Aerial Manipulator for Structure Inspection by Contact from the Underside

A.E. Jimenez-Cano, J. Braga, G. Heredia and A. Ollero

Abstract—This paper presents an aerial manipulator consisting of a multirotor equipped with a robotic multi-link arm attached to the top of the multirotor body. This setup has strong potentialities for inspection of structures, since the arm is able to safely touching the structure surface with a sensor while flying, taking measurements from the underside for example in bridges. The paper presents the dynamic model of the system and the derivation of a nonlinear controller, which is tested in simulation. First flight experiments with prototype of the system are also presented.

I. INTRODUCTION

In the last years the development of autonomous aerial robots that are capable to operate in unstructured and partially known natural environments is catching much interest in robotic research. The integration between these Unmanned Aerial Systems (UAVs) and robotic manipulators extends the range of possible applications. For instance, these aerial manipulators offers strong potentialities for the inspection and maintenance of aerial power lines, the building of platforms for the evacuation of people in rescue operations, construction or taking samples of material from areas difficult to access.

Initially most of the research progress in this field has been devoted to object grasping applications with simple manipulation devices for structure construction [1], and cooperative grasping and transporting loads [2]. In [3], the inertial parameters of the grasped object are estimated and used to adapt the controller and to improve performance during flight. Furthermore, algorithms for quadrotor stabilization and force control are studied in [4] and [5].

In the last years aerial manipulators with multi-link manipulator arms which have more advanced manipulation capabilities have been developed. [6] and [7] present prototypes of helicopters with attached manipulators, and experimental results of a helicopter equipped with a fully actuated redundant robot manipulator have been presented by [8]. Similarly, multirotor-based aerial manipulators have been also developed [9]. A multirotor with a redundant 7 degrees of freedom arm for outdoors has been presented in [10]. There have been some attempts to derive general methodologies for controlling aerial vehicles equipped with robotic manipulators [11][12]. Control and stabilization of an aerial system composed of an aerial vehicle and a manipulator arm is complex due to the variable dynamics of the vehicle when the arm is moving, grasping and manipulating objects. This effect is due to the modification of the aerial vehicle mass centre and mass distribution when performing these operations. Similarly, the contact forces that appear when interacting with the environment are an additional influence on the dynamics. These effects are usually not taken into account explicitly in the vehicle controllers and hence left to the integral action in the feedback loop. In this respect, [13] presents stability limits within which the changing mass-inertia parameters of the system would not destabilize quadrotors and helicopters with standard PID controllers. Controllers based on integral backstepping which takes into account the mass variation produced when the arm is moving have also been implemented in quadrotors with multi-link manipulators [9][10]. The dynamics of aerial vehicles in contact with the environment has also been analyzed [14].

Figure 1. AMIS aerial manipulator for structure and bridge inspection, developed by the GRVC at University of Seville.

New applications are continuously emerging with the continuing development of aerial manipulators. One of these applications is the inspection of difficult-to-access areas of the civil infrastructure in general and bridges in particular. Recently, standard multirotors with cameras have been used for an initial visual inspection of difficult to access areas of bridges. When cracks or other damages are detected in the images, an in-depth inspection has to follow with experienced human inspectors in need of hands-on-access to bridge elements, and assess the crack depth using ultrasound.

* A.E. Jimenez-Cano, J. Braga, G. Heredia (e-mail: guiller@us.es) and A. Ollero (e-mail: aollero@us.es) are with the Robotics, Vision and Control Group at University of Seville, Spain.
testing sensors which need to be in contact with the bridge to take measurements.

The use of aerial manipulators provide an excellent solution for conducting the inspection by contact of bridge elements without human intervention, since the arm can be used to hold the ultrasound sensor that has to be in contact with the bridge while the multirotor is hovering. Furthermore, since in many cases the bridge elements have to be inspected from below (i.e. the aerial robot should fly below the bridge, and the surfaces that it has to inspect are located above the robot), a new aerial manipulator configuration is proposed in which the arm is attached on top of the multirotor body above the rotors, and not on the belly below the rotors as is the case for all the published works.

