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Snake Aerial Manipulators: A Review

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ABSTRACT In this document, a review about snake aerial manipulators is presented. The most common mechatronical implications found in their design are described. The text is presented to the reader as a set of modules, this include topics about structural dynamics, aerodynamics, power and energy, propulsion, thrust-vectoring and level of autonomy of aircrafts, also highlights about use of sensors, control methods and flight schemes.

INDEX TERMS Aerial manipulator, cooperative systems, UAS.

I. INTRODUCTION

To follow it is convenient to expose a brief introduction to coupled and decoupled task aerial manipulation concepts. Which are the basis of snake aerial manipulators. Both concepts are widely described in [1]–[5].

A. AERIAL MANIPULATION OF DECOUPLED AND COUPLED TASKS

Since the beginning of the decade of 2010, the MM-UAV (Mobile Manipulating Unmanned Aerial Vehicle) is an area of gradual growth. Until 2012 the concept was limited to aerial vehicles with robotic manipulator arms attached to their structures. In this way, and according to the requirements of [6], these are systems of decoupling tasks, that is to say, systems in which the dynamics and kinematics between the manipulator and the aircraft can be controlled with certain degree of independence or decoupling [3], [7]–[18] **Fig. 3**. Thus, this scheme is restricted to the use of multiple coordinated MM-UAVs each one equipped with a robotic arm coupled in a rigid way or by means of cables (e.g. AEROARMS and ARCAS projects). [19]–[22].

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On the other hand, since 2011 approximately, the essential notions of coupled task aerial manipulation theory were developed [23]–[36]. Although their approaches covered exclusively the cargo-lifting and coordinated transport of objects rigidly attached to the body of each member of an aircraft team, also suitable by means of deformable and elastic cables. Such publications are the basis for understanding the coupled task aerial manipulator concept, that where manipulation and transport tasks cannot be separated because the aircraft-team or the array of propellers, are by themselves the engine elements and also the channel of dexterity and manipulation. **Fig. 1,2,4,5,6,7,8,10**. **Table.1**

B. DEFINITION OF SNAKE AERIAL MANIPULATOR

They are a kind of coupled task aerial manipulator with bidimensional or three-dimensional robotic handling skills through the interaction of multicopters or propellers that constitute two or more bifurcated kinematic chains called arms, with dexterity and transitional capacity between open and closed kinematic structures. This bifurcation starts from a common point of reference and analysis, which can be, the geometric center, the gravity center, the mass center, the flotation center, or any other point of particular interest.

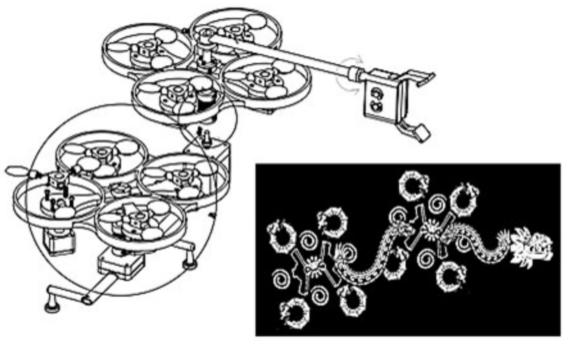

FIGURE 1. Air-Arm,J.Mendoza-Mendoza-2015.

TABLE 1. Aerial manipulators classification based on decoupling between dexterity and mobility.

Kind	Decoupling	Short definition
Classical	Partial under special conditions	Aircraft transporting robotic arms
Snake	Null	Robotic arms made of interconnected aircraft or props

Such structures can be reconfigurable and shape morphing [37]–[41].

C. APPLICATIONS AND DRAWBACKS

With the existing technology their immediate application is not entirely feasible due to power consumption and omnidirectionality challenges even with tethered power supplies (tethered in the sense of power because concerning to this topic is also employed in the sense of linkage). However, they allow the study and research on derived applications such as the reconfigurable robotics [38], [42], [43] **Fig.2**, the continuum robotics [44], flying humanoids and non-flying vehicles. In the first case, they are modular shape-morphing structures moving through the three-dimensional space. In the second case, snake aerial manipulators can be seen as discrete systems powered by the action of propellers and thus, they lay the preliminary notions for the study of continuous systems driven through valves and pneumatic or hydraulic fluids, leaving in this case the open problem on the efficiency between using actuators based on the motor-propeller interaction or those based on valves and flows. Concerning to flying humanoids, snake aerial manipulators can be seen as the subsystems or limbs of this kind of robots [45]–[47]. Finally, with respect to non-flying vehicles it must be indicated that extrapolations of the topics described in this text to vehicles different from aircraft can be found at [48]–[52]. More details about the aforementioned drawbacks and other important problems will be analysed in the next sections.

D. CURRENT KNOWN PROJECTS

DRAGON. 12 This configuration [39], is characterized by using propellers as hovering elements and servomotors as elements of three-dimensional manipulation. **ODAR FAMILY Fig. 12** In this case, multirotors are used at the same time as elements of hovering, dexterity and three-dimensional manipulation, through the interaction with three-dimensional joints, for example spherical or ball-joints [53], [54]. **EHECATL Fig. 12** In this case, the multirotors or propellers are used as elements of hovering, dexterity and manipulation with selective assistance of servomotors and interaction with variable three-dimensional joints (as clutches) or restricted three-dimensional joints (for example, spherical joints with a slot for yaw restriction) [55].

