Chapter 8

Application of Intelligent Aerial Robots to the Inspection and Maintenance of Electrical Power Lines

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This Chapter deals with applying several technologies developed in the H2020 project AERIAL-CORE (AERIAL COgnitive integrated multi-task Robotic system with Extended operation range and safety) to inspect and maintain electrical power lines. The Chapter includes the following methods and technologies developed in AERIAL-CORE: application of perception-aware model predictive control for the aerial tracking of electrical power lines without prior information about the power line infrastructure; long-range powerline and vegetation mapping by using a 3D solid state LiDAR and a RGB camera for user visualization; aerial manipulators for the installation of bird-diverters and a recharging station, by including a high payload light arm, a linear actuator platform, a dual arm platform, a large general-purpose 45 kg take-off weigh manipulation platform and magnetic gripper to battery charging from the power line; human-machine interfaces; and a formation of aerial co-workers to monitor the safety of a human worker performing maintenance activities on the powerline. Experiments with real electrical power lines are included in the paper.

8.1 Introduction

It is well known that Unmanned Aerial Systems and Aerial Robotics have the potential to bring a revolutionary transformation in the industrial inspection market [1] by increasing productivity, reducing inspection time, improving data quality, and eliminating the risks for human operators. They can be used to regularly inspect the power line infrastructure to prevent power outages and natural disasters [2].

Aerial Robotics emerged in the nineties of the last century, fueled by the development of Unmanned Aerial Vehicles (UAVs), either fixed-wing or rotary-wing platforms, providing basic onboard autonomous functionalities. In the last decade, aerial robotics has experienced a very important growth with significant perception, reactivity and planning capabilities. Autonomous detection, tracking, simultaneous localization and mapping and other functionalities have been developed.

Aerial robotic manipulation also emerged by the beginning of the second decade of the last century. The FP7 ARCAS (Aerial Robotics Cooperative Assembly System) project (2011–2016) played an important role in developing general control, perception and planning functionalities. Later, the H2020 AEROARMS (AErial RObotic system integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance) project (2015–2019) further developed aerial robotic manipulation and applied it to inspection and maintenance. Surveys in Aerial Robotic Manipulation can be found in [3, 4].

However, by 2019, inspection and maintenance based on aerial robotics, and particularly aerial robotic manipulation, was mainly constrained to local interventions. Also, aerial manipulation was limited to contact inspection without the applications of the forces required to perform many maintenance activities. Moreover, the safety of aerial robots in inspection and maintenance activities and the collaboration with human workers were not considered.

Furthermore, at that time learning and other Artificial Intelligence techniques offered many new possibilities for detection, tracking, recognition and real-time decision and control.

The main objective of AERIAL-CORE is the development of innovative aerial robotics technologies resulting from the application of Artificial Intelligence. Notably, we are looking to extend the operational range of aerial robots, improve the performance of aerial manipulators, and increase safety in the interaction with people for applications such as the inspection and maintenance of large infrastructures. Thus, AERIAL-CORE targets the Research and Innovation in the following topics:

(1) Long-range, accurate inspection of the infrastructure.
(2) Maintenance activities based on aerial manipulation.
(3) Aerial co-working helping human workers in inspection and maintenance tasks.

AERIAL-CORE includes the application of the above methods and technologies to the inspection and maintenance of Electrical Power Lines, which is very challenging application with a strong impact.

In this Chapter, we present several AERIAL-CORE results in the above topics. Thus, the following section describes intelligent systems for long-range inspection. The third section deals with aerial robotic manipulation for maintenance and includes installing battery recharging stations on the line. The fourth section focuses on human-machine interfaces, and the fifth section on multiple-UAV for monitoring the safety of human workers. Finally, the sixth section is devoted to the conclusions and future work.

It should be noted that not all the AERIAL-CORE technologies are included in this Chapter. In particular, UAV morphing and bioinspired technologies used to design and develop new platforms that can combine long-range and local inspections are not considered.

8.2 Intelligent Systems for Long-Range Inspection

Intelligent systems for long-range inspection in AERIAL-CORE include a variety of technologies such as sensor data fusion, learning techniques, line tracking, mapping and planning of multiple aerial systems. In this section, only the line tracking and mapping are included.

8.2.1 Perception Aware Model Predictive Control for Inspection of Power Lines

We propose [5] a vision-based, tightly-coupled perception and action algorithm for autonomous power line inspection that does not require prior information about the power line infrastructure, such as the location of the power lines and masts. Our method plans and tracks a trajectory that maximizes the visibility of the power line in the onboard camera view and, at the same time, can safely avoid obstacles such as the power masts. We achieve this by developing a perception-aware Model

Predictive Controller (MPC) that includes two perception objectives: line tracking and collision avoidance. To detect the power lines, we propose a novel perception module that extends the deep-learning–based object detector in [6] to the case of power line detection. The perception module is trained only on synthetic data and transfers zero shots to real-world images of power lines without fine-tuning. In this way, we overcome the problem of the limited amount of annotated data for supervised learning.

8.2.1.1 System design and validation

Our system is based on the MPC formulation for quadrotors proposed in [7]. We extend this MPC by including two new perception objectives: one for line tracking and another one for collision avoidance.

