Design, modeling, and control of an aerial manipulator for placement and retrieval of sensors in the environment

Salua Hamaza1 | Ioannis Georgilas2 | Guillermo Heredia3 | Aníbal Ollero3 | Thomas Richardson1

1Department of Aerospace Engineering, University of Bristol, Bristol, UK
2Department of Mechanical Engineering, University of Bath, Bath, UK
3Department of Systems Engineering and Automation, University of Seville, Seville, Spain

Correspondence
Salua Hamaza, Bristol Robotics Laboratory, Bristol, UK.
Email: salua@ieee.org

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Abstract
On-site inspection of large-scale infrastructure often involves high risks for the operators and high insurance costs. Despite several safety measures already in place to avoid accidents, an increasing concern has brought the need to remotely monitor hard-to-reach locations, for which the use of aerial robots able to interact with the environment has arisen. In this paper a novel approach to aerial manipulation is presented, where a compact manipulator with a single degree-of-freedom is tailored for the placement and retrieval of sensors in the environment. The proposed design integrates on-board sensing, a high-performance force controller on the manipulator, and a thrust-to-force mapping on the flight controller. Experimental results demonstrate the high reliability achieved during both placement and retrieval tasks on flat surfaces (e.g., a bridge wall) and cylindrical surfaces (e.g., tree trunks). A total number of 89 flight experiments were carried out to demonstrate the robustness and potential of the compact, bespoke aerial design.

KEYWORDS
aerial robotics, environmental monitoring, forestry, manipulators, mechanisms

1 | INTRODUCTION

In the past few decades the increasing interest towards Unmanned Aerial Vehicles (UAVs) has sprouted a number of industrial and civil applications in which these platforms are being used. Thanks to their inherent versatility, UAVs are deployed for a number of contact-less operations which exploit advanced on-board sensing, for example, cameras, pressure sensors, flow sensors, LIDAR. Some example applications in which aerial vehicles are currently being used are civilian security, border security, fire and rescue, mountain rescue, distribution network monitoring, environmental monitoring, aerial photography, mapping, and surveying. Despite proving very useful and successful, these applications are mostly limited to passive observation. However, huge potential lies in tasks that do require manipulation and physical interaction with the environment (Ruggiero, Lippiello, & Ollero, 2018).

Since 2009 (Bernard & Kondak, 2009) a new research area has risen, aerial manipulation, which considers endowing multicopters with mechanical devices to enable airborne manipulation tasks. Multicopters, for example, quadcopters, hexacopters, octocopters, are Vertical Take-off and Landing (VTOL) aircraft that can hover, take off, and land vertically. This feature, together with the ability to fly stably at low speeds, greater maneuverability and greater payload capacity has made them particularly attractive for these type of applications. In its early stages, aerial manipulation main focus of interest laid in load transportation (Palunko, Cruz, & Fierro, 2012; Pounds, Bersak, & Dollar, 2011b) and grasping (Mellinger, Shomin, Michael, &...
In more recent times, the scope has extended to the application of force in the environment for non-destructive testing (NDT; Fumagalli et al., 2014), assembly and disassembly (Augugliaro et al., 2014; Jimenez-Cano, Martin, Heredia, Ollero, & Cano, 2013), peg-in-hole (Korpela, Brahmbhatt, Orsag, & Oh, 2013) or positioning (Kim, Choi, & Kim, 2013; Suarez, Soria, Heredia, Arrue, & Ollero, 2017).

Aerial manipulators (AMs) could be deployed to carry out inspection and maintenance in remote and hard-to-reach locations, performing tasks that are too risky for human operators and that require costly equipment. Some example scenarios where AMs could be exploited are illustrated in Figure 1 and include the insulation of cracks on wind turbine blades, cleaning of clogged-up thermocouples on industrial chimneys, contact-based inspection of bridges and dams, placement and retrieval of smart sensors in widespread areas and infrastructure. Some of these example scenarios have been the case study of several investigations as part of multiple European funded projects in the past few years, starting from (AIRobots, 2012) until most recently (AEROARMS, 2018, 2020; ARCAS, 2015).

In this study, the ability for an aerial manipulator to place and retrieve sensing devices in the environment is addressed. Remote sensing can bring several advantages as real-time monitoring of infrastructure and on-line surveying, therefore, contributing towards hazard prevention and a prompt response in case hazards occur. To carry out placement and retrieval tasks, the AM should be capable of exerting a force in the environment by means of a tool that aids the positioning of such sensing devices. Besides positioning, other limitations are posed in the amount of force exerted by the AM. For instance, in case of interaction with delicate objects or surfaces, the use of a compliant approach becomes necessary.

This paper is outlined as follows: related works in the state of the art are presented in Section 2; the design considerations and concept that channeled the manufacturing of the AM are discussed in Section 3. Section 4 presents the modeling of the system, the solution of the kinematics and dynamics problem. Section 5 introduces the control laws implemented in the aerial manipulator. In Sections 6 and 7, flight experiments carried out indoors and outdoors are presented and discussed with an in-depth analysis of both the aircraft’s and the manipulator’s performance to validate the robustness and reliability of this approach. Finally, Section 8 presents the conclusions drawn from this study.

2 | RELATED WORK

The state-of-the-art in aerial manipulation mostly relates to solutions to perform aerial grasping and transportation of an object. The application of force on a surface is first addressed in Albers et al. (2010), where a quadcopter is endowed with an additional propeller oriented horizontally to generate a normal force to a vertical wall. In this study there is no specific design for a manipulator, but rather the addition of a cleaning tool/brush on the aircraft frame for cleaning purposes. Results show that a mean force of 2.5 N is achieved over a period of 50 s. The major drawback of this solution relates to the limited flight time due to the presence of an extra rotor and the narrow scope of applications that can be achieved with the fixed tool (cleaning brush). Similarly, in more recent work in McArthur, Chowdhury, and Cappelleri (2018) a tricopter UAV is equipped with an additional horizontal propeller for physical interaction with the environment. The “boomcopter” utilizes the horizontal propeller propulsion to apply forces in hover state through a fixed end-effector. The scope for such design is the ability to position objects...

FIGURE 1 Example applications for aerial manipulators include contact-based inspection of wind turbines, bridges, dams; or the placement of smoke detectors in forests for monitoring and fire prevention (Pexel, 2018) [Color figure can be viewed at wileyonlinelibrary.com]
over flat vertical surfaces thanks to a press-to-release mechanism embedded in the end-effector.

In Scholten, Fumagalli, Stramigioli, and Carloni (2013) the ability to exert contact forces up to 3 N on a vertical wall is demonstrated with the use of a compact delta-robot mounted on the surrounding structure of the vehicle for gentle contact NDT purposes. In Ryll et al. (2017) a novel approach is introduced with the use of tilt-rotor to apply a force over an inclined surface and be able to control independently both linear and angular accelerations of the UAV to counteract any opposing wrench. Similarly, in the work Papachristos, Alexis, and Tzes (2014) the exertion of large forces for object manipulation is achieved through the use of a direct thrust-vectoring actuation on a tilt-rotor, with resulting forces over 20 N. Along the same lines, the work proposed by Jiang and Voyles (2013) shows a hexarotor performing a peg-in-hole task using a 6-Degrees-of-Freedom (DoFs) manipulator inspired to a HEXA parallel robot. To generate a force on the interaction plane, that is X–Y plane of the aerial manipulator, the rotors' axes are tilted of a certain cant angle. This inclination distributes part of the aircraft thrust into a force normal to the wall for peg-in-hole purposes.

In Darvianakis, Alexis, Burri, and Siegwart (2014) a hybrid model predictive control framework is proposed for a quadcopter able to conduct stable physical interaction on the side without the use of a manipulator. Convex optimization techniques are used within the attitude controller, which accounts for the dynamics during physical interaction. Experiments include "aerial writing tasks, where a marker pen is mounted on the aircraft frame for interaction with textured surfaces and obstacle avoidance maneuvers. On the same line, the work by Hamaza, Georgilas, and Richardson (2019) shows an aerial manipulator contour following a two-dimensional (2D) surface while exerting a continuous force. The difference in the latter approach lays in the use of a passivity-based force controller on the active manipulator which compensates for any drifting and shaking in the near proximity with the surface, while the on-board attitude controller remains a standard one. This results in consistent and uninterrupted contact while the AM flies across the surface.

In Bartelds, Capra, Hamaza, Stramigioli, and Fumagalli, (2016) collision absorption is evaluated by means of a passive compliant manipulator. It is demonstrated how high forces deriving from an impact are effectively absorbed by the on-board compliant manipulator and the resulting kinetic energy is stored within the spring element of the manipulator itself. In Hamaza, Georgilas, and Richardson (2018) a UAV equipped with a 2-DoF manipulator featuring active variable compliance can adjust the output force on a vertical wall by tuning the manipulator’s controller gains. This allowed the AM to tailor the force at the end-effector following a task-specific outcome. Another key result is the ability to apply rapid physical pulses over a surface for a period over 2 s with an average tapping frequency of 10 Hz. In Wopereis et al. (2017) substantial forces up to 16 N are applied by an aerial vehicle equipped with a passive manipulator pitching at high angles against a flat vertical surface. This study mainly focuses on the control strategy over the pitch and yaw angles to guarantee stable contact for prolonged periods of time, however, it has the limitation of a static contact point and limited end-effector motion due to its passive nature.