This paper presents the modelling and control of an aerial manipulator composed of a multirotor and a manipulator arm attached to the top of the multirotor body (see Fig. 1), intended to be used for infrastructure and bridge inspection by contact, and flying below the elements that are being inspected. To the authors’ knowledge, it is the first time that this aerial robot configuration has been proposed and tested experimentally.

The organization of the paper is as follows: the next section presents the dynamic modelling of the aerial manipulator including the multirotor and the arm, and the contact forces that may appear during inspection. Then, Section III presents the control approach and the multirotor and arm controllers. Section IV shows several simulation cases comparing the results with a baseline controller. First experimental results with a prototype aerial manipulator inspecting a bridge are shown in Section V.

II. DYNAMIC MODELLING OF AERIAL MANIPULATOR

This section presents the dynamic model of the aerial manipulator, considering explicitly the forces and torques that appears when the sensor located on the arm end effector contacts the surface it is inspecting. The dynamic model for a multirotor and a $k$-link manipulator arm of $m$-DOF can be obtained using the Euler-Lagrange formulation. The generalized coordinates of the multirotor with manipulator system can be defined as $\xi = [p, \eta, \gamma]^T \in \mathbb{R}^n$, with $n = 6 + k$; where $p = [x, y, z]^T \in \mathbb{R}^3$ represents the translation coordinates of the multirotor center of gravity relative to the inertial frame, $\eta = [\phi, \theta, \psi]^T \in \mathbb{R}^3$ describes the vehicle attitude by the classical roll, pitch, yaw Euler angles commonly used in aerospace applications, and $\gamma = [\gamma_0, \gamma_1, \ldots, \gamma_m] \in \mathbb{R}^k$ are the joint angles of the arm.

The general Euler-Lagrange equations describing the dynamics for each of the coordinates are

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\xi}_i} - \frac{\partial L}{\partial \xi_i} = \mathcal{F} + \mathcal{F}_E$$

(1)

where $\mathcal{F}$ is the vector of forces and torques generated by the actuators. It can be decomposed into the thrust forces $F_q \in \mathbb{R}^3$ and moments, $\tau_q \in \mathbb{R}^3$ generated by the rotors, and the torque of each link of the manipulator, $\tau_m \in \mathbb{R}^k$. External forces and moments are represented by $\mathcal{F}_E$, which include the contact forces and moments of the end effector with the structure or bridge surfaces that it is inspecting. The Euler-Lagrange equations are derived directly from the energy expressed in the generalized coordinates. First the system Lagrangian is derived as the difference between the kinetic and the potential energies of the system. For the typical manipulators the Lagrangian function is

$$L(\dot{\xi}, \ddot{\xi}) = K(\dot{\xi}, \ddot{\xi}) - P(\xi)$$

(2)

where $K(\dot{\xi}, \ddot{\xi}) = \frac{1}{2} \dot{\xi}^T M(r) \dot{\xi}$ is the kinetic energy and $r = [\eta, \gamma]^T \in \mathbb{R}^{3+6}$ represents the multirotor rotation and the manipulator’s joint angles. The inertia matrix, $M(r) \in \mathbb{R}^{n \times n}$, is given by:

$$M(r) = \sum_{k=1}^{3+m} \left[ m_i J_\nu J_{\nu} + J_\omega R_i l_i R_i \right]$$

(3)

Here, $m_i, l_i, R_i, J_{\nu}$ and $J_\omega$ are respectively the mass, the moments of inertia matrix, the rotation matrix of the manipulator and the translation and rotation Jacobians [12] of each links of the manipulator arm.

The potential energy of the system can be written as:

$$P(\xi) = \sum_{i=0}^{n} m_i g^T z_i$$

(4)

where $g$ is the acceleration due to gravity and $z_i$ is the position of the center of mass of the aircraft $(i = 0)$ and each of the links of the manipulator $(i = 1, 2, \ldots, k)$.