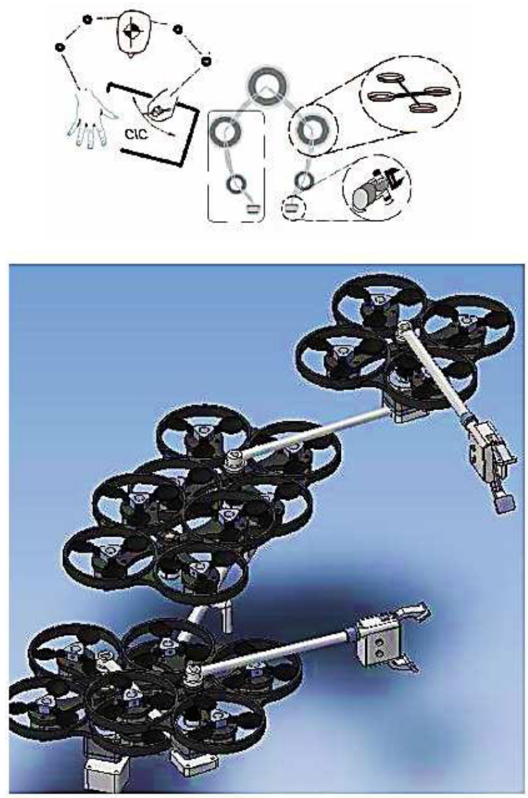

FIGURE 2. Air-Torso,J.Mendoza-Mendoza-2015.

E. OUTLINE

From computational and mechatronical points of view, the rest of the paper is divided into two main sections: The first is dedicated to hardware, this section is about mechanical considerations, power and aerodynamics. The second one is related to software and electronic and deals about electronics, programming and control topics.

The hardware section is a review based on the compilation of several publications and our own experience on topics related to structural dynamics, aerodynamics, power and energy, propulsion, thrust-vectoring and level of autonomy of propellers and individual aircrafts. While the section of software and electronics, is a compilation also based on the current state of the art and our own experience on computing, use of sensors, control methods and flight schemes. For practical purposes, this section is subdivided into general considerations of each individual UAV, collaborative flight considerations and transformation towards the operating area, take-off and landing considerations, as well as control design in aerial manipulation mode. Finally, the last section shows the general conclusions.

II. MECHANICAL CONSIDERATIONS, POWER AND AERODYNAMICS

A. COMMON COMPONENTS

Guiding element, base element, reference element or branching element: All these are synonymous and they are defined as a reference point from which at least 2 arms, also called kinematic chains, fork.

Kinematic chain: successive union of engine elements (multicopters, individual propellers and/or motors) with elements of transmission or propagation of movement (bar linkages), by using connecting elements (joints or the motors by themselves).

Engine elements: they are the multicopter aircraft or individual propellers which, in addition to allowing the hovering and flight of the whole system, produce the rotational movements necessary to transmit and propagate to more complex movements through the kinematic chains with or without the assistance of auxiliary motors. **Table.2**

TABLE 2. Kinds of engines for snake aerial manipulators.

Engine	Characteristics
Team of aircraft as engines	Voluminous and massive. High power consumption. In certain configurations they can be seen as a team of classic aerial manipulators. They allow centralized or decentralized control methods
Set of Propellers or turbines as engines	Lighter versions than the previous. Less power consumption. By using coaxial motors they could be also seen as a team of aircraft engines. They allow just centralized control
Set of Valves as direct engines	The weight depends on the valve system and the circulating fluid. As they are more mechanical, they have slow response in control. Currently is arguable if they are or not power efficient, and also if this efficiency is increased with the use of valves and pumps or through specialized pneumatic or hydraulic motors. By using turbines they can be seen as the previous description

Elements of transmission or propagation: they are bar linkages that connect one drone to other or one propeller to other and allow the chained transmission of their rotations and translations

Joint elements: the driving elements with the linkages are connected through joints. They allow the general mobility and the propagation or suppression of one or more relative movements. They could be any type of bearing, for example standard bearings, ball-joints (which particularly allows three-dimensional mobility), rigid bearings (like bronze bushings), restricted rotation bearings (that have no free rotation of yaw movement as a cardan joint or a locked ball-joint), magnetic joints, clutches (they allow a variable type connection), or even auxiliary motors by themselves according to the usage and design

Damping elements: they are used to control or suppress unwanted movements such as bumps, and vibration or misalignment between the driving elements, the transmission elements and the joints. Examples are rubber shock-absorbers or flexible couplings

Power elements: they allow the aircraft and the auxiliary engine elements to be energized. Examples are batteries, electrical extension cords, power cells, solar cells etc.

Elements of sensing and control: They are on-board electromechanisms such that certain effects such as the altitude, orientation and position can be measured, stored and regulated, the most representative is the autopilot.

Discussion: This section describes the basic components of a snake type aerial manipulator. Regarding each one of the elements, the following open questions are formulated:

Regarding the branching element, due the fact that this is the reference of the entire vehicle to be controlled and no matter that it is located inside or outside of its body (mass or gravity center for example), the research open question is: must it be necessarily a fixed point?, is there the possibility of move it according to the type of task that is executed? (take off, landing, free flight, manipulation, etc.). And if the answer is affirmative, how to recalculate said different reference points ? Moreover, considering that snake aerial manipulators are morphing surfaces that move in the three-dimensional space. In addition to said question, maybe it is convenient to relate this reference points with each one of the representative planar projections of the aircraft in the manner of what in robotics is already known as a support polygon.