In Ikeda et al. (2017) an octo-rotor UAV with a 1-DoF manipulator on-board is used to exert a constant contact force over a bridge wall. The force generated at the end-effector is proportional to the pitch angle of the UAV when in contact with the bridge pier. Both the vehicle attitude controller and the manipulator’s force controller use a standard proportional integral derivative method.

Inspired by the above efforts, this study presents a novel, compact design of an aerial manipulator capable of exerting considerable force to achieve such tasks as the placement and retrieval of smart sensors in different environments. The scope envisioned for the proposed aerial manipulator is the same as the one seen in McArthur et al., (2018), that is positioning of sensors in the environment, however, the methodology differs in the following ways: the use of an active manipulator on-board to accomplish the task is endorsed, as opposed to using a custom-made multicopter with tilted rotors or booms. The aerial manipulator combines the manipulator’s force output with the vehicle motion to generate a force at the end-effector that can be adjusted in-flight. The active manipulator operates autonomously and its force output is independent of the UAV’s. The main challenge tackled in this study is the ability to seamlessly combine the two systems in a single multivariable platform to perform force-based operations airborne. The ability of retrieving such mounted sensors is also demonstrated with our setup for the first time, using a different end-effector design and different control inputs.

A novel force generation approach is also hereby introduced, where the actively compliant manipulator combined with the UAV pitching motion generates a force on the wall that is proportional to the pitch angle and is buildable over time. The combination of the two subsystems, namely the manipulator and the UAV, is possible thanks to a high-performance force controller at the end-effector which allows for real-time force adjustments while in contact. The active feature of the manipulator also favors faster dynamics than those of the under-actuated flying robot. These together are the key contributors to robust and repeatable behavior, successfully tested over flat and cylindrical surfaces, namely tree trunks.

3 | AERIAL MANIPULATOR DESIGN

3.1 | Design considerations and requirements

A recurrent approach found in the state-of-the-art when it comes to designing a manipulation system intended for aerial applications is to use serial types of manipulators, comprising n-joints providing n-DoFs to the overall structure. However, despite the dexterity that a higher-DoF manipulator allows in terms of tasks that can be accomplished, there are several drawbacks that come with it. Primarily, a higher number of DoFs demands a higher number of actuators, therefore greater payload, higher control complexity, higher associated repair and maintenance costs, but also decreased maneuverability and battery life (Huber
et al., 2013). Hence, it is essential to limit the overall mass where possible and avoid redundancy while still devising the right tool for the job. Tasks that require limited object manipulation capabilities, for instance the exertion of a force normal to a surface for NDT, inspection by contact or the placement of sensors, can be achieved with a simple probe oriented towards the contact surface. Despite its simplicity, this type of approach provides a minimal, weight-efficient solution to the problem.

Hence, the first design requirement is posed to the manipulator’s weight and the number of DoFs. A single-DoF manipulator is proposed, comprised of an active prismatic joint. To allow for a high force output within a compact lightweight solution, the use of rotation motors is favored over linear motors: for the same force output, linear actuators are larger, heavier but also have less power efficiency than their rotational counterparts. Therefore, the use of a high-performance brushless DC motor paired with a rack and pinion transmission is utilized. Where possible the use of light sturdy materials is employed, such as polymer linear bearings (igus DryLin®), custom-made aluminum parts, and a rapid-prototyped ABS polymer housing for the rack and pinion mechanism.

Another design consideration relates to the distribution of mass and the overall AM inertia: for aerial manipulators it is desirable to keep a compact design and move the end-effector contact point as close as possible to the aircraft Centre of Gravity (CoG). When manipulating an object, the added mass and gravitational force generate a momentum pivoting about the aerial platform that is directly proportional to the vector distance between the aircraft CoG and the contact point. In case the interaction takes place on the side of the vehicle, for example, interaction with a wall, the vertical component of such a vector is crucial. Hence, reducing the vertical misalignment between the contact point and the CoG aids the overall stability. For this reason, the prismatic joint is oriented forward by means of an inclined support, making the tip of the rack tilted towards the center of the platform.

Lastly, the presence of the manipulator and any moving masses act as disturbances on the aerial vehicle and tend to destabilize it. Therefore, it is desirable to reduce the relative motion between the manipulator and the aircraft and group heavier components closer to the vehicle’s CoG, minimizing the induced instability. This is frequently addressed in the literature with the use of one or multiple retractable arms, where the manipulator’s configuration is kept compact and its CoG is close enough to the aircraft’s CoG while not in operation. A compact design with minimal moving masses is not only beneficial to the aircraft stability, but also to its aerodynamics and battery life. In this sense, the proposed design with a single slider joint complies with these criteria more than other solutions with retractable arms, as no moving masses are present, except for the sliding rack (≈90 g).

3.2 | Manipulation system overview

The manipulation system consists of a single-DoF manipulator integrated with proximity and position sensors and communicating to the aerial platform via an on-board computer. The choice of a slider joint is made based on the requirement that the AM needs to interact with the environment by applying a lateral force. The use of a passive slider was initially contemplated as a tool with which the UAV could have applied a force just by pitching towards an obstacle, propagating part of its thrust through the slider. However, the active joint solution was preferred to better control the end-effector position and force output.

The slider is embodied by a rack and pinion transmission, driven by a high-performance motor controller. The mechanical components are manufactured in aluminum as they deliver high precision and accuracy within a low mass, low wear coefficient component. The pinion-rack mechanism is directly driven by the motor without any gear reduction. A double-sided pinion is coupled with the motor-shaft via a set screw. Two ball bearings are held in place at the extremities of the pinion to release the motor from any radial tension that might generate during interaction. A round rack gear slides within two polymer linear bearings, essential to ensure the adherence of the rack’s teeth over the pinion during transmission. Figure 2 illustrates a cross section of the prismatic joint and its components. The module of the gears was chosen to be the lowest as possible to minimize the pinion’s pitch diameter and provide a higher feed force to the end-effector. In fact, the feed force is:

$$F_{rack} = 2 \times \frac{T_{motor}}{d_p} = \frac{T_{motor}}{r_p},$$  \hspace{1cm} (1)$$

where $d_p$ and $r_p$ are the pitch diameter and pitch radius of the pinion, respectively. Rearranging Equation (1), the nominal torque $T_{nom}$ required by the motor to generate an interaction force $F_{rack}$ is derived.

![FIGURE 2](http://example.com/image.jpg) Cross section computer-aided-drawing of the transmission mechanism and relevant components. A double-sided pinion (in green) drives the motion of the rack, while the encoder measures the relative position. A set of ball bearings and linear bearings (in yellow) assure accurate positioning of the pinion and the rack, respectively, also distressing them from any lateral tension/momentum that may generate. The electronics and the distance sensor are not present in this figure [Color figure can be viewed at wileyonlinelibrary.com]
This torque must be less than the available stall torque to prevent overheating and to work within the reliable mechanical limits of the actuator itself.

To select the motor a rough estimate of the application force is necessary. According to the experimental results in (Bartelds et al., 2016), in a scenario where a small-sized aerial manipulator is impacting rigidly with a wall the resulting forces may reach approximately 60 N. To be able to overcome different conditions with the proposed approach and provide a versatile solution that can be deployed with larger multi-rotors, the brushless DC motor which drives the pinion has a nominal torque \( T_{\text{nom}} = 83.4 \, \text{mNm} \) and stall torque \( T_{\text{stall}} = 780 \, \text{mNm} \). The selected pinion has a pitch radius \( r_p \) of 2.5 mm, hence the nominal feed force generated by the selected motor is \( F_{\text{rack}} = 33.3 \, \text{N} \), and the maximum force over a short period (e.g., 3 s) would be \( F_{\text{max}} = T_{\text{stall}}/r_p = 312 \, \text{N} \).

### 3.3 Sensing

The manipulator is equipped with two high-performance sensors: an inductive MILE quadrature encoder on the actuator and a rangefinder located at the front of the aircraft. Both sensors have an update frequency of 1 kHz, allowing real-time control over the end-effector.

The encoder is directly coupled with the motor and measures the end-effector’s relative position. The readings from the encoder are sent to the motor driver via a Quadrature Encoder Interface, then converted to metric measurements and updated in the Forward kinematics control block. Knowing the position of the slider joint and its relative displacement helps towards the accurate positioning of the end-effector, and also it enables the controller to safely work within the rack’s available length, that is within its physical boundaries.