Thus, after some computations the equations of motion can be written as:

$$M(r) \ddot{\xi} + C(r, \dot{\xi}, \xi) + G(\xi) = \mathcal{F}_T$$

(5)

where $G(\xi)$ are the gravitational force terms and $C(r, \dot{\xi}, \xi) \in \mathbb{R}^{n \times n}$ is the Coriolis matrix that has its element to be

$$C_{kj} = \sum_{\ell=1}^{n} c_{\ell kj}(r) \dot{\gamma}_\ell$$

(6)

with the property $M(r) - 2C(r, \dot{\xi})$ is skew-symmetric. Then, the gravity force vector in (5) can be rewritten as:

$$G(\xi) = -g \left[ 0, 0, \sum_{i=0}^{n} m_i \Delta z_\phi, \Delta z_\theta, \Delta z_\psi, \Delta z_{\gamma_1}, \ldots, \Delta z_{\gamma_k} \right]^T$$

(7)

Where $\Delta z_\eta$ is each term of the gravitational force vector in Euler angles and $\Delta z_{\gamma_j}$ are each term of the gravitational force due to each link of the manipulator. Both can be computed as follows:

$$\Delta z_{\eta_\ell} = \frac{\partial \eta_{\gamma_\ell}}{\partial \eta_\gamma} \sum_{i=0}^{n} m_i \Delta z_\phi, \Delta z_\theta, \Delta z_\psi, \Delta z_{\gamma_1}, \ldots, \Delta z_{\gamma_k}$$

(8)

The equations of motion (5) can be rewritten without loss of generality [21] as:

$$\begin{bmatrix} M_q & M_{QM} \\ M_{QM}^T & M_M \end{bmatrix} \begin{bmatrix} \dot{\gamma} \\ \tau_\gamma \end{bmatrix} + \begin{bmatrix} C_q & G_q \end{bmatrix} + \begin{bmatrix} F_q \\ G_M \end{bmatrix} = \begin{bmatrix} \dot{F}_q \\ \tau_M \end{bmatrix} + \begin{bmatrix} \dot{G}_q \end{bmatrix}$$

(10)

where $M_q \in \mathbb{R}^{6 \times 6}$, $M_M \in \mathbb{R}^{6 \times k}$ and $M_{QM} \in \mathbb{R}^{6 \times k}$ are aircraft, manipulator and coupling inertia matrices, $C_q \in \mathbb{R}^{6}$, $G_M \in \mathbb{R}^{k}$ are aircraft and manipulator Coriolis and centrifugal forces and $G_q \in \mathbb{R}^{6}$, $G_M \in \mathbb{R}^{k}$ are aircraft and
manipulator gravity forces vector. The spatial forces due to manipulator contact is denoted by \( F_E \).

From (12) the matrix equations of motion for the manipulator can be expressed as:
\[
M_M \ddot{q} + C_M + G_M = \tau_M
\]
(11)
where \( \tau_M = \tau_M + \theta^T F_E - M_{GM} \begin{bmatrix} \dot{\theta} \\ \dot{\theta} \end{bmatrix} \) denotes all forces and moments acting on the coordinates joints.