Regarding the kinematic chain, it is convenient to develop research in the limit conditions where the morphing structure changes from parallel to serial configurations, as well as to determine the scenarios of force, speed and dexterity in which is more convenient to use each one of these kinematic chains, all this is required in order to calculate manipulation indexes.

Concerning to the type of engine, since this determines whether the snake aerial manipulator is a system based on an aircraft-team, a propeller-team, a set of valves and pump action, or even a combined propulsion. The question that stands out and remains as an open problem takes place with respect to which kind of the aforementioned engines is more efficient and under what conditions is this efficiency achieved?. It must not be forgotten as indicated in the **Table.2**, that there are boundary conditions where one type of propulsion system resembles or equates another, for example is it convenient to continue thinking on the snake aerial manipulators as systems propelled by motor-props elements or is it more convenient to use specialized valves with a minimum of propellers? This also determines the degree of independence of the engine units, because as indicated, the snake-type aerial robots based on aircraft-team, allow both a decentralized control of each aircraft to achieve a common purpose, such as one centralized acting on a reference point of the structure, where each aircraft is simply an individual generator of forces and moments. In this way although this kind of aerial snakes are not as efficient as the other two types of engines, they are more versatile in relation to the controller design, because the other methods impose a centralized behavior.

On the subject of the linkages, unlike a fixed robot manipulator, it must be investigated the way in which the use of standard techniques for weight reduction alters the aerodynamics of the vehicle. For example if the use of holes over the structure is adequate and what type of holes are useful. In addition, it must be investigated if the connection of the engine elements is more efficient to be placed over them, under them or at the same engine-thrust level (this situation is in fact debatable and it is very common to talk about pendular or drag effects depending on where the propellers of a multicopter are placed with respect to the frame).

On the part of the joints, this implies different degrees of transmissibility and mobility according to the type used, and they can lead to conditions of immobility, damage or destruction. In all the papers at the present time available, options based on spherical movement and in consequence omnidirectional transmission, whether through spherical joints or cardanic combinations are employed, but it is appropriate to ask ourselves if there is any new design that makes aerial movement more efficient, as in the EHECATL [55] project, where reduced or lockable joints are used (a clutch for example) [56], [57].

Regarding to the damping elements, it is advisable to think about where they should be placed, this is, place them at the joint level, at the linkage level or in both places, and also by considering that this placement obviously modifies the response times and the type of the desired response, acting under certain tasks, such as free flight and takeoff, as an inertial load or a brake.

Finally, the power, sensing and control elements will be discussed in the following sections.

B. DESIGN CONSIDERATIONS OF STRUCTURAL DYNAMICS

According to [32], [58]–[60] there are two main variants of snake aerial manipulators and their combinations, based on the way in which the UAVs or propellers are joined to compose a floating structure:

Flexible Aerial Snakes Fig. 4. In this case, the current technology has focused on the use of cables, however, [58] proposes mechanisms and controllers that can vary from the suspended cable, to the rigid union passing through different types of flexible linkages. Representative publications are: [27], [29], [30], [33], [61]–[65].

Rigid Aerial Snakes the rigid case **Fig. 1,2,3,5,6,7,8**. They are UAV teams [55], [66]–[68] or a set of independent propellers [69]–[74], which are capable of moving the structure to which they are rigidly mounted by using various methodologies of thrust vectoring [75]–[79]. Also, they provide dexterity, additional degrees of mobility and capacities of an aerial like-robotic arm manipulator.

A subclassification, occurs according to the kinematic chain that conform the airships or propellers [80]–[83].

Rigid Parallel Aerial Snakes The parallel approach. In this classification, the movement and force resulting in a specific point of the structure (where a gripper or end effector is usually placed), is determined by the coordinated operation of each individual engine-element in a closed kinematic chain (UAVs or propellers), [24], [69], [84] **Fig. 5,7,8**. The fact of having a parallel structure has the advantages that the center of mass, gravity, geometric and pressure, as well as the general form of the aerial structure do not vary considerably

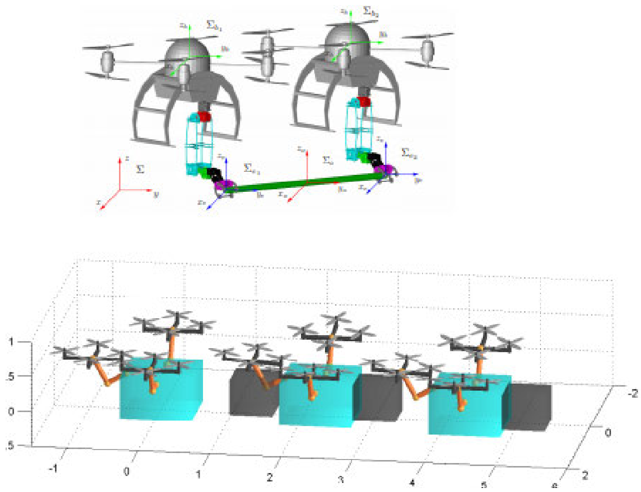

FIGURE 3. Rigid Manipulation,F.Caccavale-2015,H.Yang-2015.

