LICAS A1 – LIGHTWEIGHT AND COMPLIANT ANTHROPOMORPHIC DUAL ARM SYSTEM: APPLICATIONS IN AERIAL MANIPULATION

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Dual arm aerial manipulation robots have been a topic of research for ten years, from the mechatronics, control, and application point of view, motivated by the convenience of replicating the skills of human operators to perform in high altitude workspaces certain operations that cannot be conducted by other means. This paper presents the LiCAS A1, the Lightweight and Compliant Anthropomorphic Dual Arm System Model 1, a platform designed at the University of Seville derived from the research work developed in the context of previous European projects in aerial manipulation. The refinement and improvement in the manufacturing procedure of the LiCAS arms, along with the extensive experimental evaluation with previous prototypes, has allowed us to obtain a customizable dexterous manipulator that has served as research platform for several projects, demonstrating its use for the installation of bird flight diverters on power lines as part of the AERIAL-CORE project, or in aerial parcel delivery in the context of the euROBIN project. The paper presents the main features of these arms, and describes several practical aspects in the mentioned applications.

1. INTRODUCTION

Aerial robotic manipulation [1], that is, the combination of flying platforms with some kind of mechanism that allows to perform physical interactions with the environment, has consolidated during the past decade as a solid research topic that, nowadays, is reaching relevant application domains, like the inspection and maintenance of infrastructures such as power lines, pipelines, viaducts, bridges or tunnels, among many others. Although the first papers presenting this concept in the form of quadcopter or unmanned helicopter equipped with grippers are from early 2010, the idea of using flying robots to perform the grasping and transportation of objects was demonstrated back in the 90's with the International Aerial Robotics Competition [2]. The concept of an aerial manipulator as an aerial platform equipped with a robotic arm providing a higher level of dexterity than a simple gripper was introduced in 2011 with the ARCAS (Aerial Robotics Cooperative Assembly System) European project, which merged the field of UAVs (Unmanned Aerial Vehicles) with the space robotic manipulation field, popular in the past. Diverse designs and prototypes have been proposed since then, as collected in [1], comprising diverse configurations for the aerial platform (multi-rotors in most cases [3]), and for the manipulator [1], which may be a gripper, a simple link, linear actuators or delta manipulators, multi-joint robotic arms, multi-arm systems, long-reach or cable suspended manipulators, or even the body of the aerial platform may become the manipulator itself [4]. Besides the design and mechatronic aspects, significant effort has been devoted to the modelling and control, perception, planning, and teleoperation of the aerial manipulation robots [1], non-trivial problems due to the dynamic coupling between the aerial platform and the manipulator, along with the important payload constraints that result in significant technological challenges.

The development of this research field in Europe has been mainly possible through funding from the European Commission for research and innovation projects from the FP7 and H2020 frameworks, starting in 2011 with ARCAS (6 M€), followed by AEROARMS in 2014 (4.7 M€), HYFLIERS in 2017 (3.9 M€), and more recently PILOTING (8.2 M€) and the very successful AERIAL-CORE (8.6 M€) project, both starting in 2019. More generally, the interest and impact of the aerial manipulation field in the scientific community can be evidenced for example from the statistics provided by SCOPUS.

Within the wide variety of manipulators that have been proposed for their integration in multi-rotors, dual arm manipulators [5][6][7] represented a significant advance in terms of dexterity and capabilities with respect to a single robotic arm or other simpler mechanisms like grippers. A dual arm system allows for replicating the dexterous manipulation skills of humans when the aerial robot is intended to perform maintenance tasks in high altitude workspaces, removing the risk for the human workers. Roughly speaking, an aerial manipulator may perform two types of operations: those involving positioning the end effector at a desired point, for example for object grasping, and those for exerting forces/moments at a certain point. Although a simple gripper or a simple rigid bar attached to the multi-rotor frame may accomplish this goal by relying on the appropriate position [8] or wrench [9] control of the aerial platform, without increasing the complexity or weight of the system, the purpose of the arms is to increase the dexterity in the realization of the manipulation task in several senses: by compensating position deviations of the aerial platform, by accessing the point of interest with certain poses, allowing the rotation of the object once grasped, using one arm for grabbing and stabilizing the platform while the other conducts the task.