Line Tracking Objective: The purpose of this objective is: (1) to keep the power line in the center of the image, to maximize data quality for visual inspection, and (2) to keep a safe distance from the power lines. Specifically, we convert the positions of line endpoints from a world frame into polar coordinates in the image frame. We add a perception cost to force the lines to be centred in the image frame. We also introduce an objective to maintain the desired distance between the drone and the power lines.

Obstacle Avoidance Objective: For obstacle avoidance, we employ a collision cost and a collision constraint [8]. The collision cost is determined using a logistic function that considers the distance between the drone and the detected obstacles. The collision constraint is established as a probabilistic chance constraint to account for uncertainty in drone and obstacle states. The goal is to ensure that the collision probability with an obstacle remains below a specified threshold. Obstacles are modeled as ellipsoids. The uncertain nature of the positions is accounted for by assuming Gaussian distributions for the position of both the quadrotor and the obstacle.

8.2.1.2 Line detection and tracking

We propose a deep-learning-based power line detector based on the object detector [6]. The detector takes a single RGB image as input and outputs end points of the detected power lines in pixel coordinates. The centre patch of each detection is matched with the prediction of the previous patch using the Hungarian method [9]. We use a KLT tracker [10] to perform tracking. The final output is the tracked lines endpoints which are given to the MPC. To overcome the problem of the lack of datasets containing labelled images of power lines, we created a new synthetic dataset for power line detection based on the Flightmare simulator [11].

Figure 8.1. A quadrotor performing power line inspection in a power line test environment with three masts (labelled: A, B, and C) using our proposed approach. The original rough reference trajectory is depicted in yellow and the drone deviates from it while avoiding obstacles (the power masts) and keeping the power line visible in the field of view of the onboard camera.

Our model is trained on circa 30k simulated images. We show real-world deployment without any fine-tuning on real images.

8.2.1.3 Validation

We validated our system on a custom-made quadrotor [12]. Our quadrotor is equipped with an Intel RealSense T265 tracking camera and an Intel Realsense D435i depth camera. The onboard computer is a Nvidia Jetson TX2. We use the VIO algorithm from the tracking camera to obtain an estimate of the 6-DoF pose of the quadrotor and the depth camera to obtain RGB images for the line detection algorithm and depth measurements for the collision avoidance algorithm. All the components of our system run on the onboard computer in real time. A top view of one of our experiments is represented on Figure 8.1.

8.2.2 Long-Range Powerline Mapping

The need for cost-effective solutions for powerline mapping and inspection has motivated the development of aerial robots based on unmanned autonomous helicopters, Vertical Take-Off and Landing (VTOL), or multi-rotors. Despite the shorter flight endurance of multi-rotors, in the last years, there is significant research to provide multi copters with the capacity to perch on powerlines for recharging batteries, see e.g., [13]. These robots are equipped typically with visual cameras and LIDARs. Although they implement different autonomous functionalities, in all cases, powerline mapping is performed in a non-autonomous way that is structured in two stages. First, the robots fly through teleoperation or use predetermined missions to register measurements without performing any online processing. Second, in the office/lab, inspection is performed by offline, analysing the collected data using processing and artificial intelligence methods. In this procedure, the operators cannot be sure that the obtained maps have sufficient resolution or accuracy, potentially requiring repeating the data collection flights weeks after the data collection flights, hence involving delays, costs and operational problems.

This mapping system and methods developed in H2020 AERIAL-CORE enable the fully autonomous and online building of accurate 3D maps suitable for long-range powerline inspection. The developed system builds online and fully on board the robot an accurate (mean error of <5 cm) 3D map of the area surrounding the powerline, enabling measuring distances between vegetation and the electrical system without requiring offline processing. The developed system is based on a fully autonomous multi-rotor aerial robot capable of performing Beyond Visual Line of Sight (BVLS) flights. The robot flies 10 m above the powerline and towers. It follows the powerline describing a trajectory specified as a set of waypoints defined by the operator based on existing maps of the electric system. It includes a GNSS-based Trajectory tracker module that gives the commands to the robot autopilot. During navigation, the point clouds from the 3D LiDAR are collected and logged and processed to online build an accurate 3D map of the environment. The robotic system is also endowed with methods that process the obtained LiDAR-based geometrical map to segment the map points into four classes *Powerline*, *Tower*, *Vegetation*, and *Soil*.

The mapping engine is based on FAST-LIO2 but enhanced to integrate GNSS measurements in the Update of its iterated Kalman Filter scheme to improve robustness in scenarios with poor geometrical information content. FAST-LIO2 works directly with full LiDAR scans instead of with feature points as the other methods; it is based on error-state manifold-based iterative Kalman Filter, which enables reducing the memory footprint (suitable for long-range missions) and has moderate CPU consumption that enables online execution without discarding data. Refer to [15] for further details. Autonomous real-time 3D segmentation was performed by first using the reflectivity component of LiDAR points to differentiate whether the object is metallic (*Powerline* or *Tower*) or not (*Vegetation* or *Soil*). Second, using Principal Component Analysis (PCA), the geometrical information of the point clouds of objects classified as metallic or non-metallic was used to differentiate between *Powerline* or *Tower* (for objects classified as metallic) and *Vegetation* or *Soil* (for objects classified as non-metallic). Refer to [16] for further details.