Now, let us focus on the end-effector of manipulator as reference. Denote \( q \in \mathbb{R}^n \) as a system of generalized coordinates for a non-redundant manipulator. Then using the operational space formulation \([15]\), the end-effector equations of motion in operational space can be written as:
\[
\Lambda(q) \dot{q} + \mu(q, \dot{q}) + g(q) = \Gamma
\]
(12)
where \( \Lambda(q), \mu(q, \dot{q}) \) and \( g(q) \) represent the inertia matrix, the end-effector centrifugal and Coriolis forces and the vector of gravity forces. And their relationships with the equations of motions of the system can be expressed as follows:
\[
\Lambda(q) = J_E^T(r)M_M(r)J_E^{-1}
\]
(13)
\[
\mu(q) = J_E^T(r)C_M(r, \dot{r}) - \Lambda(q)h(r, \dot{r})
\]
(14)
\[
g(q) = J_E^T(r)G_M(\xi)
\]
(15)
\[
h(r, \dot{r}) = j_E(r)\dot{r}
\]
(16)
where \( J_E(r) \) is the Jacobian matrix and represents the relationship between the position and orientation of the end-effector, \( X_E = [x_E, y_E, z_E, \phi_E, \psi_E, \theta_E]^T \in \mathbb{R}^6 \) and the joints coordinates and Euler angles of the multirotor as:
\[
X_E = J_E(r)^{\xi}
\]
(17)

Finally, using (12), (13), (14) and (15) the relationship between the generalized forces can be written as
\[
\tau_M = J_E^T(r)\Gamma
\]
(18)
which represents the relationship between the operational forces in the Cartesian space and the joint forces in accord with the multirotor and manipulator system equation and the end-effector equations.

III. MULTIROTOR AND MANIPULATOR ARM CONTROL SCHEME

The control scheme that has been followed in the paper uses a controller for the multirotor and another one for the manipulator arm. Both have access to the full aerial manipulator state. The multirotor controller is responsible for stabilizing attitude and global position of the aerial vehicle, taking into account and compensating the movements of the arm and the contact forces with the environment. The manipulator controller takes care of controlling arm joints angles and velocities, and the generalized forces \( \Gamma \) that are generated by the aerial manipulator in the operational space, considering the movement and dynamics of the multirotor.

A. Multirotor controller

Variable Parameter Integral Backstepping (VPIB) has shown as an effective control technique for aerial manipulation vehicles \([9][10]\). This controller is an extension of the well-known backstepping technique that includes integral action for the arm joint angles. It is based on a nonlinear backstepping controller whose parameters vary accordingly with the dynamics of the manipulator and provides a good dynamic response when the manipulator moves.

A multirotor is an underactuated system: it has four control input \( U = [U_x, U_\phi, U_y, U_\psi]^T \) and six degrees of freedom (DoF). The states, \( z \) and \( \eta \) (the three multirotor attitude angles) have been chosen as the controlled variables, and then the \( [x, y] \) position control loops are built on top of the attitude control loops, generating desired attitude references that are passed to the inner loops.

Assume without loss of generality that only four generalized forces are generated by four rotors. Hence, the generalized multirotor control forces and torques vector can be redefined as:
\[
\begin{bmatrix} F_Q \\
\tau_Q \end{bmatrix} = R_Q \begin{bmatrix} 0 \\
0 \end{bmatrix} \begin{bmatrix} \sum_{i=1}^{4} f_i \\
\sum_{i=1}^{4} \tau_m \end{bmatrix} - \begin{bmatrix} (f_3 - f_1)l_l \\
(f_2 - f_4)l_l \end{bmatrix}
\]
(19)

where \( R_Q \) is the rotation matrix of multirotor and \( l \) is the distance between the rotor and the geometric center of multirotor. Therefore the control input vector can be redefined as:
\[
U = \begin{bmatrix} U_x \\
U_\phi \\
U_y \\
U_\psi \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{4} f_i \\
(f_3 - f_1)l_l \\
(f_2 - f_4)l_l \end{bmatrix}
\]
(20)
The multirotor equations of motion can be decoupled from the upper part of (10):
\[
M_Q \begin{bmatrix} \dot{\eta} \\
\dot{\theta} \end{bmatrix} + C_Q + G_Q = \begin{bmatrix} F_Q \\
\tau_Q \end{bmatrix} + \theta^T F_E - M_{GM} \dot{\theta}
\]
(21)
where the inertia matrix, \( M_Q \) can be simplified for control as follows:
\[
\dot{\mathbf{q}}_Q = \begin{bmatrix} \sum_{i=6}^{n} m_i \\
0 \\
I_\eta(r) \end{bmatrix}
\]
(22)