In a similar way to what occurred with multi-rotors and UAVs (Unmanned Aerial Vehicles) during last years, it is expected that dexterous aerial manipulators evolve from research prototypes to become a consolidated technology with higher technology readiness level (TRL), supporting new research and application domains. This motivated the LiCAS Robotic Arms initiative started in 2020 with the aim of manufacturing a reliable and cost effective dual arm manipulator that exploits the benefits of the lightweight and compliant robots.

2. MECHATRONIC DESIGN

The Lightweight and Compliant Anthropomorphic Dual Arm System Model 1 (LiCAS A1), shown in Figure 1, is an evolution of the dual arm prototypes developed in our previous works [5][7] for aerial robotic manipulation in the context of the AEROARMS project, motivated by the necessity to provide dexterous manipulation capabilities to multi-rotors with limited payload capacity. Note that the integration of "lightweight" industrial manipulators like the KUKA LBR iiwa (24 kg weight) required an unmanned helicopter for its operation on flight [10], with the associated complexity and risk of operation due to the size and weight of the vehicle.

The LiCAS A1, derived from the LiCAS Robotic Arms initiative [11] funded by the regional government of the Junta Andalucía in Spain, follows the design principles stablished in [5][7]:

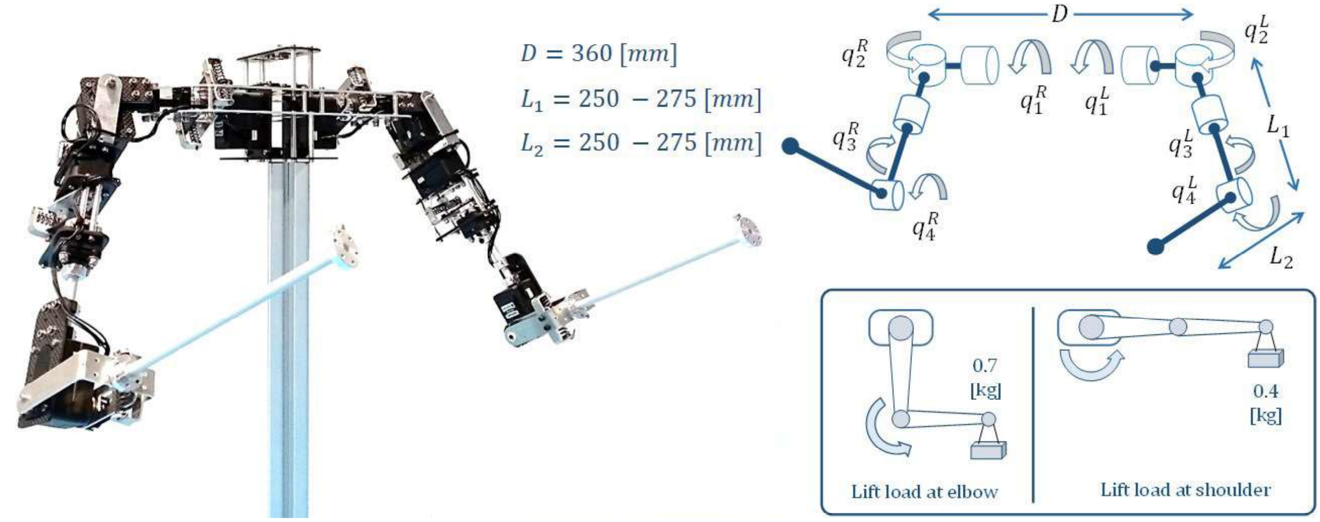

Figure1
LiCAS A1 (left), kinematic configuration with 4-DOFs for end effector positioning (right-up) and maximum payload capacity at elbow and shoulder joints (right-down).