The method was implemented on the *LR-M* aerial robot developed by the GRVC Robotics Lab at the University of Seville, see Figure 8.2-left. *LR-M* is based on the DJI Matrice 600 hexacopter platform, and its main sensors are a Livox Horizon 3D solid-state LiDAR pointing at a pitch angle of −40 degrees and an

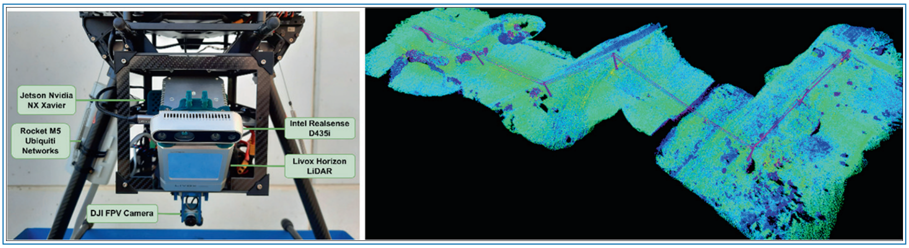

Figure 8.2. (Left) Sensors and computers on board LR-M robot used in the experiments. (Right) Powerline map built by LR-M in Alcala scenario (Sevilla) covering >1.8 km.

Intel RealSense RGB camera mounted with the same orientation for user visualization. In addition, it is equipped with a Jetson NVIDIA NX Xavier for online computation and logging. The Livox Horizon is a high-performance solid-state 3D LiDAR with a non-repetitive horizontal scanning pattern. It has a field of view of $81.7^\circ \times 25.1^\circ$, a detection range of 260 m, an angular precision of 0.05°, and a point rate of 240,000 pts/s. The mapping system implemented on *LR-M* was validated in experiments performed at (i) School of Engineering of Seville (ETSI, Seville, Spain), (ii) Burguillos (Seville, Spain), and (iii) Alcala de Guadaira (Seville, Spain). Figure 8.2-right shows the powerline map resulting in long-range mapping mission experiments performed in the Alcala scenario.

8.3 Aerial Robotic Manipulation for Maintenance

In the development of aerial manipulation robots intended to conduct maintenance operations involving physical interaction with the environment using tools or devices, like in the installation of bird flight diverters on power lines considered in AERIAL-CORE, it is possible to identify three design approaches, as described in [4], depending on the main constraint to be satisfied: weight or force required to manipulate the devices or tools, maximum payload capacity provided by the aerial platform, or level of dexterity needed to conduct the task.

The comparative case study presented in [17] identifies three modes of operation for the aerial robot depending on the way the manipulation task is conducted: (1) while flying as occurs with the linear actuator platform developed in [18] and as typically considered in most aerial manipulation works [4], (2) in grabbing conditions using one arm while the other operates, exploiting the passive accommodation capabilities of the compliant arm [19], and (3) perching the platform or deploying the manipulator on the workspace, detaching it from the aerial platform, used for its transportation and retrieval [20].

The dichotomy between developing general-purpose aerial manipulators or platforms to conduct specific tasks more efficiently or more suitably has been addressed

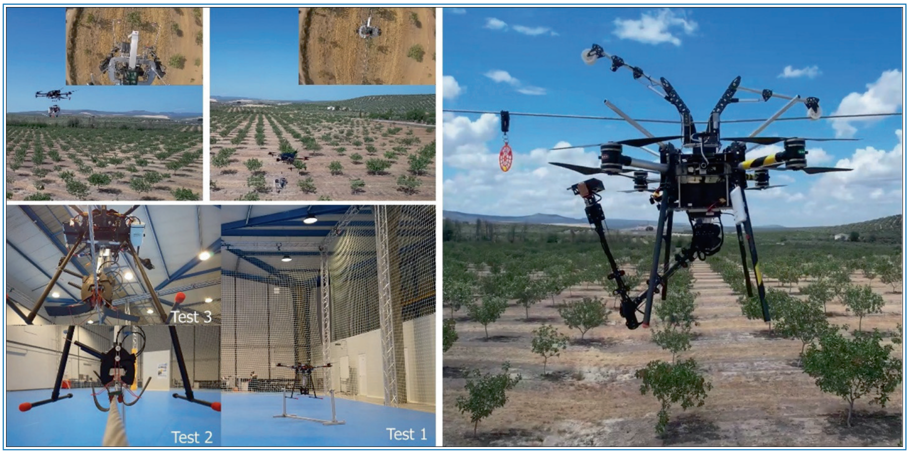

Figure 8.3. Linear Actuator Platform (LAP, up-left), Dual Arm Platform with Cart (DAP-C, down-left), and Main Local Manipulation Platform (MLMP, right) developed as part of the AERIAL-CORE project.

within the AERIAL-CORE project, resulting in the three different prototypes shown in Figure 8.3. These are Linear Actuator Platform (LAP, up-left) [18], Dual Arm Platform with Cart (DAP-C, down-left) [20], and the Main Local Manipulation Platform (MLMP) which is a high payload capacity multi-rotor, with a maximum take-off weight of 45 kg, providing electrical shielding against high voltage power lines, equipped with a high payload capacity (5 kg) robotic arm capable of conducting the installation of different types of devices considered within the project.

Subsection 8.3.1 describes a high payload manipulator for large platforms, particularly the MLMP. Subsection 8.3.2 summarizes the main characteristics of the Linear Actuator Platform and the Dual Arm Platform with Cart. Finally, Subsection 8.3.3 describes the *MLMP*.