The rangefinder is mounted at the front of the vehicle and informs the manipulator’s on-board computer of the relative position between the UAV and the obstacle ahead. The selected sensor uses the time-of-flight technology and it is preferred over ultrasound or infrared triangulation technologies as it allows for a much higher sampling frequency and long range measurements (over 12 m). Similarly, laser technology was also discarded due to the bulkiness and high payload of commercially available laser scanners. The selected distance sensor is sized 35 × 29 × 18 mm, weighs 8 g and can measure distance within 14 m under different light conditions, making it suitable for both indoors and outdoors testing.

### 3.4 End-effector designs

Two different end-effectors are devised to address sensor placement and retrieval operations. For the placement task, the use of magnetic force is adopted to hold the sensor in place during release. The tip of the rack is equipped with a flat surface that resembles a lid. On top of it, a series of small Neodymium magnets are arrayed in such a way to prevent repulsion forces in between them. The same configuration is replicated on the outside of the sensor case, by mirroring the magnets. The adhesion force produced by the magnets \( F_{\text{grip}} \) must be enough to hold the sensor in place in-flight and overcome the forces generated by aerodynamic disturbances, especially during take-off and in proximity of the wall

\[
F_{\text{grip}} \geq m_p g + F_{\text{dist}},
\]

where \( m_p \) is the payload mass (e.g., sensor), \( g \) is the gravitational acceleration and \( F_{\text{dist}} \) is the force due to disturbances in flight, for example, turbulence generated by the surrounding propellers during take-off, or due to the wall-effect. The accurate computation of \( F_{\text{grip}} \) can be quite complex, especially because this force is proportional to the in-flight disturbances \( F_{\text{dist}} \), which are unknown and vary within each flight. To derive \( F_{\text{grip}} \) empirically some preliminary experiments were performed testing the reliability of differently sized areas. Through trial and error it was found that 2.5 cm² of magnetic area provided a reliable adhesion between the gripper and a sensor of approximately 40 g, experiencing a failure rate below 1% spanned over 48 flights conducted.

For retrieval tasks the end-effector consists of a square hook with a threaded hole at one end. To secure the hook in place, a bolt is fastened along the hole, inside the rack. This design is selected as it facilitates the grasp, and for its manufacturing simplicity. For the hook to engage with the sensor a metal string was looped around the sensor case to ease the pull. Figure 3 illustrates a close-up of both designs.

![End-effector designs](https://wileyonlinelibrary.com)
3.5 | Integration with the aerial platform

3.5.1 | Aerial platform

The proposed 1-DoF manipulator design is manufactured and it is integrated on a small-sized aerial platform, namely the Lumenier QAV400 quadcopter (1.1 kg) powered by a 4 s 2,200 mAh battery (250 g). The main features of this aerial platform are listed in Table 1. The choice of a suitable platform for placement and retrieval tasks on a side wall mainly focuses on the vehicle's available payload and flight time to carry out such operation. In the case of the proposed compact manipulator the total mass of mechanical and electronic components is 500 g, allowing to select a smaller-sized platform that is safer to interact with, easier to fly and less costly to maintain and repair in case of failure. The choice of a commercially available UAV is preferred over customized solutions to make aerial manipulation technologies more accessible to end-users. In fact, thanks to a modular design which can act as an add-on feature on an existing platform, users have the flexibility to transit from UAV to AM applications as they like.

3.5.2 | Aerial manipulator layout and mass properties

The selected aircraft has a lightweight structure consisting of several carbon fiber layers at the core. Within such layout, the manipulator can be mounted on the top or bottom plate of the frame. The general rule when it comes to add masses on the aircraft is to position them as close as possible to the core of the aircraft to reduce the overall inertia of the aerial system. The "top" configuration is preferred as it generates a more favorable vehicle response: that is during aerial interaction the force generated at the tip of the end-effector induces a momentum on the aircraft that is anticlockwise if the point of contact is above the vehicle CoG, causing the UAV to back off the wall. Viceversa, if the point of contact is below the vehicle's CoG, the induced clockwise momentum would cause the aircraft to tilt towards the wall, potentially leading to collision. Moreover, the available space on the bottom plate is dependent on the landing gear's geometry, and this places additional constraints to both the volume available and the range of motion of the manipulator.

The manipulator's components (motor board, computer, pinion-rack mechanism, sensing) are placed in such a way that the weight is distributed and symmetrical with respect to the vehicle's CoG. In this respect, the prismatic joint is mounted towards the front of the aircraft, while the battery is placed at the back to balance out the weight. Figure 4 illustrates some computer-aided design (CAD) drawings of the AM from different views and the hardware layout.

In Table 2 the mass properties of the UAV and the AM are presented. The center of mass (CoM) coordinates are calculated based on a reference frame positioned in the center of the vehicle with z-axis pointing upwards, x and y axes pointing towards the front and the side of the vehicle, respectively. One can notice that the presence of the lightweight manipulator does not have much impact on the position of the CoG and on the moments of inertia along the main axes. In fact, the CoM of the system is only shifted by 1 cm along the z-axis and 2 cm along the x.

3.5.3 | Hardware and software architecture

The on-board flight controller Pixhawk 4 uses the PX4 firmware and offers several flight modes: attitude, position, via-point, and manual.

| TABLE 1 System components and specifications |
|-----------------------------------------------|
| QAV400 quadcopter | 1-DoF manipulator |
| Rotors | FX2216-9 1100kv | Motor | Maxon motor DC45 flat 50 Watt, 780 mNm stall torque |
| Propellers | 8 × 5" | Motor controller | Maxon EPOS 24/3A Digital Controller 24 V, 3 A, 10 kHz sampling rate, 10 g |
| Battery | LiPo 4 s 2,200 mAh | Battery | LiPo 4 s 2,200 mAh |
| Flight controller | Pixhawk 4 PX4 firmware | On-board computer | Raspberry Pi 3 |
| Sensing | • 2 IMUs • Barometer • GPS | Sensing | • Terarager One distance sensor 0.2-14 m range, 1 kHz sampling rate • MILE Maxon Encoder, 1024 CPT |
| Max. payload | 0.8 kg | Max. payload | 0.2 kg (1 kg if used stand-alone) |
| Flight time | 10 min at 0.5 kg | Operation time | max. available flight time or 2 hr if used stand-alone |
During flight experiments, the UAV flies in position mode and is remotely controlled by a pilot via a FrSky Taranis X9D radio transmitter. The ground control software used to calibrate the vehicle’s gains is QGroundControl, which provides full flight control and vehicle setup for PX4 powered vehicles.

The manipulator’s on-board computer is the Raspberry Pi 3 (1.4 GHz 64-bit quad-core ARM Cortex-A53 processor) with wireless LAN connectivity and logging capabilities. This processor is responsible for the AM task management during operation and the manipulator’s force control. A brushless DC motor “Maxon EC45 flat” with Hall sensor and MILE encoder actuates the motion of the pinion-rack mechanism through a Maxon EPOS2 24/3 motor digital controller board. This motor board is mainly selected as it offers a high sampling rate frequency for all its operation modes: 10 kHz in current mode, and 1 kHz in position and velocity mode. These rates make real-time control over the manipulator possible within a compact and lightweight solution (10 g). Lastly, a Teraranger One rangefinder is mounted at the front of the aircraft and sends distance information to the on-board computer.

The software implementation is in robotics operating system (ROS). The main control node runs on the on-board Raspberry Pi and communicates with the UAV flight controller through a MAVLink/MAVros bridge. The overall system architecture is presented in Figure 5.

**TABLE 2** A comparison between the aircraft only and aircraft + manipulator mass properties: mass, CoM coordinates and central axes moments of inertia

|                  | Aircraft only | Aircraft + manipulator |
|------------------|---------------|------------------------|
| m (kg)           | 1.35          | 1.85                   |
| xCoM (m)         | 0.48          | 0.5                    |
| yCoM (m)         | 0             | 0                      |
| zCoM (m)         | 0.17          | 0.18                   |
| Jxx (kg m²)      | 0.03          | 0.03                   |
| Jyy (kg m²)      | 0.04          | 0.05                   |
| Jzz (kg m²)      | 0.07          | 0.07                   |

**FIGURE 4** Computer-aided design drawings of the aerial manipulator and components layout [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 5** Hardware and software components and system architecture of the proposed aerial manipulator. The red blocks display the microprocessors on-board, while the green boxes highlight the sensing devices on the manipulator. The software integration is done in ROS. The aircraft states are communicated to the manipulator’s controller via a MAVLink to MAVros bridge. ROS, robotics operating system [Color figure can be viewed at wileyonlinelibrary.com]
4 | MODELING

The modeling of the proposed compliant manipulator is a key component when describing the behavior of the integrated system as a whole, namely the AM. In this section, the kinematics of the aerial manipulator is presented, the solution of which will be used in the Control section. The dynamic analysis of the coupled system is also presented.

