformations of each link where \( T_0 \) is the rotation matrix that describes the orientation of the aerial vehicle in the inertial reference frame. Through the equation (4) the Jacobian that relates the translational velocities of the end effector and the velocities of the generalized coordinates can be obtained:

\[
v_{EE} = f_E(r)\dot{\xi}
\]  
(5)

Using this Jacobian, it is possible to rewrite the model (1) as the end-effector equations of motion in operational space formulation [15]:

\[
\Lambda(x)\ddot{x} + \mu(x, \dot{x}) + g(x) = \Gamma
\]  
(6)
where $\Lambda(x)$, $\mu(x, \dot{x})$ and $g(x)$ represent the inertia matrix, the end-effector centrifugal and Coriolis forces and the vector of gravity forces. The vector of external forces, $F_{\text{ext}}$, is related with the external torques, $\tau_{\text{ext}}$, via $\tau_{\text{ext}} = J_E(r)^TF_{\text{ext}}$. Therefore, the forces vector, $\Gamma$, is given by:

$$\Gamma = J_E(r)^T N(u, \theta, q) + F_{\text{ext}} \tag{7}$$

The other relationships with the equations of motion of the system can be expressed as follows:

$$\Lambda(x) = J_E^T(r)M(r)J_E^{-1} \tag{8}$$

$$\mu(x) = J_E^T(r)C(r, \dot{r}) - \Lambda(q)h(r, \dot{r}) \tag{9}$$

$$g(x) = J_E^T(r)g(\xi) \tag{10}$$

$$h(r, \dot{r}) = J_E(r)\dot{r} \tag{11}$$

The matrix $\Lambda(x)$ must be symmetric and positive definite for all positions of the end effector.

### IV. Altitude-Force Control Strategy

Considering the compliant robotic arm presented in section II and using the equations shown in the previous section, the main goal was developing a controller for the forces acting on the end effector. To perform it we assume that the aerial platform is stabilized hovering over a desired altitude:

$$\ddot{z} = z_d + \Delta z \tag{12}$$

where $z_d$ is the desired altitude and $\Delta z$ is the oscillation error over time. In these conditions, a desired force over the end effector, $\Gamma_d$, can be defined using the equation (7) and the force error is given by:

$$e_F = \Gamma_d - \Gamma \tag{13}$$

Using the equations (3) and (7), a desired joint torque is given by:

$$\tau_d = J_E(r)^T \Delta \rho e_F \tag{14}$$

where $\Delta \rho$ is a diagonal gain matrix. Using the equations of the compliant arm this desired torque can be defined as:

$$\tau_d = K \Delta \theta_d \tag{15}$$

Herein, $\Delta \theta_d$ describes the desired deflection. Substituting the equation (15) in the equation (14):

$$\Delta \theta_d = K^{-1}J_E(r)^T \Delta \rho e_F \tag{16}$$

Now, defining the desired deflection with the actual servo joint position, $\theta_0$, and the desired angular joint as,

$$\Delta \theta_d = \theta_0 - q_d \tag{17}$$

and substituting in the equation (17), the desired angular joint can be written as:

$$q_d = \theta_0 - K^{-1}J_E(r)^T \Delta \rho e_F \tag{18}$$

Since torque control is not admitted by the Herkulex servos, a classical control over the arm joint torques could not be implemented. Therefore, the controller must act on the angular servo position:

$$\theta_d = q_d + K^{-1}(g(q_d)) \tag{19}$$

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**V. Experiments**

One of the tasks in bridge inspection that needs contact consists in measuring the deflection of the girders over time. To accomplish this task the inspector must catch the girder using a ladder or scaffold and hold a position with a topography prism while a total station in ground makes the measurements. To reach enough measurements accuracy, the inspector must hold the topography prism for a certain time. To obtain this deflection, the process should be repeated for some desired positions along the girder.

The goal of these experiments is to use the aerial manipulator presented in this paper to perform the above operation, holding the topography prism in a desired position in contact with the girder (see figure 5).

An octocopter platform equipped with a 4-DoF compliant robot manipulator has been made to perform these experiments (see Figure 1). The aerial vehicle has a maximum take-off weight of 10 Kg. and it is equipped with an IMU, external magnetometer and a Px4Flow optical flow device. For these first experiments the topography prism is replaced by a PLA prism mockup. Cascade PID controllers has been implemented for the multicopter attitude and using the ultrasonics included in the Px4Flow sensor, an altitude cascade PID controller has also been implemented.
Figure 6 shows the results of a first test performed with the prototype. In this experiment, the multirotor has taken off and has hold a desired altitude. Then the compliant arm has started to move until it has contacted with the girder. The manipulator has tried to hold the contact with a desired force. As Figure 6 shows, the contact force is not very stable. To a large degree, this force error has been generated by the multirotor altitude, which has had an error of up to ±10 cm and the frequency of these oscillations in altitude. Due to the compliant mechanism, the contact force is absorbed and the influence over the platform stability is greatly reduced.