8.3.1 High Payload Light Arm for Aerial Manipulation Tasks

The tasks to be conducted by the manipulator entail installing and removing different types of devices from the power lines. These include bird diverters (helical and clip diverters) used to prevent bird collisions, threatening birds and placing electrical cable spacers. Additionally, the power lines are exploited to improve the efficiency of the aerial system: recharging stations may need to be installed to extend the UAVs' battery life.

The proposed manipulator is an anthropomorphic arm featuring six degrees of freedom (DoFs), accompanied by a gear-based spherical wrist that supports the end effector. This configuration is essential to achieve a superior level of dexterity,

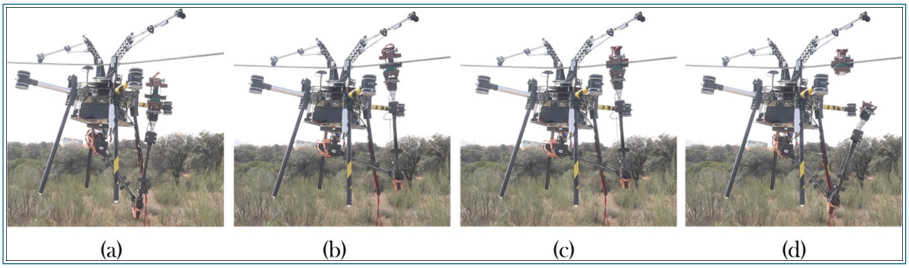

Figure 8.4. Real world experiment tests case: installation of a recharging station on a power line. (a) Approaching, (b) tool inserting, (c) clamping, (d) releasing. A video of this process can be seen at http://y2u.be/kvChEYhnxtY.

enabling the arm to accomplish all the designated tasks.The last joint of the arm has been thoughtfully designed with a versatile flange, allowing for easy attachment of different end-effectors specifically tailored to carry out specific tasks.

From the first prototype, the arm has been designed to weigh 3 kg, making it lightweight and agile. Despite its compact size, it boasts a payload capacity of 5 kg. This remarkable payload/weight ratio of 1.67 sets it apart from other similar solutions proposed in the literature (e.g., 0.5 for Haddington Dynamics Dexter HDI, which has a similar mechanical structure). The first version of the spherical wrist was built in plastic; even if the mechanism worked correctly, the material strength and rigidity were insufficient to perform all the required tasks. Also, using belt transmissions in the arm introduced inherent challenges related to elasticity. Displacements of the end effector caused by elasticity made it incapable of autonomously executing assigned motion tasks.

The latest version of the arm has solved previous issues. The wrist has been remade in steel (AlSi10Mg DSLM), achieving better stability and performance with a negligible increase in weight. The low-level control is implemented on an onboard microcontroller, making the system stand-alone. It can be teleoperated and used autonomously, providing an additional communication channel to an external PC for high-level controls. By leveraging the data provided by two IMUs, it is possible to calculate the precise position of the end effector, applying corrective measures and allowing the arm to execute tasks even in the presence of elasticity successfully. The proposed system has proven to complete all the assigned tasks in a mock-up scenario and on a real powerline, as illustrated in Figure 8.3-right and in Figure 8.4.

8.3.2 Linear Actuator Platform and Dual Arm Platform

The Linear Actuator Platform (LAP) [18] is developed for the installation of a particular model of clip-type bird flight diverters, extensively used on the Spanish power grid, shown in Figure 8.5, that replicates the shape of birds of prey to fear

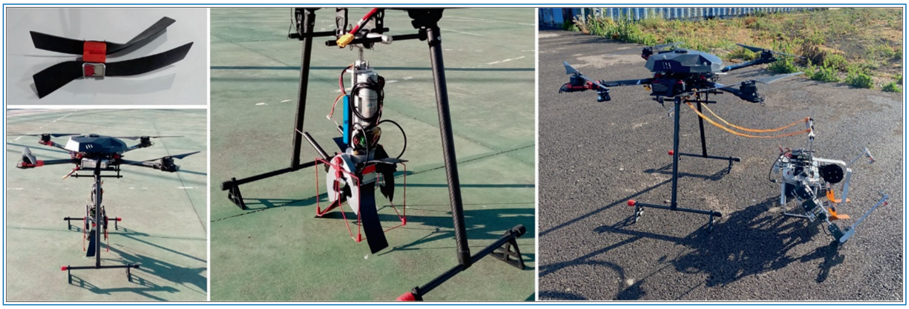

Figure 8.5. Linear Actuator Platform (left and middle) used for the installation of clip-type bird flight diverters (up-left), and Dual Arm Platform with Cart (right) for its deployment on the power line and installation of customized clip-type bird diverters.

birds approaching the power lines. The operation requires the application of very high forces (up to 100 kg) using a Firgelli linear actuator equipped with a clamp mechanism that isolates the aerial platform from the exerted pushing force by creating a closed kinematic chain when acting on the cable. The installation mechanism integrates the onboard control electronics, battery and a radio link, resulting in a compact device weighing 2 kg capable of conducting the installation of the device in 12 seconds. The motion constraint imposed by the clamp mechanism during the operation requires a certain level of accommodation of the aerial platform to unavoidable small position deviations, taking into account the typical positioning accuracies that can be achieved outdoors, incorporating for this purpose a passive spherical joint to attach the mechanism at the base of the multi-rotor to avoid destabilizing it due to the interaction wrenches exerted on flight.