4.1 | Kinematics

Let us consider a quadcopter equipped with 1-DoF manipulator as depicted in Figure 6. By defining two coordinate frames, that is the ground frame $\mathcal{G}$ and the body-fixed frame $\mathcal{B}$, one is able to fully describe the motion of the aerial platform in space. However, in aerial manipulation two additional reference frames are adopted to account for the presence of the manipulator and the object to manipulate. The first, $\mathcal{M}$, is centered in the manipulator’s CoG and the second, $\mathcal{E}$, is centered in the end-effector.

In this case, it is assumed that the manipulator CoG coincides with the one of the aircraft. This assumption is based on the design choices discussed in the previous section and on the values found in Table 2: the proposed compact manipulator gathers its components at the base, shifting the manipulator’s CoM towards the core of the platform where it is mounted. Also, while in operation the only moving part is the rack, which accounts for less than 5% of the AM total mass. Therefore, thanks to the limited inertia generated by the rack’s motion, no major impact is produced over the CoG position.

The reference frames used to solve the kinematic problem are displayed in Figure 6. Let us define three pose vectors: $\vec{\pi}_B$ describes the pose of the aircraft with respect to the ground frame, and vectors $\vec{\pi}_C$ and $\vec{\pi}_E$ describe the pose of the end-effector with respect to the ground and aircraft frames, respectively. Vectors $\pi$ consist of linear and angular terms about the $x$-$y$-$z$ axes, as illustrated in Figure 6.

The position of the AM depends on the relative position of the body-fix frame $\vec{\pi}_B$, and the end-effector $\vec{\pi}_E$. From Equation (3) it is now possible to solve the 1-DoF manipulator FK as a decoupled problem. Let us consider Figure 6: the UAV frame $\mathcal{B}$ has the $z_B$ axis pointing upwards; frame $\mathcal{E}$ is rotated clockwise about $y_B$ of an angle of $90^\circ + \delta$, where $\delta$ takes into account the small inclination of the prismatic joint on the platform. Therefore, the end-effector is aligned with $z_E$ and the distance between frames $\mathcal{B}$ and $\mathcal{E}$ along $z_E$ varies with the motion of the slider, namely variable $\varepsilon$ along $z_E$.

Due to the nature of quadcopters being underactuated systems the kinematics problem of the AM is considered as a whole, as disturbances in the roll-pitch-yaw states affect the position of the end-effector. Hence the kinematic chain $X = [\zeta_x \ \zeta_y \ \zeta_z \ \phi \ \theta \ \psi \ \mathbf{q}]$ describes the aerial system as a single, where $X$ represents a ($6 + 1$) dimension vector consisting of the aircraft linear and rotational terms (6-DoFs in space), and the scalar $\mathbf{q}$. The position of the end-effector with respect to the ground frame is represented by vector $\vec{\pi}_E$, which combines the multiplication of three homogeneous transformation matrices as follows: Each homogeneous transformation matrix is a $(4 \times 4)$ matrix encompassing rotational and translation information of a space vector from frame $i$ in superscript, to the resulting frame $i + 1$ in subscript. Following the assumption that frames $\mathcal{B}$ and $\mathcal{M}$ coincide, the forward kinematics (FK) problem yields to:

$$\vec{\pi}_E = \vec{\pi}_B + \vec{\pi}_C = \vec{\pi}_B \cdot (\vec{\pi}_C - \vec{\pi}_B) = \vec{T}_B(\zeta_x, \zeta_y, \zeta_z, \phi, \theta, \psi) \cdot \vec{T}_E(\mathbf{q}).$$

(3)

The position of the AM depends on the relative position of the body-fix frame $\vec{\pi}_B$, and the end-effector $\vec{\pi}_E$. From Equation (3) it is now possible to solve the 1-DoF manipulator FK as a decoupled problem. Let us consider Figure 6: the UAV frame $\mathcal{B}$ has the $z_B$ axis pointing upwards; frame $\mathcal{E}$ is rotated clockwise about $y_B$ of an angle of $90^\circ + \delta$, where $\delta$ takes into account the small inclination of the prismatic joint on the platform. Therefore, the end-effector is aligned with $z_E$ and the distance between frames $\mathcal{B}$ and $\mathcal{E}$ along $z_E$ varies with the motion of the slider, namely variable $\varepsilon$ along $z_E$.

With the above conditions, the Denavit–Hartenberg parameters are: which yields to:

$$\vec{T}_E(\mathbf{q}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(90^\circ + \delta) & -\sin(90^\circ + \delta) & -\varepsilon \sin(90^\circ + \delta) \\ 0 & \sin(90^\circ + \delta) & \cos(90^\circ + \delta) & \varepsilon \cos(90^\circ + \delta) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(4)

The last column of the matrix displays the end-effector $x$-$y$-$z$ coordinates with respect to frame $\mathcal{E}$. By knowing the extension of the rack, namely variable $\varepsilon$ thanks to the on-board encoder, and the angle $\delta$ as part of the manipulator’s design choices, the manipulator’s FK problems is solved. The computation of the FK will then be used in the control block of the manipulator, as seen in the following section.

4.2 | Dynamics

The dynamics of aerial manipulators have been extensively analyzed in the literature, where the most recurrent approach uses the Newton-Euler

| Link | $i$ | $a_{i-1}$ | $d_{i-1}$ | $d_i$ | $\theta_i$ |
|------|----|----------|-----------|-------|-----------|
| 1    | 0  | $90^\circ + \delta$ | $\varepsilon$ | 0     |
formulation to model the aerial system as a whole (Fumagalli et al., 2014; Huber et al., 2013; Korpela et al., 2013; Orsag, Korpela, Bogdan, & Oh, 2014, 2013; Palunko et al., 2012; Suarez et al., 2017; Tognon et al., 2018; Wopereis et al., 2017). In this section, we will briefly represent the dynamics of the aerial manipulator Figure 7.

For a general multirotator, the thrust $T(u)^i$ generated by each propeller $i$, is directed along the $z$-axis in the body-fixed frame $\mathcal{B}$. Similarly the torque $\tau(u)^i$ generated by each rotor is about the same axis, $z_i$. The total thrust vector $F_\mathcal{B}(u)$ is the summation of all $T(u)^i$ terms measured in the ground frame $\mathcal{G}$. In a quadcopter, this is

$$F_\mathcal{B}(u) = \sum_{i=1}^4 T(u)^i,$$

(5)

$$\tau_\mathcal{B}(u) = \sum_{i=1}^4 \tau(u)^i + \Delta r_i \times T(u)^i.$$ 

(6)

The above equations represent the force and torque of the aerial system generated by the rotors. Vector $\Delta r_i \times T(u)^i$ is the torque generated by the thrust vector $T(u)^i$ about the center of the vehicle, with arm $\Delta r_i$. The aircraft lift force in Equation (5) must be enough to counteract the vehicle's gravitational force and other nonlinear aerodynamic effects, for example, gusts, turbulence due to the presence of obstacles (the wall-effect), and the presence of the manipulator. The equations of motion of the manipulation system can be derived using the Newton–Euler approach

$$F_m(q, \dot{q}, \ddot{q}) + F_{ext} = M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G(q, \dot{q}).$$

(7)

$$B \ddot{\theta} + \tau_m = \tau - \tau_r,$$

(8)

$$\tau_m = K(\theta - q) + D(\dot{\theta} - \dot{q})$$

(9)

where $\theta$ and $q$ represent the vector of joint angles and generalized coordinates, respectively, $M$ is the generalized mass matrix comprising the inertial terms, matrix $C(q, \dot{q})$ represents the Coriolis and centrifugal terms, and $G(q)$ comprises of all gravitational terms acting on the manipulator. $F_m$ and $F_{ext}$ represent the total force generated by the manipulator and the external inputs respectively; $B$ is the motor inertia matrix, $\tau_m$ is the torque generated by the manipulator, and $\tau_r$ contains the friction torques. The manipulator's torque is here modeled as a linear spring-damper system with joint stiffness matrix equivalent to $K = \text{diag}(k_i)$ and damping matrix $D = \text{diag}(d_i)$.

For a 1-DoF manipulation system, vectors $q, \dot{q}, \ddot{q}$ are reduced to scalars, and likewise matrices $M, C(q, \dot{q}),$ and $G(q)$. In our case, the scalar quantity $q$ consists of the prismatic joint variable $\epsilon$.