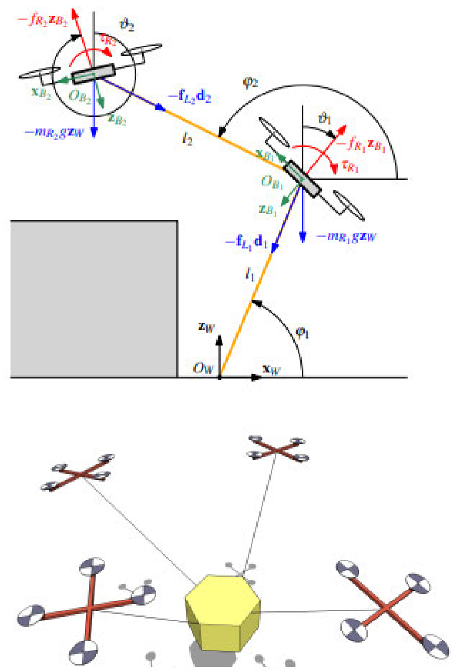

FIGURE 4. Flexibe Manipulation,M.Tognon-2015,C. Masone-2016.

with the execution of a task (at least not as drastically like the serial approach), this allows to focus the design on contact force assignments.

Rigid Serial Aerial Snakes The serial approach. In this case, the movement and force applied to the point of interest follows an open kinematic chain, which, in addition to bring more mobility to the aerial mechanical structure, has the problem of introduce severe inertial changes. This is because the position of the center of gravity, mass, geometric and pressure, could change with the shape and trajectory variations during the execution of the entire task (such as a human arm for example). So the tasks to be performed are not only those for generating contact forces but also movement,

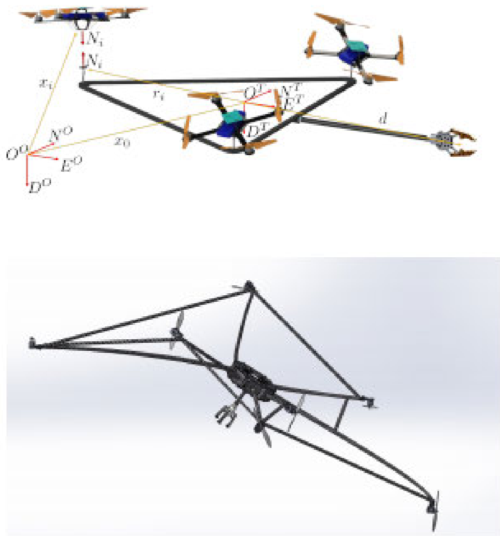

FIGURE 5. Parallel Aerial Manipulators,Nguyen-2015,Nikou-2014.

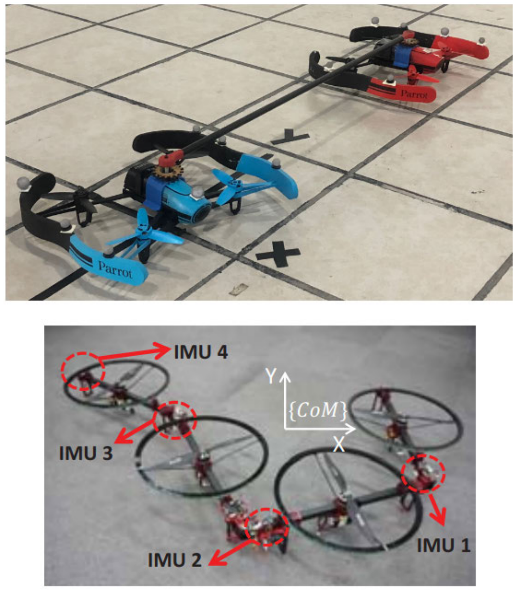

FIGURE 6. Serial Aerial Manipulators,J.Mendoza-Mendoza-2015,Shi-2019.

reconfigurability and dexterity [55], [58], [72] **Fig. 1,2,6,8**. Another challenge here is that, as it is presented in [23], [66], [69], [70], [85], the dynamic and kinematic equations between the propellers and some center of reference, that is usually placed in the center of mass or gravity, now is fixed to a movable point. This way, some considerations such as lever arms, moments of inertia and the control design by itself, are related intrinsically to the shape of the system and not only to the tasks.

Discussion: This section has discussed a preliminary classification based on the aircraft or propeller interconnection. A flexible configuration was shown, and also two rigid configurations, the serial and the parallel approaches. The known details above these configurations was already indicated, but it is convenient to investigate:

The rigidity usually implies density and this consequently entails weight, although there are widely used materials such as carbon fiber, it would be convenient to use designs whose 3D-printing layers are by defect shock resistant, very hard (through high porosity, but high density) and over all ultra-light [86]. Other option is to take up the use of inflatable structures with highly resistant coatings. Based on the above, it would be appropriate not only to do research on fully rigid designs or fully flexible ones, but on intermediate or variable hardness designs, considering aerodynamical effects.

The previous point would also implies an additional application to aerial robotic manipulators: physical systems test-benchs for mathematics and control on continuous, discrete and hybrid systems.