The Dual Arm Platform [19] and Dual Arm Platform with Cart (DAP-C) [20] consist of a human-like and human-size dual-arm manipulator providing dexterous manipulation capabilities, with four joints for end effector positioning that allow replication of the bimanual dexterity of human workers. The very low weight of the arms (3 kg) facilitates its aerial transportation and deployment on the power line using medium-scale aerial platforms like the one shown in Figure 8.5(right). At the same time, the rolling base provides an energy-efficient way of moving along linear infrastructures. The arms integrate a compact spring-lever transmission in all joints to provide mechanical compliance, which contributes to protecting the servo actuators from impacts and overloads and results in safer physical interactions with the environment. In general, the idea of deploying the manipulator on the power line and detaching the multi-rotor from it results more convenient than operating on flight in terms of positioning accuracy, reliability, and energy efficiency. However, the realization of the manipulation operation is constrained by the kinematic configuration of the dual arm system concerning the power line, whereas the realization of the aerial manipulation on flight extends the effective workspace of the arms.

The use of dual manipulators presents two significant benefits, explored in AERIAL-CORE. On the one hand, taking into account the positioning accuracy required to conduct the manipulation task (in the range of 1 cm), it is interesting to consider the application of one of the arms to measure the position of the aerial robot concerning the workspace when the arm is grabbed to a fixed point, taking benefit of the passive compliance of the arm, as reported in [19]. On the other hand, the symmetry of a dual-arm manipulator makes it possible to maintain the equilibrium on linear infrastructures like cables or pipes as long as the centre of mass of the manipulator is below the perching point.

8.3.3 The Main Local Manipulation Platform

The Main Local Manipulation Platform (MLMP), depicted in Figure 8.6, represents the fourth demonstrator of AERIAL-CORE's aerial robotic manipulation module. Designed as a versatile system, it can install, remove, or manipulate various equipment typically employed in electrical infrastructure. During the project, four devices were targeted for this demonstrator: clip-type bird diverters, cable separators, and two types of drone charging stations [21]. The operating principle of the platform consists of navigating to an energized power line, perching on it, and turning off the motors to conserve energy. Afterwards, it moves along the line while installing the equipment.

Considering that the MLMP has been designed as a general-purpose platform, it should be capable of installing various types of devices without requiring extensive modifications between operations. To achieve this goal, it was decided to perform

Figure 8.6. MLMP using the robotic arm to charge its batteries from a drone charging station on a controlled environment.

the manipulation with a robotic arm with specific end effectors for each device rather than a general one. In this way, the versatility of the arm is balanced with the efficiency and customization of the end effectors, significantly reducing the difficulty of the manipulation. As mentioned above, the robotic arm was designed with six degrees of freedom to ensure good manoeuvrability, with the main motors located in the base and connected to the joints by a belt system. This ensures that the drone's centre of mass is not excessively disturbed, which could cause problems during flight. On the software side, both joint and cartesian controllers were developed, using a standard gamepad to command the references.

Another challenge was the perching process from below, integrating a specially designed mechanism with a dedicated perception and control system. The mechanism allows the drone to perch on the cable smoothly and robustly using only one servo motor connected to a proprietary hook design. It also includes two pulleys attached to DC motors, allowing the drone to move along the cable (see Figure 8.6). Additionally, to minimize the difficulty of inserting the cable inside the mechanism, a V-shaped structure capable of folding itself using two linear motors was integrated on top of the mechanism, acting as a guide for the cable when the perching manoeuvre is being performed, and pressing the cable when it is inside the mechanism to increase the stability of the drone in the line.

The perching software is built around two sensors: a pair of two-dimensional LIDARs and an RTK GPS. The drone initiates the mission with prior knowledge of the approximate GPS position and elevation of the line. It flies with a standard navigation system complemented by the centimetric precision of the RTK GPS. Once there, the drone initiates the perching phase by approaching under the cable while the perception system, which employs both LIDARs, attempts to detect it. When the line is detected, the drone begins to ascend. If the cable is detected inside the mechanism, the rotation is activated, and the cable is locked, completing the perching phase. Finally, the drone turns off its motors and starts the manipulation phase.

With the manipulation and perching challenges solved, the final step was to design a platform that was robust enough to integrate the robotic arm and all the necessary sensors and capable of operating in contact with a live power line with hundreds of kilovolts of tension. To address the two primary issues that arise when a drone touches a high-voltage power line, which are the voltage itself and the electromagnetic interference (EMI), the solution adopted was to build the drone with a closed metal frame and place all the electronics inside with their grounding connected to it. To test this solution, a prototype was made and tested by touching a 125 kW power line with excellent results. In all attempts, the drone touched the line without any problem, and neither the sensors nor the control suffered any interference or disturbances due to the line.

The final platform was developed by combining all the above technologies, and numerous integration and validation experiments were performed in controlled and realistic environments. For the controlled experiments, a mock-up cable was installed at the ATLAS Flight Test Centre in Villacarrillo (Spain). All the devices were installed, and several perching attempts were made with very positive results. The realistic experiments were also conducted at ATLAS, but in a real power line located close to the facilities. A complete operation of installing a bird diverter was performed, including autonomous navigation to the line, autonomous perching, teleoperated installation and removal of the device, releasing and returning to home.

In conclusion, the MLMP represents a breakthrough in power line inspection and maintenance operations. It is the world's first drone capable of perching on live high-voltage power lines and installing multiple types of devices using a six-degrees-of-freedom robotic arm while moving along the cable.