As the manipulator dynamically interacts with an obstacle, the forces and torques generating at the end-effector propagate to the floating base. Hence, the coupled dynamics of the AM system calculated with respect the the body-fixed frame $\mathcal{B}$ yield to

$$\begin{bmatrix} F_\mathcal{B}(u) \\ \tau_\mathcal{B}(u) \end{bmatrix} + \begin{bmatrix} F_m(q, \dot{q}, \ddot{q}) \\ \tau_m(q, \dot{q}, \ddot{q}) \end{bmatrix} = \begin{bmatrix} m \ddot{R} R e_3 e_3 \\ 0 \end{bmatrix} I(q) \ddot{v} + \begin{bmatrix} 0 \\ \omega \times I(q) \omega \end{bmatrix},$$

(10)

where $m$ represents the AM overall mass, multiplied by a $(3 \times 3)$ eye matrix $e_3$ and rotation matrix $\ddot{R}$; $\dot{v}$ and $\omega$ are the linear and angular accelerations acting on the AM, including the linear gravitational term $g = -9.81\, m/s^2$, $I(q)$ is a $(3 \times 3)$ null matrix and $I(q)$ is the inertia tensor about frame $\mathcal{B}$. The above equation describes the nonlinear dynamics of the AM and clearly shows how the propulsion and actuation systems of the vehicle and manipulator (left side of the equation) counterbalance the linear and angular dynamics of the system (on the right side).

5 | CONTROL

The control approach implemented in this study enables the aerial manipulator to exert a force on the side of the aircraft through the combined action of the manipulator and the vehicle itself. The contribution of the UAV towards the magnitude of the force output facilitates adhesion of the sensor during placement operations, and eases the pull during recovery. Breaking down the task requirements, the ability to apply a compression or tension force over a surface is tackled, hence the ability to control the interaction force.

The active slider fully controls the way in which contact is established between the AM and the target surface. The slider is in fact used as an impedance tool that facilitates the interaction with the environment. Another advantage brought by the active manipulator as opposed to a passive one, is that it caters the UAV with an additional DoF and allows for a prompt, quicker response to the system as a whole. This is possible thanks to the simpler dynamics governing the manipulator and the embedded high-performance motor board of the joint.

In this section, the control approach implemented on the AM is discussed, and each subsystem’s contribution towards the resulting force is examined. At first, the mapping between the current controller (running on the slider joint) and the force output is evaluated. The manipulator generates a lower force compared to the aircraft, and it does so thanks the rack and pinion transmission which converts the DC motor’s torque into force at the end-effector.

Then, the mapping between the aircraft thrust and the force at the end-effector is presented. As the vehicle tilts forwards, the thrust vector has an horizontal component to the force, which enables the...
UAV to move forwards. When in contact with a surface, however, such force is propagated through the manipulator to the target. The mapping between the pitch motion of the vehicle and the resulting force sensed at the end-effector is hereby also evaluated.

### 5.1 Current-to-force mapping

The active prismatic joint is controlled in force through a proportional integral (PI) current controller. Brushless DC motors present a linear relationship between the input current and the generated output torque, in accordance with the motor’s specifications. For the selected motor the torque constant provided by the manufacturer is $K_T = 33.5$ mNm/A. The estimated manipulator’s force $F_m$ is proportional to the output torque (as seen in Equation (1)), hence introducing $K_T$ yields to

$$F_m = cK_T f_p \varepsilon \varepsilon_m.$$  \hspace{1cm} (11)

where $c$ is the input current, $K_T$ is the torque constant, and $f_p$ is the pinion pitch radius. The above equation also factors in the efficiency loss in the actuator due to its internal friction $\varepsilon_m$. Both $\varepsilon_e$ and $\varepsilon_m$ are <1 and can be derived experimentally. Preliminary experiments are conducted to evaluate the manipulator force output in static condition and the mapping between the current and the rack feed force. The experiments consist in generating a step signal in current on the motor, increasing by 100 mA every 5.5 s while the tip of the rack is in contact with a surface. The output force along the rack is then measured at the tip, via a 6-axis force/torque sensor.

Results are shown in Figures 8 and 9. Figure 8 shows the force and current signals plotted over time. The horizontal blue lines show the mean value of the force data, while the grey vertical lines display where an abrupt change in the mean value of the force is met. The current steps are in line with the force output measured, despite a minor latency due to the time delay from the moment the signal is sent to the motor and a rise in force is measured by the force/torque sensor. It can be observed that the minimum current required to overcome the static friction of the system and sense a force of about 1.6 N is 100 mA. Figure 9 shows a line connecting the mean values in force (yellow line) and the linear regression of those (orange line). The equation displays the relationship between force and current found experimentally and can be compared to Equation (11) where the product of coefficients $K_T f_p \varepsilon \varepsilon_m$ can be grouped in single constant, namely the slope of the linear fit. The range of operation of the motor current used in the later flight experiments is below 600 mA; even so the current-to-force linear relationship shown in Figure 8 is expected to hold for higher values.

### 5.2 Pitch-to-force mapping

Force exchange conducted at the side of an aerial vehicle is a challenging task because of the asymmetrical distribution of forces and moments acting on the aerial vehicle. These disturbances may lead to instability, early battery drainage and poor performance. In recent years aerial force-exchange conducted on the side of the UAV has been addressed in the literature, those include the works of (Darivianakis et al., 2014; Ikeda et al., 2017; Papachristos et al., 2014; Ryll et al., 2017; Scholten et al., 2013; Wopereis et al., 2017) which have been previously discussed in Section 2. In this section, force generation exploiting the UAV’s thrust is discussed. The approach is very similar to some of the works mentioned above, as they exploit the UAV attitude controller to transfer a physical force onto an object. The main difference brought by this study lies in the use of such attitude controller in combination with the manipulator’s force controller to deliver a slow force build-up at the end-effector and compliant interaction, suited for placement and recovery operations with unknown surfaces of different shape and texture.

The aerial vehicle contributes to the largest part of the force exerted on the surface. Let us consider the UAV in contact with the surface by mean of a rigid rod, pitching forwards at an angle of $\theta$. As the rod lies on the $y$-$z$ plane, the force $F_y(\theta)$ generated by the vehicle and propagated through the stick will lie on the same plane, as illustrated in Figure 10. This force represents the horizontal component of the vehicle thrust vector and it has two elements to it: one static and one dynamic

$$F_{x,z} = F_{x,z} \text{ static} + F_{x,z} \text{ dynamic}.$$  \hspace{1cm} (12)

$$F_{x,z} \text{ static} = m g \tan(\theta),$$  \hspace{1cm} (13)

$$F_{x,z} \text{ dynamic} = m d\theta = m \frac{dv}{dt}.$$  \hspace{1cm} (14)

![FIGURE 8](wileyonlinelibrary.com) Evaluation of the manipulator feed force in static condition: mapping between the input motor current (right axis) and resulting output force measured via a force/torque sensor (left axis). The relationship between the two variables is linear [Color figure can be viewed at wileyonlinelibrary.com]
The static component of the force propagated at the target surface is proportional to the vehicle weight and pitch angle and it does not take into account the motion of the vehicle. The dynamic component depends on the vehicle's acceleration. To evaluate each component's contribution towards $F_{az}$, a set of 10 experiments were conducted where the vehicle approaches a vertical wall at a constant speed and the manipulator is kept at a fixed position, that is motion of the rack is prevented. The total force sensed at the wall is the summation of the static and dynamic components and it is measured by a 6-axis force/torque sensor mounted on the surface. The following table shows the values of UAV's speed of approach, speed variation after contact and angle of approach, averaged over 10 data sets Table 4.

Now, let us substitute the values found during the control experiments into Equations (13) and (14). The static component equals $F_{az,static} = 3.69$ N, and the dynamic component equals $F_{az,dynamic} = 26.71$ N, where the mass of the UAV $m$ approximates 1.9 kg. The total force transferred by the aerial system is therefore the summation of the two, $F_{az} = 30.4$ N.

Results of a sample test are displayed in Figure 11 which represents one of 10 control experiments conducted to describe the pitch-to-force mapping. It can be seen from the figure that the force exerted at the wall has an oscillatory behavior and exhibits several peaks, with maximum measured force equivalent to 30 N. If the conditions were static, that is stationary conditions, the curve would show a more constant behavior. However, as the force transferred by the vehicle also depends on the instantaneous acceleration, it is affected by the presence of impacts. It is important to highlight that the manipulator is kept fixed in these experiments, that is rigidly attached, therefore, bouncing and impacts are more likely to occur. In “normal” conditions the manipulator is activated, operating as an impedance tool and partially absorbing the kinetic energy transferred to the vehicle within the spring's stroke, that is the rack’s motion.

In general, the forces resulting from the UAV’s pitching motion were found to be consistent throughout multiple data sets, with measured magnitudes above 22 N on average at approximately 10°, and a standard deviation of 4.3 N.