Figure 7 shows the deflection of the joints during the contact. While there has not been contact, the deflection is due to the gravity forces acting on the arm joints. During the contact, the deflection has increased and the controller has tried to hold the desired force. Figure 8 presents the altitude error for the same experiment.

The experiment has demonstrated that the contact with the girder can be possible without compromising the multirotor stability. Thanks to the compliant arm designed and implemented, the influence of the contact force over the multirotor can be absorbed. Furthermore, the robotic arm can hold a desired force due to the developed controller strategy, although the multirotor should have better sensors equipment for a better behavior. Given that the platform should work in an environment without GPS, an improvement can be using the measure of the position topographic prism obtained by the robotic ground station. With these position measures a coupled controller of both multirotor and compliant robotic arm can be developed.

Figure 9 shows a sequence of photos of the experiment in which the contact with the girder can be seen.

VI. CONCLUSION

This paper has presented the design and implementation of a compliant aerial manipulator for bridge inspection. The robotic arm is equipped with an innovative and simple compliant mechanism that allows to reject the disturbances generated by the contact forces over the aerial platform. Furthermore, thanks to the control strategy developed, the manipulator can hold a desired contact force. This is needed by a total station for making measurements over a topographic prism with the required accuracy. The goal of this work is providing a tool for measuring the deflection of the bridge’s girder over time. This tool can be very useful for improvement the safety of the structures’ inspectors.
As a future work, the multirotor should be equipped with better sensor for improvement the stability and position error. Furthermore, the measures of the robot ground station can be used for the position estimation and for developing a coupled fully controller of both compliant robot arm and multirotor.

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REFERENCES

[1] I. Palunko, P. Cruz and R. Fierro. Agile Load Transportation: Safe and Efficient Load Manipulation with Aerial Robots. in IEEE Robotics & Automation Magazine, vol. 19, no. 3, pp. 69-79, Sept. 2012.
[2] Q. Lindsey, D. Mellinger, V. Kumar. Construction of Cubic Structures with Quadrotor Teams. Robotics: Science and Systems, June 2011
[3] A. Q. L. Keemink, M. Fumagalli, S. Stramigioli and R. Carloni, "Mechanical design of a manipulation system for unmanned aerial vehicles," 2012 IEEE International Conference on Robotics and Automation, Saint Paul, MN, 2012, pp. 3147-3152.
[4] M. Fumagalli, R. Naldi, A. Macchelli, R. Carloni, S.Stramigioli and L. Marconi. Modelling and Control of a Flying Robot for Contact Inspection, IROS 2012, Vilamoura, Portugal.
[5] K. Kondak, F. Huber, M. Schwarzbach, M. Laiaacker, D. Sommer, M. Bejar, A. Ollero. Aerial manipulation robot composed of an autonomous helicopter and a 7 degrees of freedom industrial manipulator. Proceedings of the ICRA 2014, pp. 2107–2112.
[6] G. Heredia, A.E. Jimenez-Cano, I. Sanchez, D. Llorente, V. Vega, J. Braga, J.A. Acosta and A. Ollero. Control of a Multirotor Outdoor Aerial Manipulator. Proceeding of the IROS 2014, pp. 3417-3422.
[7] S. Kim, H. Seo, S. Choi and H. J. Kim, "Vision-Guided Aerial Manipulation Using a Multirotor With a Robotic Arm," in IEEE/ASME Transactions on Mechatronics, vol. 21, no. 4, pp. 1912-1923, Aug. 2016.
[8] Hyunsoo Yang; Dongjun Lee, "Dynamics and control of quadrotor with robotic manipulator," Proc. of the ICRA 2014, pp.5544-5549.
[9] V. Lippiello et al., "Hybrid Visual Servoing With Hierarchical Task Composition for Aerial Manipulation," in IEEE Robotics and Automation Letters, vol. 1, no. 1, pp. 259-266, Jan. 2016.
[10] M. Jafarinasab and S. Sirouspour, "Adaptive motion control of aerial robotic manipulators based on virtual decomposition," 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, 2015, pp. 1858-1863.
[11] A. Suarez, G. Heredia and A. Ollero, “Lightweight compliant arm for aerial manipulation,” 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, 2015, pp. 1627-1632.
[12] L. Marconi, R. Naldi and L. Gentili. Modeling and Control of a Flying Robot Interacting with the Environment, Automatica, vol. 47, no. 12, pp. 2571-2583, 2011.
[13] A. Suarez, G. Heredia and A. Ollero, "Lightweight compliant arm with compliant finger for aerial manipulation and inspection," 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, 2016, pp. 4449-4454.
[14] A. E. Jimenez-Cano, J. Braga, G. Heredia and A. Ollero, "Aerial manipulator for structure inspection by contact from the underside," 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, 2015, pp. 1879-1884.
[15] Aerial RObotic System for In-Depth Bridge Inspection by Contact. http://www.aerobi.eu/
[16] Dongbu Robot website. http://www.dongburobot.com
[17] M. Spong, “Modeling and control of elastic joint robots,” Trans. ASME: J. Dyn. Syst., Meas., Control, vol. 109, pp. 310–319, 1987.