This also implies the design of new centralized and decentralized cooperative control schemes, including new optimization problems. As it will be seen later, these problems are based on the fact that it is not very convenient to allow the reversibility of a propeller (because is not an instantaneous action and also it implies destructive inertial effects), examples of this, were highlighted and addressed by Nikou [], Tognon and Franchi [87]

C. DESIGN CONSIDERATIONS OF AERODYNAMICS

Concerning to aerodynamics, design is divided into three groups:

On the flight: this is a dynamic operation, requires standard aerodynamic design, which corresponds to wind interaction, vortex effects, and other common phenomena acting on regular aircraft [88]–[93]. It's convenient to transform the aerial manipulator into a tandem helicopter, a counterrotating one or an airplane and to develop ways for keeping the frame rigid, the task is devoted just to translate the full aerial robot to a distant workplace. As it can be noticed, this is a full structure task, and it is also useful for transporting objects [55], [85].

In situ: this is a quasi-static operation, because is required a hoovering base in order to manipulate objects or to do miscellaneous robotic manipulator-like tasks, also if the aerial robot is in movement the velocities are expected to change slowly or in a constant manner for considering a kinodynamic model and control [67], [94], where the dynamic control is just for translation and the kinematic like-manipulator control is concerned to orientations. The in situ tasks are related to hovering power consumption, distance among propellers, distance among manipulated and interacting objects and distance with respect to the floor [95]–[99].

Transformation: is needed to apply methods and algorithms in order to change between on the flight and in situ modes [100]–[103] (also see helibot throughout this text). This change also needs to do be done in a smooth way in cases of interacting with fragil materials or living beings. In the case of massive or volumetric aircrafts the transformation phase is by itself a challenge (e.g. V-22 Osprey) [104], [105].

Discussion: This section has remarked the three main flight operations of snake aerial manipulators and their inherent aerodynamic design considerations. Among the described, the most complex aerodynamic problems occur in the stages of transformation, manipulation and dexterity, especially if they are open kinematic chains, and it is convenient to analyze the turbulence and vortexes induced by arm-movements (as when swimming), and indicate how they affect both the hovering and the execution of the task to be performed. For this, even in an indoor test where the air flow is usually laminar, arm-movements can lead to chaotic effects and disturbances (it should be mentioned that the existing demonstrations of snake aerial manipulators have been conducted at low speeds). Here the point also implies a more specialized design of the linkages which at present are just solid and tubular assemblies, perhaps it is even advisable to think on like fish-scaled surface patterns to counteract the effect of such vortexes and turbulence.

On the other hand, just as in the standard robotics of manipulators there are inoperability or redundant conditions known as singularities, it is also convenient to investigate for the these aerial manipulators if there are aerodynamic singularities, that is to say, configurations beyond the limits of mobility and force where the flight flows are canceled or become too much chaotic to allow the correct operation of the system, remembering that in this type of aircraft the interaction is not only mechanical but also fluidic.

With the above it is also feasible to determine the previous question on which is more stable and efficient: an snake aerial robot based on aircraft interaction or the versions based on propellers or valves.

Finally, as already noted, many types of stability and efficiency have been mentioned: aerodynamics, power consumption, task efficiency, control efficiency, etc., the next question is: How to rank these efficiencies and determine which of them is more relevant in these morphing-shape systems and their variable operating modes?

D. DESIGN CONSIDERATIONS OF ENERGY AND POWER

The snake aerial manipulators with our actual technology are feasible in three manners:

By propellers: almost all the cases previously described have as reference, vehicles based on propellers, mainly by their cost of development and acquisition

By valves: they are relatively new designs and instead of aircraft or propellers, they use a set of valves and pumps systematically commanded

By turbines: the use of turbines is promoted because moving large masses or volumes involves a proportional change of propellers, however in turbines, the relation thrust vs propeller dimension is acceptable and not so abrupt, remarkable attempts to have mini turbine - drones with vertical take off and landing correspond to [106], [107] (although they have been around for aeronautical and aerospace applications). It is also feasible to think of aircraft combining propeller technology and turbines such as turbojets (e.g. V-22 Osprey) [105], [108].

TABLE 3. Snake aerial manipulators power methods.

Power method	Open problems
Electrical tethered	Cable maneuverability, Cable mechanical and electrical effects
Fuel tethered	Cable maneuverability, Cable mechanical effects, Slow response control
Pneumatic or fluidic tethered	Cable maneuverability, Cable mechanical and fluidic effects, Valves vs motors efficiency
Electrical On board (solar or batteries)	Reduced flight time, voluminous devices and payload
Fuel On board	Slow response control
Electrical wireless	Currently in development, high risk of obstruction

Whatever the selected option, it will require a power source and according to commercially available sources of energy, there are four alternatives: fuel sources, solar sources, battery sources and direct wired connection (electrical or not like the pneumatic pump case). **Table.3**

A serious problem to deal with aerial manipulation is power consumption. Consider, for example, an air-torso [55], suppose that coaxial bicopters are used instead of quadrotors, in order to provide a waist, 2 shoulders and 2 elbows, 10 propellers will be required and their respective servo steering system, suppose that all the system without batteries or fuel weights 15kg and that it is required a capability of manipulation of another 10 kg at 50 m of altitude at least for 1 hour.