### 5.3 Force control

Let us consider the control problem of a mass $m$ (UAV) attached to a spring element (manipulator) with stiffness $k_m$. The final goal is to be able to control the UAV and maintain a desired contact force $F_{des}$ with the environment, which is the force acting in the spring element $F_m = k_m x$, where $x$ is the relative position of the spring. The equation that describes this physical system is:

$$\ddot{x} + \frac{1}{m} (F_{des} + k_m \dot{x} + k_m x) + F_m + F_{dist} = 0,$$

where $F_{dist}$ is the force due to disturbances, for example, friction in the manipulator gearing, $\dot{x} = F_{des} - F_m$ is the force error between the desired force $F_{des}$ and the contact force $F_m$. In the manipulator case, $x$ is represented by the state vector $q$. Moreover, the above equation

### TABLE 4

| Angle of approach $\theta$ (deg) | UAV approach speed (m/s) $dv$ (m/s) | Time interval dt (s) |
|---------------------------------|-----------------------------------|----------------------|
| 11.2                            | 1.6                               | 2.53                 | 0.18                  |

Note: The experiments were conducted to map the aircraft pitch to force sensed at the wall.
considers a close-loop system where the force output on the environment $F_m$ is sensed and fed back, leading to the control law

$$\ddot{e}_f + k_{ef} \dot{e}_f + k_{ef} e_f = 0.$$  \hfill (16)

Following the method proposed by Craig (2005), one can assume that while the end-effector is in contact with the environment, its dynamics do not change over time. Accordingly, the contact forces do not change over time in static conditions, except for some small oscillations present in the system, for example, noise. Therefore, the time derivatives terms of the force can be set as zero: $F_{des} = \dot{F}_{des} = F_m = 0$. Hence rearranging Equation (15) for an open-loop system and including $F_{des}$ yields to

$$F = m k_{pf} k_{mf} \dot{e}_f + F_{des}. \hfill (17)$$

The AM control architecture is illustrated in the block diagram of Figure 12 and follows a decentralized approach (Jimenez-Cano et al., 2013; Ruggiero et al., 2018) to take advantage of the high performance embedded motor controller of the manipulator.

Starting from the left side, the desired force $F_{des}$ is subtracted to $F$, generating an error $e_f$ that is the input of the proportionnal control law seen in Equation (17). The force demand is then converted into a desired current value $c_{des}$ and inputted in the motor controller board Maxon EPOS2 24/3 that runs a PI controller. The motor board actuates the slider joint and moves the manipulator towards the target, that is the environment block. The position, velocity and current states at the end-effector are measured and sent to the forward kinematics block. The force exerted by the UAV pitching motion is estimated and corrected by adjusting the desired pitch angle $\theta_{des}$, the resulting angle is then converted to force using the mapping seen in the previous section.

The task manager and main force controller run on the on-board Raspberry Pi 3. The internal PI current control runs on the Maxon EPOS2 24/3 digital board operating at 10 kHz. The motor states $q, \dot{q}$ are measured by the digital encoder; the vehicle relative position is measured by the distance-sensor. Both sets of data are processed by the Raspberry Pi which computes the forward kinematics and the mapping between force and current, as discussed in Section 5.1.

6 | INDOOR EXPERIMENTS

This section presents the validation of the novel lightweight aerial manipulator’s design in an indoor setting. The proposed mechanical design, combined with dedicated sensing and the control laws previously discussed are tested with the goal to validate the proposed setup in real conditions. Ultimately, the proposed solution would be used to facilitate the placement and retrieval of smart sensors in hard-to-reach locations, without the use of additional supporting equipment, or scaffolding around the structure itself.

A total of 48 flight experiments are conducted to validate placement and retrieval operations indoors over a flat vertical surface. An interaction with a vertical surface already encompasses the vast majority of targeted environments where the aerial manipulator could be deployed, such as a bridge wall, a dam, a wind-turbine blade with low-curvature profile, the side of a building, and so on.

6.1 | Experiment outline

Each experiment is staged as follows: at first, the UAV approaches the target through a waypoint mission, flying in position mode. This represents the approach stage. The use of a VICON motion capture system is employed for the pose estimation of the UAV at all times. The UAV approaches the contact surface, that is a flat wooden panel, and once the vehicle is stably hovering in proximity of it, the
manipulation task is autonomously initiated. The autonomous behavior on the manipulator is dependent on three conditions: one is the range information by the on-board rangefinder, the second condition is given by reading the UAV’s angular states and establishing if they are within a certain threshold. The third condition is based on a visual check run by the pilot who supervises the operation. Once the pilot is satisfied with the stable hovering of the vehicle next to the target, a switch is released on the radio controller. By meeting these three conditions, the manipulator triggers autonomously and the interaction stage begins. Although the manipulator relies on the supervision of a pilot to start the operation, it was found that by having this additional condition the behavior experienced by the system was more robust and repeatable over time. Lastly, in the settling stage the manipulator has completed the placement/retrieval task, the rack retracts and the UAV is homed.

During the interaction, force measurements are collected by a 6-axis force/torque sensor (Robotiq FT 300) mounted on the target surface. The sensor sampling rate is 100 Hz and provides readings up to ±300 N on the force and ±30 Nm on the moment. It is important to highlight that the force information from the sensor is used as a ground-truth measurement during the indoors experiments, and not as a way to close the force control loop. Lastly, all force data presented in this section follow the convention seen in Figure 6, namely $F_z$ is the force normal to the wall and it is the one to be controlled.

6.2 | Sensor placement indoors

The objective of these experiments is to validate the bespoke manipulator design and control laws for placement tasks that require a considerable exchange of force with the environment. The challenge faced in these experiments is to seamlessly combine the force output of the manipulator and of the vehicle in a stable and safe way with a slow force build-up, and to be able to use this force to place a sensor securely onto a flat surface. The second challenge is to control the direction of the force to guarantee a correct placement; if the lateral component of the force is too high due to undesired yaw on the UAV, the end-effector may slip over the target inducing a sudden rotation in the system, leading to failure and potential damage to the UAV. This will be further discussed in the following section “Outdoor Experiments.”

A total of 33 experiments were performed to validate placement tasks indoors. In Figure 13 results of a single sample flight during a successful placement are illustrated, with a focus on the range information of the distance sensor, the force generated by the manipulator, the end-effector position, and the UAV angular states. Figure 14 displays the force measured by the force/torque sensor mounted at the target during the same experiment.

To begin with, the UAV approaches the target surface at a constant speed of 0.2 m/s. To place the sensor, a sinusoidal signal is used to slowly protrude the end-effector outwards. The low current that drives the end-effector outwards allows for a gentle, compliant touch with the surface and establishes a safe contact. The sensor case is provided with adhesive pads on the wall side to allow it to stick on the target surface. Once in contact, the force is progressively increased to ensure a sufficient adhesion of the pads and therefore secure the object in place. The manipulator’s force output reaches about 5 N during the placement, while the highest proportion of the force output is generated by the UAV itself progressively pitching against the surface. Before contact, a few oscillations in pitch occur due to the turbulence in the wall proximity. However, in the majority of the cases these disturbances did not affect the positive outcome of the placement and were overall below ±5°.

In this particular experiment, a maximum pitch angle of 16.2° is reached and a high compression force up to ~46 N is sensed at the target (see Figure 14). From the previous section, we recall that the force output is also dependant on the vehicle dynamic response when approaching the surface, that is speed of approach and momentum generated during the impact. These factors contribute towards higher forces resulting from each placement task. At $t \approx 9s$, the manipulator begins to retract and simultaneously the UAV’s pitch angle is decreased, moving the force output $F_z$ towards zero. At the beginning of the vehicle “settling stage,” a minor overshoot below the zero is sensed in pitch as the UAV enters the hover state following the detachment with the target surface.
The range measurements present no drastic change throughout the data set as the AM approaches, places the sensor, and homes back. This is mainly because the vehicle positioning is corrected by the flight controller in close-loop control with the motion tracking system, allowing it to adjust any sudden undesired movement due to, for example, an induced momentum. As the UAV hovers in proximity of the wall at the start of the operation, the distance from the target oscillates around 0.5 ± 0.05 m, while it starts to diverge more noticeably as the rod retracts, causing a rapid change in the distribution of masses on the vehicle. In Figure 15 a time-lapse sequence of a single successful placement indoors is displayed.

In Table 5 a summary of the statistical evaluation of the overall performance of the AM during placements indoors is illustrated,

along with the success rate over the 33 attempts. Overall, 28 out of 33 placements are successful, with a failure rate of about 15%. Failure was associated with the AM failing to secure the pad on the target surface and this was mostly due to a positioning error in yaw, which prevented the system from reaching the necessary pitch to guarantee enough adhesion of the sensor’s pads on the wall.

For each flight the mean value $\mu$ and standard deviation $\sigma$ for roll, pitch, yaw angles and the force output sensed at the wall are computed for both the contact and settling stages. Subsequently, the values of each variable are averaged over the total number of flights and presented in Table 5 as $\text{AVG } \mu$ and $\text{AVG } \sigma$ respectively. The table provides an idea of the overall trend of the vehicle stability and force output measured in the experiments. The average $\mu$ values are below $\pm 1^\circ$ along roll and yaw.
angles and likewise the respective standard deviation $\sigma$, meaning that the angular disturbances of the aircraft during interaction are quite low and that the vehicle is stable. The pitch angle presents a higher mean value and standard deviation as we would expect. The average force measured during indoor placement tasks is 27 N, while the maximum force reached in the experiments is $-47$ N. The standard deviation $\sigma_{\text{force}}$ shows that the difference in the force output is dependent on the dynamic response of the UAV during contact and the momentum gained before the impact.