VERY LOW WEIGHT (2.5 KG)

The main design requirement for the arms is to reduce by one order of magnitude their weight compared to conventional commercial manipulators so they can be integrated into medium scale multi-rotor platforms like the DJI Matrice 600 [6], relying on a carefully designed aluminium and carbon fibre frame structure that supports the Herkulex smart servo actuators (DRS-0402 and DRS-0602) of the joints, while providing high rigidity and low aerodynamic profile, convenient for the long reach [12] or cable suspended [13] configurations in order to avoid perturbations caused by wind. It is not only the weight of the manipulator itself, but conventional industrial robotic arms also require relatively heavy and voluminous controllers and power supplies that are not suitable for aerial platforms. Related to its weight, the payload capacity of the LiCAS A1 is defined as the lift load benchmark represented in Figure 1, considering the maximum load at the elbow (0.7 kg) and shoulder (0.4 kg) that may be lifted and hold for at least 10 seconds.

MECHANICAL JOINT COMPLIANCE (5 - 20 NM/RAD)

The incorporation in all the joints of the arms of a spring-lever mechanism that transmits the torque of the servo actuators to the output links has been proven to be an effective feature in extending the robustness, sensing capacity, and ability of accommodation of the arms when these are exposed to uncertain physical interactions with the environment, even more, when the arms are operating on flight [5][12][14]. The natural damping and elasticity of the compression springs is exploited for filtering mechanically force peaks and accommodating passively the arms to overloads that, if rigidly transmitted to the actuators, might damage the gearbox. This passive compliance becomes particularly useful in bimanual manipulation tasks or in grabbing situations in which the stability and integrity of the aerial platform, the environment, or the manipulator itself may be severely affected if there is no accommodation to the generated wrenches. Table I collects the main specifications of the four joints of the arms, including the stiffness.

Table 1
Mechanical specifications of the shoulder and elbow joint of the LiCAS A1.

Joint	1	2	3	4
Designation	Shoulder pitch	Shoulder roll	Shoulder yaw	Elbow pitch
Motion	Flexion / Extension	Abduction / Adduction	Medial / Lateral Rot.	Flexion / Extension
Rotation range [°]	±90	[-15, 90]	±90	±150
Max. speed [°/s]	250	250	250	250
Max. deflection [°]	10	15	15	15
Stiffness [Nm/rad]	15	10	5	10

HUMAN-LIKE AND HUMAN-SIZE (500 MM REACH)

The anthropomorphic kinematics of the LiCAS A1, with three joints at the shoulder and one at the elbow, along with its dimensions (250 mm forearm and upper arm, 360 mm between left and right arms), makes it easy and intuitive to replicate the motion of human operators in the realization of tasks requiring a certain level of dexterity, like the installation of bird flight diverters on power lines as considered in the AERIAL-CORE project [12][13]. Figure 2 shows the frame structure of the arms, with the shoulder structure that integrates the actuators for the flexion/extension motion, the upper arm structure supported by the actuators that perform the adduction/abduction rotation, followed by the medial/lateral rotation servo, and the elbow joint actuator. The forearm is a simple aluminium link with a Pololu universal mounting hub (8 mm diameter, M3 screws) at the tip, used as flange for the end effector. Minimizing the weigh at the forearm and at the end effector is highly desirable to avoid reducing the effective payload of the arms and increase the inertia, taking into account that the deflection of the joints due to the gravity effect affects the positioning accuracy of the end effector.