1) Attitude Control

The multirotor attitude controller is implemented in an inner loop and its proper operation is crucial for the system since it will be in charge of stabilizing the multirotor as well as maintaining the desired orientation. Defining attitude input control vector as \( U_\eta = [U_\phi, U_y, U_\psi]^T \) and following the algorithm presented by \([9]\), the VPIB attitude controller can be written as:
\[
U_\eta = I_\eta^{-1} \left[ K_1 e_\eta + K_2 e_\eta + K_3 \chi_\eta + \dot{\eta}_d \right] + \sum \tau_\eta
\]
(23)
with
\[
\sum T_\eta = C^\eta_0 + G^\eta_0 + \mathbf{N}\dot{\mathbf{y}} - \mathbf{f}_c
\]

where the tracking error, \(e_\eta = \eta_d - \eta \in \mathbb{R}^3\), the angular velocity tracking error, \(e_\omega = k_\eta e_\eta + \lambda_\eta \chi_\eta + \dot{\eta}_d - \dot{\eta} \in \mathbb{R}^3\) and the integral of the angular position tracking error, \(\chi_\eta = \int_0^t e_\eta(t) \, dt \in \mathbb{R}^3\). And the matrix gains, \(K_i\), are defined as:

\[
K_1 = I_3 - \lambda_\eta^2 + k_\eta \in \mathbb{R}^{3 \times 3}
\]

(24)

\[
K_2 = k_\eta + k_\eta \in \mathbb{R}^{3 \times 3}
\]

(25)

\[
K_3 = -k_\eta \lambda_\eta \in \mathbb{R}^{3 \times 3}
\]

(26)

where \(k_\eta\) and \(\lambda_\eta\) are positive diagonal controller matrix gain. The matrices \(C^\eta_0 \in \mathbb{R}^3\) and \(G^\eta_0 \in \mathbb{R}^3\) are the lower part of the Coriolis and centrifugal forces vector and gravity forces vector, respectively. The term \(\mathbf{N}\) introduces the estimation of the dynamic coupling due to the manipulator movements and \(\mathbf{f}_c\) the estimation of the torque induced by the contact force, \(F_E\).

2) Position control

The position controller generates the desired attitude corresponding to the position references given by the system. Now, if \(U_x\) and \(U_y\) are defined as the virtual position control inputs for the XY position controller, the position controller can be written as:

\[
U_x = \frac{M_T}{u_x} [g + K_x e_x + K_x e_x + L_x \chi_x + \ddot{\chi}_d] + C_x - \mathbf{f}_{Ex}
\]

(27)

\[
U_x = \frac{M_T}{u_x} [K_x e_x + K_x e_x + L_x \chi_x + \ddot{\chi}_d] + C_x - \mathbf{f}_{Ex}
\]

(28)

\[
U_y = \frac{M_T}{u_y} [K_y e_y + K_x e_y + L_y \chi_y + \ddot{\chi}_d] + C_y - \mathbf{f}_{Ey}
\]

(29)

where \(k_p = 1 - \lambda_p^2\) and \(k_p = k_p + k_p\) and \(\lambda_p = -k_p \lambda_p\) with \(p = x, y, z\) are positive constant controller gains, and \(e_x\), \(e_y\) and \(e_z\) are the position tracking error for the generalized position coordinates. The speed tracking errors are defined by \(e_x\), \(e_y\) and \(e_z\) and the integral of the angular position tracking error are defined by \(\chi_x\), \(\chi_y\) and \(\chi_z\). The Coriolis and centrifugal vector are defined by \(C_x\), \(C_y\) and \(C_z\), and \(\mathbf{f}_{Ex}\), \(\mathbf{f}_{Ey}\) and \(\mathbf{f}_{Ez}\) are the components of the generalized force vector, \(F_E\) which is used to describe multirotor dynamics effects due to the interaction between the end-effector and the environment. In [5], the dynamics of this interaction is described by using a Hunt-Crossley interaction model [16]. At this work, a spring model [22] has been used for modelling the contact between the end-effector and the environment. The environment is assumed to have a constant stiffness. For each contact \(n\),

\[
f^n_c = k_n \dot{x}_n
\]