6.3 | Sensor retrieval indoors

A total of 15 experiments was performed to validate indoor aerial retrieval. Within these experiments, the ability to engage with and detach an object placed on a vertical wall is validated. The challenge with retrievals is to guarantee a stable hover in close proximity to the wall, which allows the end-effector to hook the sensor in a robust way and therefore initialize the pulling motion to collect it.

To start with, the UAV flies close to the target surface, with the end-effector extended outwards. The sensor case is already placed on the flat panel by mean of adhesive pads. As the AM establishes contact with the surface, the manipulator is initially kept passive to ensure a compliant contact with the sensor case. As the end-tool engages with the sensor, the rack automatically retracts exerting a constant force in the opposite direction and pulling the sensor away from its environment. The manipulator autonomous behaviors is triggered when an error in position and force is sensed at the end-effector. Results of a single sample retrieval flight are illustrated in Figures 16 and 17.

It can be observed that between $5.2 < t < 7.5$ s the manipulator is overcoming the adherence force of the pads to retrieve the object causing an error in the force (red line). In response to this, the force controller increases the pull and successfully collects the object. The pulling motion is also visible in Figure 17 where a positive tension force is measured by the force/torque sensor of about 5 N on average.

During the "retrieve" stage the UAV also contributes towards the pulling force by pitching upwards, generating a nose-up pitching moment. Once the sensor is retrieved and the rack fully retracted, some oscillations generate in the vehicle in an attempt to regain the hover state. This is similar to what was seen in the previous section where perturbations in pitch are caused by the sudden detachment from the wall and rapid change in the inertia of the system. A time-lapse sequence of frames captured during a single retrieval task is displayed in Figure 18.

In Table 6 a summary of the statistical evaluation of the AM performance during retrievals indoors is illustrated. Overall, 15 out of 15 retrieval experiments were found to be successful. The values $\mu$ and $\sigma$ are the mean and standard deviation of the angular states and the force averaged over the total number of flights. The average pitch angle, namely $\mu_{\text{pitch}}$, measured during retrieval operations is below 10° and shows that a lower force is necessary to pull the sensor away from the surface. From the table we can derive that the angular disturbances in roll-pitch-yaw are generally lower than those found in the placement experiments. This is attributed to the nature of the operation itself which requires a less dynamic response and proves overall less challenging to handle from the UAV perspective. Likewise, the maximum force measured by the force/torque sensor is 9.23 N showing that the AM dynamics involved in these tasks are less demanding than those seen in the previous section.

| TABLE 5 | A summary of the statistics following indoors placement experiments and insights on the mean and standard deviation values of multiple variables averaged throughout the set of 33 experiments |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sensor placement indoors | Total experiments | 33 |
| Success rate | 84.8% |
| $\mu_{\text{roll}} \pm \sigma_{\text{roll}}$ (deg) | $0.90 \pm 0.45$ |
| $\mu_{\text{pitch}} \pm \sigma_{\text{pitch}}$ (deg) | $6.91 \pm 7.93$ |
| $\mu_{\text{yaw}} \pm \sigma_{\text{yaw}}$ (deg) | $0.44 \pm 0.62$ |
| $\mu_{\text{force}} \pm \sigma_{\text{force}}$ (N) | $-27.3 \pm 8.94$ |
| Max. force (N) | $-47.05$ |

FIGURE 15 | Time-lapse sequence of aerial sensor placement indoors [Color figure can be viewed at wileyonlinelibrary.com]
OUTDOOR EXPERIMENTS

A total of 41 outdoors experiments were performed outdoors to test the proposed AM in more complex conditions. Typically the majority of aerial applications for AMs includes the interaction with vertical or tilted surfaces of different materials, however the ability to perform placements on more challenging surfaces is tested to further validate the robustness of our approach. In particular, cylindrical irregular surfaces such as tree trunks are chosen for the following outdoors experiments, as they resemble one of the most challenging targets with whom AMs could operate due to their irregular shape and texture. Example applications for the proposed system could be the interaction with curved objects for inspection and maintenance, for example, dams, wind turbine blades, or the interaction with trees for the placement of humidity sensors in forests or other sensors for climate surveying in forestry environments. Other applications involving the presence of trees may include the placement of carbon dioxide detectors for monitoring and prevention of fires.

The experiments are performed on a range of several trees with the purpose to place and retrieve small sensors, such as humidity sensors or carbon dioxide detectors, to provide real-time monitoring and forest fires prevention. The condition in which the setup was tested outdoors was in warm dry weather with low speed breezes, if any. Typically, different weather conditions, for example, winds and
turbulence, can affect the well conduct of outdoors experiments in different ways. For the purpose of demonstrating the reliability of the systems outdoors in an unmonitored environment, the following results provide a solid validation. However, these results cannot be generalize for different weather conditions.

Flying outside brings additional challenges such as accurate position sensing and the presence of unknown obstacles that can generate turbulence over the vehicle. The purpose of these tests was therefore to demonstrate if placement and retrieval is in essence feasible and to identify the best approach to take to improve reliability.

### 7.1 | Experiment outline

The experimental setup used for outdoors experiments is similar to the one seen previously, except for the lack of motion capture system reading the UAV states, and the force/torque sensor measuring the contact force on the tree trunks. The lack of the VICON tracker reduces the accuracy in the vehicle's pose estimation, which only relies on the use of an on-board GPS. Due to the partial occlusion of the GPS signal in the proximity of tree branches and other obstacles, the flight controller pose estimator experiences a higher level of noise as opposed to open-field flying. An additional precaution taken in this respect was to lower the flight controller gains to have less aggressive flight maneuvers. To approach the target surface in an accurate way, the vehicle was flown manually by the pilot. In future work, visual sensing could be added in the system as part of the manipulator to aid the pose estimation of the vehicle in the proximity of the target.

### 7.2 | Sensor placement outdoors

In Figure 19 results of a single sample flight during a successful placement are illustrated. For outdoors experiments, the current input used to extend and retract the end-effector was generally lower when compared to the indoors flights. This was chosen so as to increase the compliance of the end-effector when in contact with the tree and to have a less aggressive behavior. Moreover, the sinusoidal signal in force has a shorter period compared to the previous section. This is because the duration of the contact is reduced and the force output is tailored for outdoors experiments to perform a safer interaction and account for sudden disturbances in the position estimator. Once contact is established, the UAV progressively increases its pitch to generate a good adhesion on the object, then flies backwards after a successful placement.

Results are illustrated in Figure 19. The second figure from the top shows the manipulator’s force during the task: contact with the tree occurs at $t = 7$ s, where the impact of the object on the target surface generates a force error in the controller. During this time, the manipulator is still extending (see third figure). As the object is placed and the UAV retrieves the loiter state, disturbances in pitch and yaw generate, as seen in the bottom figure (settling area).

A general trend experienced in outdoors experiments is the longer settling time needed by the UAV to retrieve the hover state and higher disturbances sensed in pitch and yaw. As previously discussed, one of the major factors that plays a role in pose estimation is the use of GPS over the VICON motion tracker, which affects the positioning accuracy. Another potential source for a longer settling time and higher angular disturbances is the presence of gusts and
other obstacles that induce turbulence, for example, surrounding trees, branches. Despite these factors, the "settling stage" had minimal effect on the overall success rate of the outdoors trials, with the main cause for failure assigned to an undesired yaw during contact that induced slippage at the end-effector. The undesired yaw generated a lateral force at the end-effector causing it to move out of the interaction plane $xy$, slipping over the trunk and therefore not generating enough adhesion on the sensor adhesive pads.

In Table 7 a summary of the statistical evaluation of the overall performance of the AM during placements outdoors is illustrated, along with successful rate throughout the 23 attempts. Overall, 18 out of 23 placements were successful, with a failure rate of about 21%. As experienced in the indoor setting, failure was attributed to an undesired yaw which caused slippage of the end-effector on the target surface, even more so as the target is a cylindrical surface. The table here presented follows the same notation as the ones seen above, where $\text{AVG } \mu$ and $\text{AVG } \sigma$ show the averaged mean and standard deviation values for multiple variables and give an idea of the overall trend of the vehicle stability measured in the experiments, validating the repeatability and robustness of our approach.