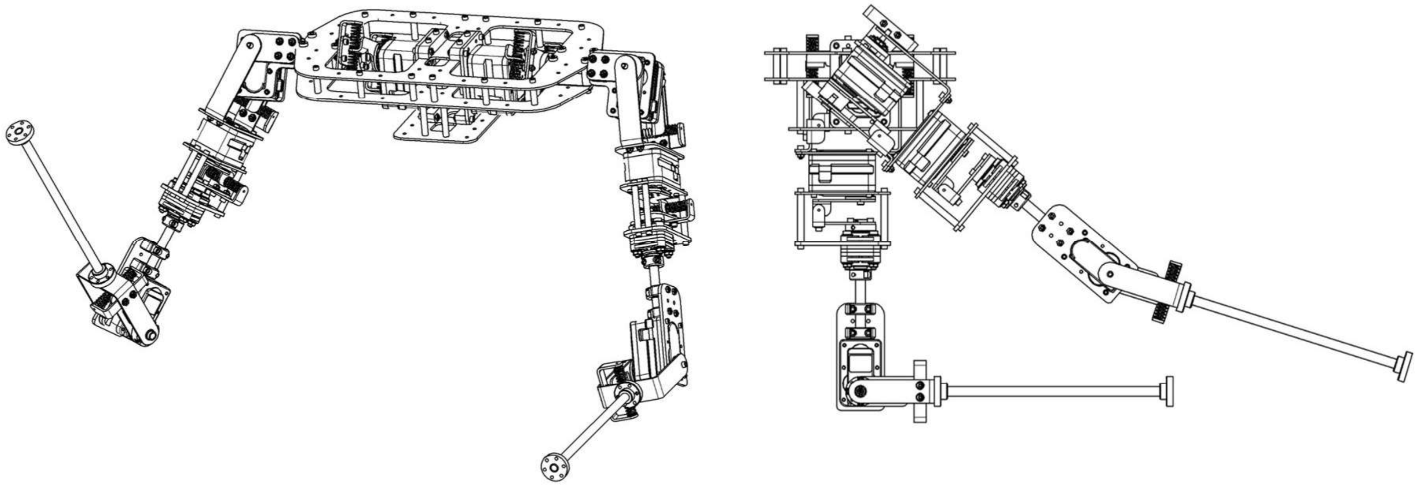

Figure 2
Two views of the LiCAS A1 design, showing the shoulder structure and the left and right arms, with a flange at the wrist point for integrating the end effector. The LiCAS A1 is a registered Community design (RCD).

Unlike the prototypes in [5][6], the A1 model increases the Technology Readiness Level (TLR) in several ways. On the one hand, this model is intended to be a product rather than a prototype, in the sense that the design and manufacturing procedure is refined to reduce the assembly time, and increase the torque capacity and positioning accuracy by reducing the misalignments and clearance in the coupling between the shaft of the servo actuators and the output links through the spring-lever transmission. The structure of the arms is designed to provide a certain level of customization and facilitate its transportation, deployment and integration in aerial or ground platforms. On the other hand, the LiCAS A1 aims to serve as a multi-purpose manipulator for different tasks and applications by exploiting its features, as indicated before. An extensively tested software architecture in C/C++ makes it fast and easy its integration into any computer board since it relies only on standard libraries, implementing the low level communications with the servo actuators, following an object-oriented approach for organizing the source code.

3. APPLICATIONS

This section presents the application of the LiCAS A1 dual arm in four experiments developed in the context of the AERIAL-CORE and euROBIN projects.

3.1. INSTALLATION OF BIRD DIVERTERS ON POWER LINES

A customized version of the LiCAS A1 was developed for the AERIAL-CORE project to perform the installation of bird flight diverters on power lines, using a multi-rotor for its transportation, deployment and retrieval as demonstrated in the video [17]. Bird diverters are visual markers installed on power lines (imposed by regulations in many countries to protect avian species) to prevent the collision or electrocution of birds. The installation of this kind of devices involves significant costs for the companies due to the huge extension of the power grid and considerable risk for human workers due to the high altitude and high voltage of the power lines.

In order to overcome the limited flight time and low positioning accuracy of aerial manipulators flying outdoors, the proposed concept consists in deploying the robot on the power line using the multi-rotor, detaching the arms from the aerial platform when the base of the manipulator rests on the line. To implement this, the robot, depicted in Figure 3, incorporates three main modifications with respect to the standard design of the LiCAS A1: a rolling base driven by a servo actuator that allows the arms to perch and move along the cable with high energy efficiency, a magnetic gripper used to grasp and install the bird diverters stored in a linear array under the shoulder structure of the arms, and a hook-handle mechanism used to detach and retrieve the arms from the aerial platform.

Several successful demonstrations were carried out in a section of power line close to the ATLAS Flight Center in Villacarrillo (Jaen, Spain), remarking the fast deployment time from the take-off area (less than two minutes), fast installation of the devices (around 20 seconds per device, with 5 meters separation), and the low impact on the power line, since the very low weight of the arms does not cause significant deflection of the cable. The video of the first demonstration on May 2023 can be seen in [17].

Figure 3
LiCAS dual arm rolling robot developed for the AERIAL-CORE project to perform the installation of bird flight diverters on power lines. The aerial transportation and retrieval of the arms is done using a multi-rotor through a hook-handle mechanism.