8.3.4 Magnetic Gripper with Charging Function for Drones on Power Lines

One limitation of drones in inspecting transmission lines is the short flight time. A promising solution is to charge the battery from the magnetic field around the power lines [22–28], allowing drones to operate continuously without returning to the base station. The charging time varies with the power line current, ranging from less than an hour to a couple of hours. In addition to the charging circuit, the grasping systems are equipped for the drone to perch on the cable. Therefore, to increase the flight time, the weight of these systems needs to be optimized to reduce the load on the drone.

Usually, the grasping systems include three components: current transformer (CT), gripper, and actuators (Figure 8.7). The current transformer, made of a magnetic core and coil, harvests magnetic energy. The gripper is employed to hold

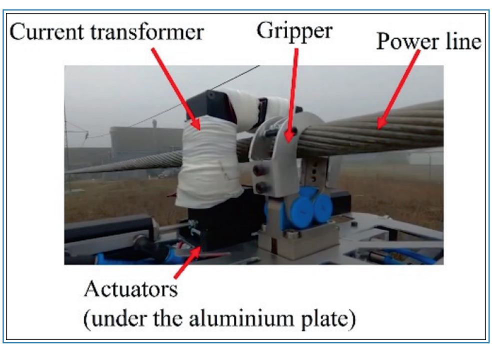

Figure 8.7. Typical grasping system of a drone charging from the power line [23].

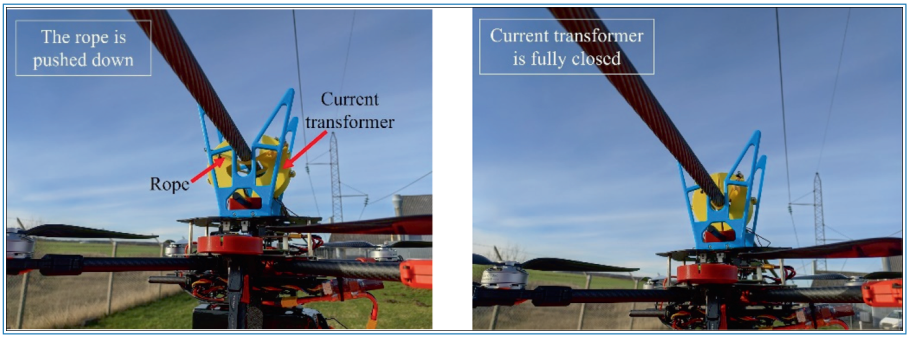

Figure 8.8. An optimized grasping system with only one current transformer [27].

the drone on the line. The actuators are typically motors that open and close the magnetic core and the gripper. Besides the function of harvesting energy, CT can act as an electromagnet when it is magnetized by the AC magnetic field. Therefore, it is possible to take advantage of this magnetic force to hold the drone on the cable and remove the gripper and actuators to minimize the payload on the drone.

The magnetic gripper in Figure 8.8 enables the drone to perch on the cable with only one CT [27]. When the drone flies upwards, the power cable pushes down on the rope that links the two halves of the magnetic core, closing the gripper. The CT maintains the grip thanks to the magnetic force and harvests energy simultaneously. The core is open by removing the magnetic force, and the drone falls off by itself. However, it is essential to know how much force is needed to hold the drone, as the magnetic force depends on the level of power line current. Assuming the fringing flux is negligible, the magnetic force at one contact surface of the core is calculated as below.

$$F = \frac{B^2 A_{CORE}}{2\mu_0} \tag{8.1}$$

Where B is the core's flux density, A_{CORE} is the cross-sectional area of the core (m^2), and μ_0 is the permeability of the air. As A_{CORE} and μ_0 are fixed values, the force varies with B, which can be electrically controlled by adjusting the magnetizing current I_m, as shown in the equation below.

$$B = \frac{N I_m \mu_0 \mu_e}{l_m} \tag{8.2}$$

Where N is the number of winding turns, μ_e is the core's effective permeability, and l_m is the magnetic path length of the core (m). The magnetizing current I_m is the amount of current used to magnetize the core, as shown in the equivalent circuit of CT in Figure 8.9-left, where I_p is the primary current (or power line current), I_s is the secondary current, and I_{Load} is the load current. The directions of

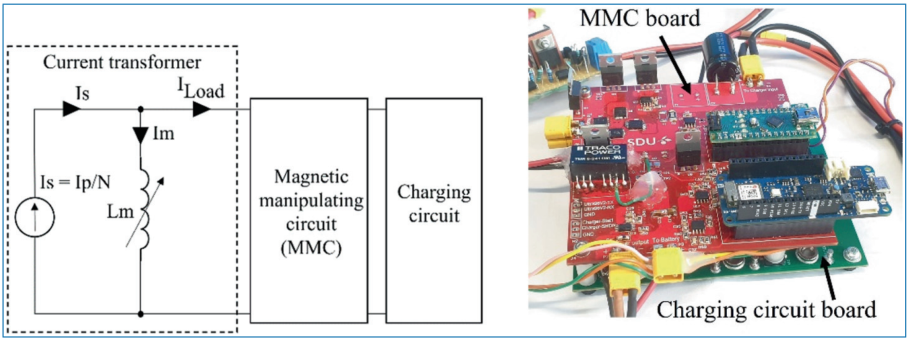

Figure 8.9. Left: The equivalent circuit of CT in connection with MMC and the charging circuit, Right: MMC and the charging circuit in practice.

currents change over time due to the AC current on the line. L_m is the non-linear magnetizing inductor.