It can be seen that the larger variations in yaw experienced during outdoors experiments are recorded within the mean $\mu_{\text{yaw}}$ and standard deviation $\sigma_{\text{yaw}}$, as these values appear to be larger than in previous cases. The pitch angles reached during placement are lower than those seen in the indoor setting, and this reflects in lower mean and standard deviation values. This is because, as previously discussed, the time of contact with the tree was reduced with respect to indoor trials, hence the pitch "build-up" is also lower. Overall, the pitch angle reached during outdoors placements ranges between $[5^\circ, 12^\circ]$. A time-lapse sequence of frames captured during a single placement task outdoors is displayed in Figure 20.

### 7.3 Sensor retrieval outdoors

Outdoor retrieval experiments were carried in the same way as indoors. Results are shown in Figure 21. In general, the same

| Sensor placement outdoors |
|---------------------------|
| Total experiments         | 23            |
| Success rate              | 78.2%         |
| $\mu_{\text{roll}} \pm \sigma_{\text{roll}}$ (deg) | $1.07 \pm 1.27$ |
| $\mu_{\text{pitch}} \pm \sigma_{\text{pitch}}$ (deg) | $3.57 \pm 5.02$ |
| $\mu_{\text{yaw}} \pm \sigma_{\text{yaw}}$ (deg) | $4.60 \pm 2.90$ |
| Estimated avg. force (N)  | $-22$         |
challenges as the indoor setting were present, however the GPS-based flight made long-term stable hovering in the proximity of the sensor more challenging outdoors as opposed to indoors. Also, the UAV settling time was also found to be longer, as with outdoor placements. Often, the pitch angle oscillates between $[-10^\circ, 10^\circ]$ after retrieving the object from the wall, with oscillations also present in yaw. As seen before for the indoor retrieval, the angular disturbances generate from the detachment with the tree as well as the end-effector retracting motion, causing a sudden change in the momentum of the vehicle. Despite these oscillations, the overall success rate in outdoors retrievals is 100% over 18 experiments performed, demonstrating a higher repeatability than outdoors placements. This is a result that was also found in the indoor setting: the nature of the retrieval task itself leads to a higher robustness during interaction, as it requires a less aggressive and less dynamic behavior on the flight controller to complete the task. A time-lapse sequence of frames captured during a single placement task outdoors is displayed in Figure 22.

In Table 8 a summary of the statistical evaluation of the overall performance of the AM during retrieval tasks outdoors is illustrated, along with successful rate throughout the 18 attempts. Overall, the angular disturbances were significantly less than those in placements outdoors. Disturbances in the pitch and yaw are still present, due to

![Figure 20](https://wileyonlinelibrary.com) Time-lapse sequence of aerial sensor placement outdoors [Color figure can be viewed at wileyonlinelibrary.com]

![Figure 21](https://wileyonlinelibrary.com) Sensor retrieval outdoors—data collected by the on-board Raspberry Pi 3. From top to bottom: range information by the distance sensor mounted at the front of the UAV; pulling force exerted by the manipulator, rack displacement and UAV angular states. UAV, unmanned aerial vehicle [Color figure can be viewed at wileyonlinelibrary.com]
the turbulence caused by the propellers moving close to branches and the trunk. However, such disturbances did not affect the positive outcome of the retrieval operations, and all attempts were successful.

To conclude, outdoors experiments demonstrated the feasibility and robustness of the proposed approach for both placement and retrieval tasks. The conclusions drawn from these experiments showed that a stable hover and a more compliant behavior were key elements to succeed in the outdoor setting. In particular, the demanded force output of the aerial system was lowered, as it was the one of the manipulator. The flight controller gains were also lowered to decrease the likelihood of any aggressive behavior of the vehicle in the proximity of obstacles. Lower pitch angles were reached to compensate for the less accurate GPS-based pose estimation, generating a lower force output and lower pitch build-up. The combination of all these factors proved that outdoor operations were possible and repeatable, where a total of 41 data-sets were produced.

8 | CONCLUSIONS

Safety is of paramount importance when it comes to the inspection of bridges, dams, chimneys, wind turbines, and other large-scale infrastructure. Where human operators are involved, additional safety measures are endorsed to allow easy access to remote sites, for example, supporting structures, on-site scaffolding, the use of special equipment. Such necessary measures often incur in extra time and costs associated to maintenance and inspection operations. Unmanned aerial manipulators capable of placing and retrieving smart sensors in hard-to-reach locations or wide-spread areas could significantly reduce risks, time and costs involved in these operations.

To address placement and recovery tasks, this study proposes a small-sized UAV equipped with a lightweight active manipulator capable of exerting a force on the side of the aircraft. The aerial system as a whole is tailored for contact-based tasks, where the delivery of force at the end-effector is the result of the combined action from the active manipulator and the aircraft pitch motion. The novel design and control approach to aerial force-based interaction is evaluated both indoors and outdoors, and with different target surfaces (vertical and cylindrical), showing robust and repeatable outcome even in challenging conditions, that is interaction with tree trunks. From this study, the following lessons have been learned:

- devising a manipulator that is tailored for the task is a key part of the design process and cannot be overlooked. The manipulator’s design has considerable impact over the aircraft’s dynamics and it affects control-related decisions. The design requirements of a manipulation system intended for aerial applications unfold in several subrequirements, including minimizing the payload, distributing the masses, optimizing the configuration/integration on the aerial vehicle, selecting adequate electronics. These are all essential elements that improve the dynamic response of the flying robot at a mechanical level and contribute towards robustness and performance during aerial interaction;
- distance sensing on the AM is beneficial and it can be used to automate the operation to some extent, however it is of limited use during the interaction and the settling stages. Other forms of visual sensing, for example, event-based cameras, could be incorporated to further improve sensory feedback on-board and refine the autonomous behavior;
- real-time control on the manipulator is an essential property for any aerial manipulator dynamically interacting with the environment. Dynamic interaction involves fast-changing conditions and it is best tackled by high-performing actuators. Based on previous work in the field and on the experiments presented in this journal, we experienced that real-time control on the manipulator is an essential element to tackle forceful interactions in-flight, and one

| Sensor retrieval outdoors                                      |
|---------------------------------------------------------------|
| Total experiments                                            | 18 |
| Success rate                                                 | 100% |
| $\mu_{roll} \pm \sigma_{roll}$ (deg)                        | 0.32 $\pm$ 0.27 |
| $\mu_{pitch} \pm \sigma_{pitch}$ (deg)                      | 1.37 $\pm$ 4.42 |
| $\mu_{yaw} \pm \sigma_{yaw}$ (deg)                          | 0.45 $\pm$ 3.95 |
| Estimated avg. force (N)                                     | 6.4 |

FIGURE 22  Time-lapse sequence of aerial sensor placement outdoors [Color figure can be viewed at wileyonlinelibrary.com]
that is best suited in the context of aerial sensor placement and retrieval tasks;

- force sensing is essential to measure the effects of the interaction over the system’s variables (UAV and manipulator states), closing the loop in the control laws;

- the integration of the vehicle states within the manipulator’s controller aids the interaction and offers ways to automate the task. Closed-loop control on the manipulator itself is certainly beneficial to the performance of the aerial manipulator as a whole, however further improvements can be brought when considering the aerial vehicle and the manipulator as a single multivariable system, that can compensate for each subsystem’s limitations;

- indoor experiments demonstrated the effectiveness of the approach in a monitored environment, that is with accurate pose estimation over the vehicle. Results showed that the aerial system can make adjustments to the angular states while in contact with the surface, allowing for smooth and compliant interaction. It is also demonstrated for the first time how the combination of the aerial system and the manipulator generate a slow force build-up at the end-effector, with unprecedented peaks delivered by a small-sized aerial platform. It is demonstrated that the AM generates a force-to-weight ratio of 130% on average during placements, with a maximum force of 230% its weight;

- outdoor experiments demonstrated good reliability of the proposed AM deployed in more challenging conditions and with less accurate pose estimation of the vehicle. Lower gains on the flight controller ensured a more gentle and compliant approach and helped handling the uncertainty of the outdoor setting, for example, unreliable GPS signal. Lower force outputs were demanded in the outdoor scenario, resulting in a less aggressive dynamic response and a safer interaction with the tree;

- the proposed AM is able to interact with different targeted environments, such as flat vertical surfaces and irregular cylindrical surfaces, demonstrating repeatable outcomes and robustness against different textures and shapes. This infers that the proposed approach is versatile in the range of different force-based tasks;

To conclude, the work presented in this paper demonstrates the capabilities of the proposed lightweight compliant manipulator for force-driven aerial tasks such as the placement and retrieval of smart sensors in the environment, and it lays the foundations towards more dexterous aerial manipulation tasks. Further work will address the refinement of the flight controller with the use of Model Predictive Control methods to minimize the angular disturbances of the vehicle during interaction, and achieve a successful rate during placement greater than 90%. Also, the design of new end-effectors will be evaluated to stretch the number of applications that can be achieved with the proposed manipulator, together with additional sensory feedback solutions.

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ORCID
Salua Hamaza  http://orcid.org/0000-0001-5261-2680

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