3.2. CABLE SUSPENDED DUAL ARM AERIAL MANIPULATION

As part of the AERIAL-CORE project, it was also explored the use of aerial manipulators in cable suspended configuration motivated by the convenience of insulating electrically the multi-rotor from the arms to prevent the electrostatic discharge raised when interacting with high voltage power lines, which could cause a platform fault and crash, as identified experimentally in [18]. Not only that, but long reach [12] and cable suspended aerial manipulators [13][19] also increase safety and reduce the risk of collisions by increasing the separation distance between the multi-rotor propellers and the environmental obstacles, the power lines in this case.

Some devices like the helical bird flight diverters extensively employed on the Spanish power grid and in other countries [15] require dexterous manipulation capabilities for their installation. Note that the realization of maintenance operations like this has been traditionally carried out by human workers, either climbing the power line, from elevated working platforms, or using manned helicopters to reach the workspace. Therefore, taking benefit of the human-like and human-size features of the LiCAS A1, the arms have been integrated into a multi-rotor to perform preliminary tests and evaluate the feasibility of conducting manipulation tasks on flight using this cable suspended configuration. Figure 4 shows the take-off manoeuvre carried out by a human pilot while the arms grab a helical bird diverter. Several practical aspects were derived from these tests. First, it is convenient that the length of the cables (employing harnesses rope for this purpose) is around one meter since too short cables tend to induce undesired oscillations that are more difficult to damp, whereas too long cables tend to reduce the positioning accuracy in the coordinated control of both aerial platform and multi-rotor. The length of the cable should also be enough to facilitate the multi-rotor take-off and landing taking into account the height of the landing gear. Second, before the take-off, the arms should be separated from the aerial platform so the cables are slightly stretched to prevent them from tangling. The torque control of the dual arm joints should be disabled so the pose of the arms is passively accommodated to the floor as the arms are lifted. Third, unlike previous works, a 4-Cable Suspended configuration is adopted to prevent the shoulder structure is tilted when the arms rotate forwards. If the center of mass of the arms is within the area defined by the four anchor points of the cables, then the reaction wrenches will not induce rotations in roll or pitch. Finally, experiments reveal that the aerial platform tends to damp oscillations relatively fast (in less than 4 seconds) thanks to the action of the cascade position controller and the aerodynamic damping that dissipates the kinetic energy of the suspended manipulator.

The modelling and control of dual-arm cable suspended aerial manipulators is still an open topic of interest for the robotics research community. Recently, a method for modelling, identification and simulation of this kind of platform was reported in [20], presenting experimental results with the LiCAS A1 along with the CRANEbot system at CERN.