Since I_m depends on I_p, I_m can be controlled based on the level of I_p. This can be done by a magnetic manipulating circuit (MMC), as shown in Figure 8.9-right. When there is no power line current or low, DC power from the battery is utilized to maintain the holding force. In this case, I_m consists of AC current from I_p and DC current from I_{Load}. When I_p is high enough, MMC starts charging the battery while keeping enough I_m. When the charging process is completed and I_p is still high, the magnetic field from the power cable is exploited to magnetize the core instead of using DC power from the battery to save energy. MMC controls I_p to increase I_m instead of I_{Load} as in the charging phase.

8.4 Human-Machine Interfaces

Some operations during inspection and maintenance are difficult to perform autonomously, and sometimes it is necessary for the operator to take control of the platform to perform such operations.

There are several existing approaches to the teleoperation of drones and manipulators. As robots intended for these applications become more complex and powerful, additional efforts are needed to implement interfaces that are both effective and convenient for most users [29]. However, standard interfaces such as remote controllers still fail to achieve this goal and require significant time and effort to be mastered by inexperienced users [30, 31]. For this reason, several new remote-control methods for drones and aerial manipulators have been developed to provide operators with more intuitive operation and feedback to all their senses. These include control methods based on the operator body pose, telemanipulation of robotic arms based on a replica of the controlled system, and control based on operator voice

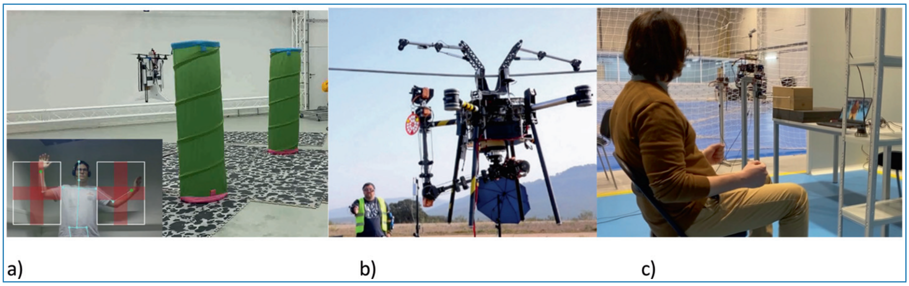

Figure 8.10. Different human-machine interfaces: (a) operator controls UAV based on human pose estimated from camera image; (b) operator controls robotic arm on MLMP based on human pose estimated from IMU measurement; (c) operator controls light dual arm based on human pose estimated from camera image.

commands. Feedback to the operator is provided through various interfaces that provide visual, haptic and acoustic information.

For control based on operators' body pose, we developed an IMU-based human pose estimation and a camera-based human pose estimation, which was then mapped to the different control laws. In [32] we presented a UAV control strategy which relies on estimating the operator's body posture from the camera image, for which a user study was conducted and assessed based on the NASA Task Load Index. The method was implemented and tested on the morphing rotary /fixed wing platform (see Figure 8.10.a)). The concept of simultaneous control of UAV and manipulator based on the operator's body pose from the camera image was presented in [33], and a similar idea was tested based on IMU estimated body pose. A similar control method with an operator equipped with IMUs was also tested in a realistic scenario with the MLMP to control the robotic arm, as shown in Figure 8.10.b.

Three different teleoperation interfaces were investigated for the teleoperation of anthropomorphic dual arms with very low weight. A comparative performance evaluation was performed in [34]. The three methods include a visual human pose estimation system that maps the pose of the human arm to the pose of the robotic arm (see Figure 8.10.c), a leader-follower scheme that uses a scaled-down dual arm that can directly transfer the joint positions of the leader arm to the follower arm, and a 6-DOF (degrees of freedom) joystick.

To provide individualized control for each operator, a learning-based approach was developed and used with different interfaces that include direct mapping of operator-attached IMU measurements, motion capture data, and hand posture-based control with hand and finger motion controllers. In this approach, the operator first attempts to mimic previously defined trajectories, and his or her movements are used to teach the system control commands. After the learning phase, the system maps the control of different movements to specific control actions, and the operator can control the system using his own control commands.

Various interfaces have been used to provide feedback to the operator. The primary method of feedback is visual, for which computer screens, head-mounted displays, and smart glasses have been used. Unlike computer screens, head-mounted displays and smart glasses provide an immersive experience for the user. Different graphical interfaces were used as needed, but the primary channel of information transmission is the first-person perspective from the teleoperated object. In addition to visual feedback, auditory and haptic feedback were also used. Different combinations of control and feedback methods were used to conduct experiments and user studies on the usability and intuitiveness of the developed methods.

8.5 Formation Control of Safety Aerial Co-Workers

Work at height, such as on power line maintenance, is physically and mentally demanding. Human operators have limited mobility for handling the required tools and situational awareness around the workplace. To this end, the Aerial Co-Workers (ACW), an Unmanned Aerial Vehicle (UAV) helping the worker, can significantly improve the effectiveness of the work and its safety. Three types of Aerial Co-workers can be employed in these situations. Physical ACW [35] that can physically interact with human workers, e.g., to deliver tools or components. Inspection ACW [36] can provide support to human operators in acquiring views of the power tower that are not easily accessible. Finally, the Safety ACWs, which we focus on in this section, can be tasked to monitor the human workers performing maintenance on the critical infrastructure of the powerlines. By doing so, the Safety ACWs reduce the probability of severe accidents leading to workers' injury while enabling better situational awareness around the worker, similar to the Inspection ACW.