(30)

where \(f^n_c\) is the n-th contact force and \(\dot{x}_n\) is the instantaneous velocity in the contact normal direction. In this case, these positions are defined in the end-effector frame, hence the generalized force vector, \(F_E\) can be defined as:

\[
F_E = \frac{\partial \mathbf{r}^T}{\partial \mathbf{r}} f^n_c(x) \in \mathbb{R}^6
\]

(31)

where \(Q_T^T\) is a spatial coordinate transform between the end-effector and the multirotor. The measurements of the contact forces can be carried out through a force sensor at the end-effector. The position controller must be capable to keep the desired XYZ position while the manipulator performs the contact task with the underside of the bridge.

B. End-Effector controller

The manipulator arm is attached to the multirotor body, and hence the multirotor needs to move to a position in which the task operational space is within the arm workspace. The multirotor is commanded to hover at this point with the controller developed in subsection IIIA, while the arm is performing the inspection (then \(p = 0\) and \(\phi, \theta = 0\)), and the arm controller considers that these terms are small. Another consideration is that \(X_{Ed} \in D_{X_E}\) where \(X_{Ed}\) represents the desired effector position and \(D_{X_E}\) represents the domain of the operational space given by:

\[
D_{X_E} = G([\mathbf{r}_E, \gamma_1^T])
\]

(32)

where \(\gamma_1^T\) and \(\gamma_1^T\) are the minimal and maximal bounds of the \(i\)-th joint coordinate, respectively.

An effective technique for dealing with these highly nonlinear and coupled systems is the nonlinear dynamic decoupling in operational space [18] which can be derived using the relationship between the generalized forces (18) as:

\[
\tau_M = J_E^T \mathbf{G}_M \mathbf{r}_E^* + \mathbf{C}_M + \mathbf{G}_M - J_E^T F_E + M_Q^T \ddot{\eta}
\]

(33)

with

\[
F_E^* = \mathbf{I}_{EE} X_{Ed} + k_p (X_{Ed} - X_E) + k_p (X_{Ed} - X_E)
\]

\[
F_E = f_{Ed} + k_f (f_{Ed} - f_c)
\]

(34)

where \(\mathbf{C}_M = C_M - J_E^T \mathbf{G}_M h(r, \dot{r})\) is estimated vector of the Coriolis and centrifugal forces into joint space of the end-effector and \(\mathbf{G}_M\) is estimated gravity forces vector. The term \(\mathbf{I}_{EE}\) represents a unity matrix. \(k_p\), \(k_p\) and \(k_f\) are gain matrices for position, velocity and force respectively. The contact force measurement done by the force sensor is denoted by \(f_c\) and the desired contact force is expressed by \(f_{Ed}\). In the real system, oscillations in the multirotor axis generate disturbances in the contact force measured by the sensor which will be compensated by the control action, \(F_E\), in (39) and the feedback force, \(F_E\), in (30).

IV. Simulations

This section presents several simulation tests that have been done using the full mathematical model of the aerial manipulator derived in Section II. In these simulations the geometric, mass and inertia parameters that have been used have been obtained from the prototype showed in Fig. 1, using a 5-DoF manipulator. Furthermore, it is assumed that multirotor is equipped with a positioning system, an Inertial Measurement Unit (IMU), a magnetometer and a sonar.
altimeter. Noise characteristics of the sensors as well as uncertainties in their modelling parameters have been also accounted for. The IMU operates at a sampling frequency of 100 Hz and it has a standard deviation of 1.2 degrees in attitude. Position estimation is supposed to be affected by a typical standard deviation of 0.04 m and its update frequency is fixed to 10 Hz.