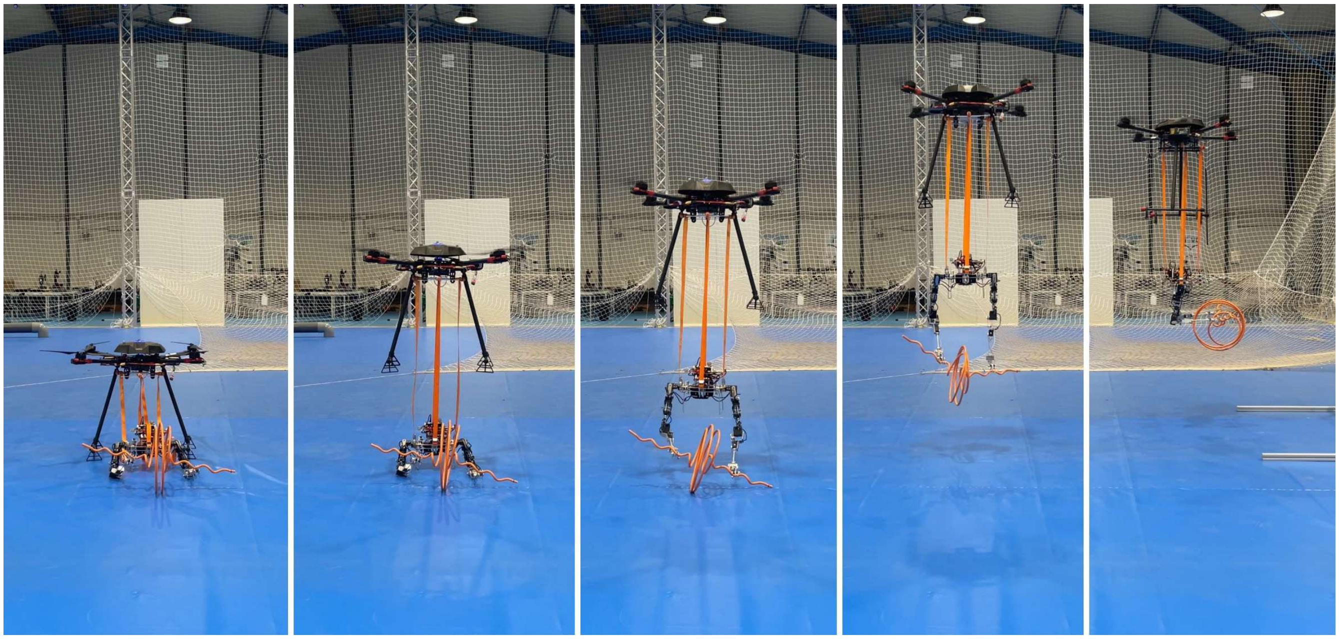

Figure 4
Sequence of images showing the take-off phase of the LiCAS A1 integrated in the multi-rotor in the 4-Cable Suspended configuration while grasping a helical bird flight diverter.

3.3. AERIAL PARCEL GRASPING AND DROP

One of the application domains of the European Robotics and AI Network (euROBIN project) is the use of outdoor robots for sustainable communities, considering the delivery of parcels as a representative use case, involving aerial, legged, and wheeled-legged robots to explore different approaches according to the locomotion capabilities of each kind of platform.

During the celebration of the euROBIN Seville Event on 15-19 May 2023, the robotics hackathon that took place at the GRVC Aerial Robotics indoor testbed brought together eight robots from several European research centers [21]. The video of the final demonstration of the event can be seen in [22]. In this case, the LiCAS A1 was used to conduct on flight the grasping of a standard parcel (DHL express, size 4) provided by the Centauro robot [23], dropping then the parcel on a box carried by the Swiss-Mile wheeled-legged robot [24]. Since these two operations required significant positioning accuracy, the arms were integrated at the base of the multi-rotor instead of considering the cable suspended configuration, retracting the landing gear to prevent the collision with the robots during the handover. For this experiment, the arms were tele-operated using a pair of LiCAS robots in leader-follower configuration as described in [25]. As it can be seen on Figure 5, the arms are installed around 15 cm backwards with respect to the center of mass of the multi-rotor to compensate the mass unbalance caused when the parcel (weighting 0.5 kg) is grasped. The mechanical joint compliance of the LiCAS A1 is particularly useful here to accommodate passively the pose of the arms during the physical interactions raised during the aerial handover and the parcel drop, reducing in this way the perturbations exerted on the multi-rotor while flying. The human-size and anthropomorphic kinematics of the arms also contributes to make the operation easy and intuitive for the human operator.