Two problems arise from these suppositions: the first is related to power consumption, calculations show that at least 8000watts are required (e.g. MORUS project) [109]. In this manner the option for this power consumption and desired flight time are internal combustion engines [109]–[112] if it is pretended to do a free flight. Or a direct electrical wire connection if it is not a drawback to fly anchored **Fig. 9** [113]–[120]. The second problem is related with density of energy, actual batteries and solar cells needs huge volumes and spaces to provide enough power and flight time. In this way, despite the efforts and popularity, these sources of energy are not a viable option for practical long flight operations of snake aerial manipulators [121]–[124]. As is noticed, the problems arise as consequence of size and mass, an useful dissertation to know when to refer to small or large scales is [125] **Table.4**.

Small scale: To the date, most of the UAV and MM-UAV designs are focused and adapted in this dimensional scale, for example, almost all the works presented in this paper, have unthinkable thrust vectoring methods for large-scale MM-UAV.

Large scale: actual approaches of MM-UAV are not feasible in large scale aircrafts, for example, researchers that change the direction of rotation of the propellers for faster control of orientation, must deal with the counterpart in big scale UAVs where this change is slow and dangerous. The approach of tilting the entire body of a propeller and its corresponding motor is also not feasible, because the required engine capable of moving a rotating propeller, demand too much power, because they work against considerable gyroscopic and inertial effects

In this way is needed to develop snake aerial manipulators focused on turbine thrust vectoring methods (in fact,

TABLE 4. Recommended thrust-vectoring methods according to aircraft scale.

aircraft scale	suggested methods of thrust vectoring
small scale	mechanical full motor vectoring, interaction of multiple motors, flaps, propeller deflection, propeller reversibility
large scale	center of mass deviation, propeller deflection, pneumatic or fluidic flow deviation

the propeller technology becomes oversized) or work in new ways for varying the angle of attack of the propellers with swashplates or another methods including non-mechanical [126]–[128], of course, if it is even possible to use propellers.

Discussion: This section has dealt with the relationship of power and scale, the existing approaches for this high-power consumption technology, are internal combustion engines and power-tethered sources, being this last one and at least to the date, the one with the greatest impact and development.

As indicated in the **Table.3**, the research to be developed is to determine the best modes of operation and control for tethered and wireless power supplies (including on-board power supplies such as batteries). Currently by the technological effects of energy density and power density, the most adequate supplies seem to be the tethered ones, but said anchors impose restrictions of operation in terms of mobility (radial geometries due to the cable and for the purpose of not self-entanglement with the vehicle) and also force restrictions (in order to avoid breaking said umbilical cord) [117], [129]. For long-time operation wireless power supplies, as on-board fuel tanks, research is still under development, the current research works in the response times of the actuators, because by the action of sprinklers mechanism for fuel injection, they have slower response times than the obtained by using electric motors [109]–[111].

Therefore, it seems that the most convenient snake aerial manipulators are those powered by electricity, however, this implies short flight operations to ensure a thermal rest of the motors or to carry cooling systems as heatsinks or fans (these motors can be optimized such that the same propellers cool them).

On the other hand recent approaches have found new methods as power supplies, for example, and even though that its power efficiency has not yet been studied, the snake aerial manipulator based on regulated hydraulic jets has an immediate application as intelligent or controllable fire hose [44].

Finally, the characteristic that will determine or will help to determine efficiencies and applications is the size of the aircraft. As suggested, some methods for vectorization and power supplies are physically unthinkable for large scale aircraft, while for smaller dimensions and weights, there are more possibilities but more restricted applications (there are more methods but as a consequence of the size there is also less force or mobility to make any possible interaction with the environment or with themselves).

E. DESIGN CONSIDERATIONS OF THRUST VECTORING AND PROPULSION

The following considerations are concerned to the degree of mobility of the entire aerial-structure **Table.5**, which is highly dependent on various thrust-vectoring methodologies (e.g by pneumatic, vacuum or hydraulic main-flow deviation, by main rotor full-body tilting, by propeller tilting with a kind of swashplate, by ailerons, by center of gravity alteration with a mobile-mass, by coordination of multiple propellers among others **Fig. 13**) [66], [67], [75].

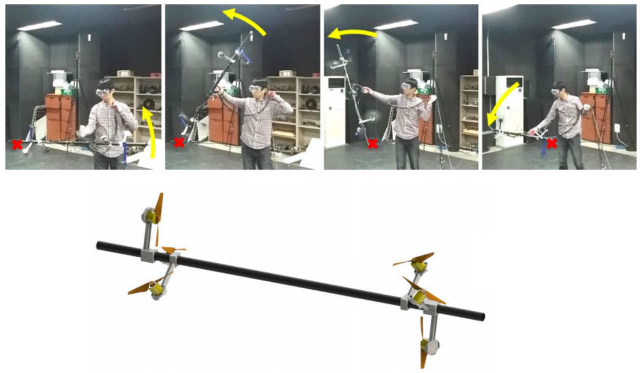

FIGURE 7. Parallel Omnidirectional Aerial Manipulator,Park-2016.

Planar operation this is the basic mode of snake aerial manipulation. The execution of three-dimensional angular movement, falls exclusively into the gripper or final effector. The full structure roll and pitch angles tend to zero, or depend on the trajectories in X and Y for its later stabilization to zero once the trajectories have been achieved [55], [66], [85]. The only feasible independent movements are three-dimensional translations and yaw rotations [55], [85], like in a quadcopter **Fig. 2,5**.