The first set of simulations that is presented in the paper analyzes the behavior of the aerial manipulator when it is flying forward to a desired position with the center of gravity off-center, and then the arm moves constantly changing its configuration (and the position of the CoG), which is one of the more demanding cases. Fig. 2 shows the X,Y,Z position errors in one of these simulations, when the aerial robot is flying toward the desired position (2,-2, 2), with the CoG off-center and there the manipulator carries out several movements, using the attitude and position controllers presented in Section III. For comparison purposes, simulations have been done also with a standard PID multirotor controller, which is not able to compensate for the arm movement, as the backstepping controller does to a large extent.

A second set of experiments studies the behavior when the aerial robot is inspecting a structure such as a bridge, touching it with the ultrasound sensor head located at the end effector of the arm, and applying a contact force so that the sensor stays in touch enough time to take measurements. Fig. 3 shows the position errors using the VPIB controller with contact force estimator and without using it, which is affected by the contact forces of the arm with the bridge (beginning at t = 10 s), as can be seen in the figure.

V. First Experiments

This section presents the results of the first flight experiments that have been performed with the proposed approach. The experiments have been done with the AMIS (Aerial Manipulator for Inspection of Structures) prototype, which has been developed by the GRVC at University of Seville (see Fig. 1). The AMIS aerial platform is a multirotor with eight rotors located at the ends of a four-arm planar structure, with two rotors positioned coaxially at the end of each arm (octoquad configuration). The multirotor has a manipulator arm attached to the top of the body. For these experiments the arm that has been mounted on the upper part of the AMIS body has three degrees of freedom. The arm has three links of length 400mm, 350 mm and 50 mm, respectively, and it is powered by Dynamixel servos. The total weight of the manipulator is 1.3 kg, and the maximum reach is about 860 mm including the sensor head. The total weight of the multirotor with the arm is 8.6 kg.

The objective of these initial experiments was to test the dynamic behavior of the AMIS prototype with the developed attitude controller when it is approaching the inspection point at the bridge, and then when the AMIS arm is touching the structure with the sensor head to take measurements. For these experiments a dummy sensor was used and no ultrasonic measurements were done.

Another very interesting point that wanted to try in the experiments was whether the stability of the aerial vehicle was affected by the contact forces in case an extra force was deliberately applied by the arm at the sensor head, so that the contact with the bridge surface can be constantly maintained enough time to take the measurements with the sensor head. From the performed experiments, it can be concluded that
this extra force did not unstabilize the aerial manipulator. In fact, it was even the opposite, the extra force decreased the multirotor pitch and roll oscillations, as can be seen in Fig. 5.

The figure shows the total thrust generated by the AMIS rotors and the multirotor pitch attitude angle. It can be seen also in the figure that the total thrust can be a good estimator of the contact forces, since the multirotor is in hover when performing these operations.

Figure 5. Bridge inspection experiment. Total thrust and pitch angle.

VI. CONCLUSIONS

Unmanned Aerial Vehicles are 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 has presented a new configuration for an aerial manipulator in which the arm is attached to the top of the multirotor. This setup is well suited for infrastructure and bridge inspection flying below the elements that are being inspected, even by contacting the bridge surface with an ultrasonic sensor located at the end effector of the arm. The paper has presented the derivation of the aerial manipulator dynamic model and suitable controller, which has been tested in simulation. The first flight experiments with the AMIS prototype are also presented, flying under a bridge and contacting the bridge surface with the sensor head located at the arm. These initial experiments suggest that the additional forces applied by the arm to the bridge surface to maintain contact are even beneficial for multirotor stability, decreasing pitch and roll oscillations. More experiments will need to be done to support this, especially in situations where the contact point is away from the multirotor axis.

ACKNOWLEDGMENT

This work has been supported by the ARCAS Project, funded by the European Commission under the FP7 ICT Programme (ICT-2011-287617).

REFERENCES