A natural way to acquire more information about the worker's surroundings and thus his safety is to employ multiple robots that form a team of Safety ACWs. The team is thus tasked to keep a formation around the worker, monitor the worker with onboard sensors, and change the appearance when commanded by the worker. This requires from the Safety-ACWs formation to perform planning and control strategies to keep the robots within the formation at a given mutual distance from each other and from the human worker. This all while observing the worker with onboard sensors and avoiding collisions with the environment. Moreover, the formation of Safety-ACWs is controlled using gesture recognition [37] to change both lateral and vertical relative viewpoints of the worker.

The Safety-ACWs uses leader-follower formation scheme, similar to our work [38], where one ACW UAV is the formation leader that carries the onboard

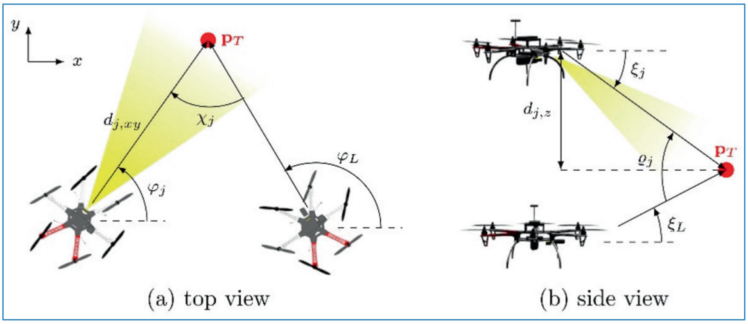

Figure 8.11. The leader-follower scheme of Safety Aerial Co-Worker formation.

sensors to detect the human worker and its gestures. The follower ACW then keeps a predefined formation with the leader relative to the detected position of the worker (shared within the team), and also keeps heading towards the worker. The reference trajectories for the follower UAVs are computed to achieve a desired leader-follower formation around the target. The desired position of the followers is influenced by the corresponding leader position $\mathbf{p}_L$ and camera orientation $\mathbf{o}_L$, the target position $\mathbf{p}_T$, the desired follower angles of j-th follower χ_j and ϱ_j, and the desired distance of the follower to the worker d_j.The desired position of j-th follower $\mathbf{p}_j$ is then given by the equation:

$$\mathbf{p}_j = \mathbf{p}_T + d_j \begin{bmatrix} -\cos(\varphi_j)\cos(\xi_j) \\ -\sin(\varphi_j)\cos(\xi_j) \\ \sin(\xi_j) \end{bmatrix}, \tag{8.3}$$

where $\varphi_j = \varphi_L + \chi_j$ and $\xi_j = \xi_L + \varrho_j$ are desired follower angles relative to the camera (see Figure 8.11).

Both the leader ACW and the followers use trajectory planning to reach a desired positions with respect to the worker as described above. The trajectory planning uses an initial path-planning phase where a collision-free path is planned using Jump Point Search (JPS) algorithm introduced for 3D in [39]. The path is then used to find a safety flight corridor between the current UAV position and the desired position. The flight corridor is a convex decomposition of the free space found on a map of the environment as described in [39]. Finally, given a collision-free path P and its corresponding safe corridor S, a final optimal trajectory is computed using a Quadratic Programming (QP) formulation of trajectory planning in a receding horizon. The particular optimization problem minimizes both the control effort and the error from the desired path. This QP constrains both the UAV inputs and speed, while it also limits the UAV positions to be within the convex polyhedron representing its flight corridor. This ensures the final trajectories of the team

Figure 8.12. Real demonstration of team of three Safety-ACWs controlled by gestures of the human worker.

are collision-free while keeping the Safety ACW-formation. A real demonstration of the system is shown in Figure 8.12.

8.6 Conclusions and Future Work

The AERIAL-CORE project has achieved relevant progress on intelligent robotic technologies and systems applied to electrical power line inspection and maintenance.

The Chapter has presented intelligent systems for long-range inspection of the power lines, by including the perception-aware model predictive control for the autonomous tracking of the line and the long-range on-board autonomous mapping of the power line and the vegetation around the line.

It also presented the application of aerial robotic manipulation technologies by including several aerial manipulation platforms and a high payload arm. These technologies are being used to install bird-diverters and also a battery charger station allowing UAVs to operate continuously without returning to the base station. The main characteristics of the magnetic gripper were also presented.

The Chapter also included human-machine interfaces and teleoperation technologies to operate the aerial platform and the arms.

Finally, the Chapter presents a team of aerial robot with formation control to monitor the safety of a human operator.

The Chapter included prototypes tested in real electrical lines. Preliminary integration and validation experiments have been performed in May 2022 and May 2023 in the ATLAS Airfield with medium and high voltage electrical lines.

The experiments have pointed out the industrial interest of the presented systems for inspecting and maintaining the power grid.

Other AERIAL-CORE technologies that will be demonstrated in the next months in ATLAS include morphing of the aerial platforms, multi-aerial robot planning techniques, learning and gesture recognition in the interaction with humans and the integration of the AERIAL-CORE system.

It is expected that several AERIAL-CORE technologies will be industrialised and applied at short term for the inspection of the electrical grid.

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