Omnidirectional operation: in this case, the aerial manipulator has total mobility or beyond the planar configuration **Fig. 7,8,11**, the three-dimensional angular movement is independent of the translational and is achieved by one or several techniques of thrust-vectoring applied to each of the propellers or vehicles [39], [70], [78], [130]–[145].

This concept also applies to both parallel and serial aerial manipulators, it is worth to mention that control strategies also change their paradigm. While the objective of the planar configurations is to keep the pitch and roll angles around zero or path-dependant of X and Y movements [85], [146], the goal of omnidirectional configurations is to achieve independence between translational and rotational modes of flight. In this way a remarkable school of control, is the one developed by Taeyoung Lee which is based on geometrical approaches [147]–[150], and the method applicable to aerial manipulators through a kino-dynamic decoupling of the orientational and translational controllers developed by Choi [67] and Lee []94.

Convertible operation: It is convenient to separate the tasks of an snake aerial manipulator into two steps [55], [85], [100]: transport to the workspace (long distance flight) and in situ aerial manipulation (short distance operations). In this way during the transport to the work area, it is desirable to keep the entire structure as some type of long-distance aircraft (airplane, helicopter), and once it arrives to the work

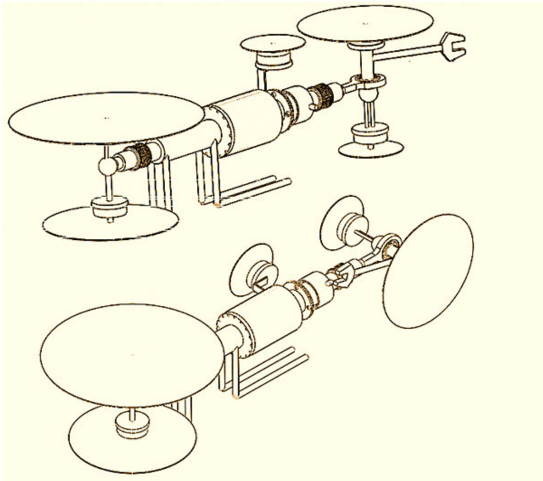

FIGURE 8. Helibot,Tandem and Counter-rotating modes.

area, transform the vehicle into an snake aerial manipulator, shutting down on the way unnecessary engines, reducing with this the power consumption and storing this power for the manipulation phase.

In order to exemplify the previous paragraphs, an aircraft called helibot based on coaxial vehicles, and currently in theoretical development and patenting, will be described.

The helibot is an UAS like-PVTOL or bicopter aircraft [151]–[153] with thrust-vectoring mountings, composed of at least two modules, one is the shoulder and the other the elbow where is mounted a gripper, these modules are coaxial drones each, one with its respective steering mechanism (e.g. a swashplate). In order to allow the transition flight tasks there is an extra propeller which can rotate 90 degrees with a servo system or an outrunner motor in order to use the system as a counter rotating helicopter. Finally, for locking and releasing yaw movements each coaxial UAV has a clutch system **Fig. 8**. It has 7 flight modes.

Serial planar snake aerial manipulator: this mode of operation is a kind of an aircraft-propelled snake aerial manipulator but by using coaxial motors instead of multirotors

Parallel planar snake aerial manipulator: in this mode of operation, the rotation of the elbow is locked by the clutch-system obtaining the coaxial aircraft version of [66] or [24],

Parallel omnidirectional snake aerial manipulator: keeping the elbow locked by means of the clutch and using the steering system of the coaxial motors, it is possible to modify the angles of the propellers and in this way they can generate omnidirectional movement as described in [67].

Serial omnidirectional snake aerial manipulator: the same as the previous one, but by releasing the rotation of the elbow while the clutch is disengaged

Tandem helicopter [99], [154], [155]: by keeping the clutch active in order to block the rotation of the elbow, this mode is achieved by deactivating the secondary counter-rotating propellers in both coaxial aircrafts and leaving the main ones

TABLE 5. Snake aerial manipulators classification based on their degree of mobility.

Kind	Suggested controller design	Main problems
Planar	Classical	Reduced dexterity
Omnidirectional	Geometric	Positive propeller thrust mapping
Convertible	Switched between Classical and Geometric	Positive propeller thrust mapping

(those that are directly linked to the steering system). This mode of flight is useful in the case of bulky or massive systems

Standard helicopter or counter-rotating helicopter [108], [156]–[158]: this mode is achieved by locking the elbow rotation and completely deactivating the elbow drone (gradually or instantaneously according to the scale of the aircraft and the task). After that, by activating the counter-rotating support propeller and placing it at 90 degrees with respect to the ground plane (the elbow drone could also function as a counter rotating propeller)

Airplane: keeping in mind that an steering system based on servomotors for moving the full propeller body could be employed at certain vehicle scales, is also possible to transform all the system from vertical takeoff and landing and use an airplane displacement by changing the variable direction propellers to an angle with a component parallel to the ground(in this case an aerodynamic redesign of the linkages must be developed). The proposed operation will be similar to that of convertible wing UAVs as in the case of a tail-sitter.

Discussion: A classification of snake aerial manipulators based on the way they can move in the space was introduced, this classification is absolutely related with several thrust-vectoring methodologies, but is limited to three categories: planar, omnidirectional and convertible, the main problem here is to select the most suitable way of thrust-vectoring technique for each kind of aerial mobility.