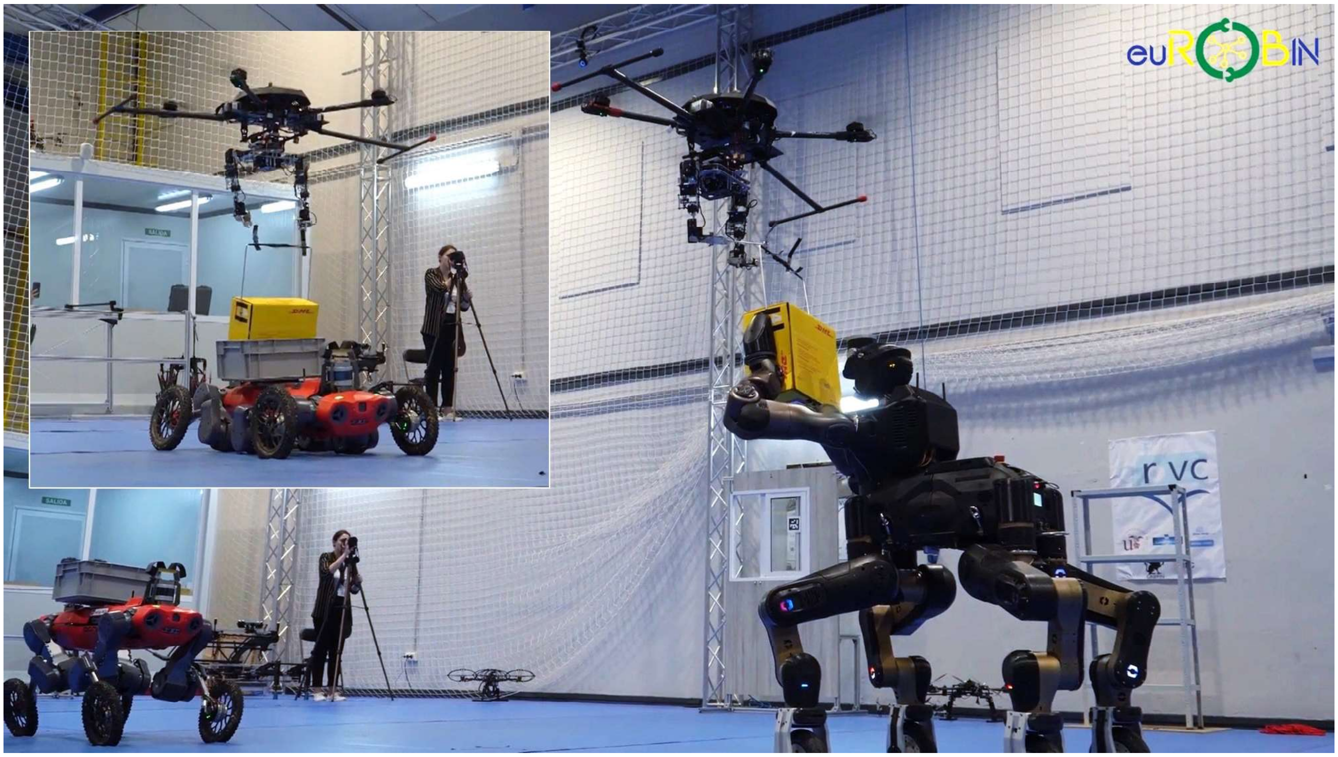

Figure 5
LiCAS A1 integrated on a multi-rotor platform conducting the aerial handover with the Centauro robot from the Istituto Italiano di Tecnologia (IIT) and the parcel drop on the Swiss-Mile wheeled-legged quadruped.

3.4.IN-FLIGHT PARCEL LOAD FOR DELIVERY WITH DRONES

Although the term “aerial manipulation” usually refers to the realization of manipulation tasks on flight from an aerial platform, with the arms integrated in the multi-rotor, a different concept was explored also in the context of the euROBIN project, inspired on the parcel delivery problem represented in Figure 6. Here the LiCAS A1 is supported by a fixed-base structure and used to load a small parcel in the front basket of a delivery drone. The mechanical features of the arms, along with their low cost compared to industrial manipulators, result particularly suitable for logistics tasks involving the manipulation of light loads. In this experiment, the flexibility of the arms facilitates the passive accommodation of the multi-rotor during the parcel drop, so the LiCAS “helps” the attitude controller to adapt to the exerted payload mass.

Figure 6
LiCAS A1 holding a multi-rotor while dropping a parcel in the front basket carried by the aerial platform.

CONCLUSION

The Lightweight and Compliant Anthropomorphic Dual Arm System Model 1 (LiCAS A1) is the result of five years of research in dexterous aerial manipulation carried out at the University of Seville, leading to the development of a reliable robotic platform that has been and it is currently being used in several research projects (European, national, and with companies). Its very low weight (2.5 kg), human-size and human-like features, and the mechanical joint compliance that enhances safety, makes these robotic arms suitable for fast integration and deployment in aerial robotics applications, being a cost effective solution compared to industrial manipulators. The paper presented some applications of this dual arm system, including practical aspects and research topics to be explored.

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