Vectorization goes hand in hand with omnidirectionality, both are the essential elements of this type of vehicles, the first concept as the cause and the second as the effect, but their applications are limited by costs, machinability and physical constraints. It is for example unthinkable to use mechanical vectorization methods to move the full body of a propeller in large-scale vehicles (for this reason it is preferred to redirect the blades of the propellers), however it is a viable technique and also widely used in small vehicles, the reason is that moving such a large propellers turning at high rpms implies moving a large amount of inertia, which is not noticeable or negligible in small aircraft. In this way, although all current projects on snake aerial manipulators are made with mechanical vectorization, it is also convenient to analyze its possible expansion at large scales by fluidic vectorization. Conversely, fluidic vectorization for small vehicles is unfeasible because of the cost and the difficulty of manufacturing miniature pumps and valves.

Another line of action is to design new methods of vectorization such as the carried out by [145], where harmonic pulsation is applied in the rotation frequency of an

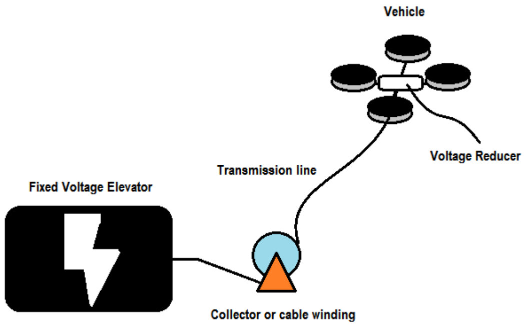

FIGURE 9. **Powerline tethered drone.**

under-actuated propeller, another example is by using the known effects of shape memory of certain materials by electrification or magnetization.

Finally, it should be remembered that these concepts can be extended in application to other work environments such as underwater or viscous places and all the elements or techniques that can be explained or discussed here should be analyzed under operating conditions such that it could be feasible to use them there. It is even possible to design aerial-powered land vehicles [49].

F. DESIGN CONSIDERATIONS ACCORDING TO THE THRUSTER AUTONOMY

Autonomous manipulation: Is that in which the aerial system works by itself, in this case, the autonomous approaches are defined as those where the UAVs or propellers perform, in addition to the transport of the whole system, the totality of the task of manipulation [55] **Fig. 1, 2,5**.

Assisted manipulation: in this case, the tasks of the UAVs and the tasks of the manipulation system are still a coupled type, but auxiliary engines are incorporated as elements of manipulation or force transmission **Fig. 2,6,8** [72].

The drones keep the entire structure hovering and the auxiliary engines modify the position of the UAVs or their propellers in a kind of exoskeleton (e.g. by servomotors), this is useful to separate the execution of tasks for which the propellers possibly do not have enough force or torque. So far and according to our investigation, such an operation is characteristic of the conventional mechanisms of steering of coaxial aircrafts and another small UAVs [76], [140], [153], [159]–[163] and the swashplate-systems of bulky and massive aircrafts [156], [164]–[166].

Discussion: As was proposed, this section talks about propeller task independence, or certain assistance by using position engines like servomotors, this is a classic deal among force, cargo and dexterity.

The purpose of a propeller is to keep an object floating on air, understanding that it will not provide greater lateral forces and moments than thrust of elevation. Therefore, snake aerial manipulators with motorized assistance in the propellers are recommended, notwithstanding the previous line facts, this could be compensated by redirecting the thrust of the propeller through a vectorizer, but since the vectorizer is a auxiliary motorization element the same point is retaken. In this way, at least for the authors, the purpose of an autonomous or non auxiliary motorized snake aerial manipulator is the development of specialized laws of control and the study of phenomena such as turbulence and vortex effects. However, their use should not necessarily applied in force tasks but in mobility and dexterity applications, one of these could be systems able to navigate between windows or pipes without the need for other things than their own propellers.

It should be remembered that each auxiliary motor also represents mechanical and electrical load and in both cases the duration of batteries is reduced or the cost for using power tethered supplies is increased. On the other hand, in the case of the methods based on valves and pumps, the assistance of a motor is questionable and in fact an open question is whether a specialized pneumatic or hydraulic motor is more efficient than the action of a valve or not.

In other words, the use of auxiliary motors to move the propellers is a necessary "exoskeleton" for physical interaction with objects, this allows the designer to assign the elevation, orientation and position task of the snake aerial manipulator to its propellers and the force of action and contact to the auxiliar engines. A very feasible line of research here is that where the auxiliary engines also work as elements of selective damping (i.e. non-passive dampers) or use them as a channel for haptic interaction.

It is also convenient to design mixed systems as for example by using clutches [55], that allow the designer to choose when the performance is assisted or autonomous and also to design fault tolerant controllers to continue using the snake aerial manipulators if one or more auxiliary engines are damaged, this implies underactuated tasks (manipulation) sharing space but different functionality with overactuated tasks (the mobility of the entire aerial vehicle)

III. DESIGN CONSIDERATIONS OF ELECTRONICS, PROGRAMMING AND CONTROL

A. GENERAL UAV DESIGN IMPLICATIONS

Generic software and electronics design implications of UAVs, are collected in [150], [167]–[172].

Each one of the elements described has different operating frequencies, in this way, a real time operating system (RTOS) is required to schedule proper reading, processing, storage, hierarchy and execution, those elements are:

Ways of collaboration, Planning methodologies and Control Techniques:

There are two ways to control a collaborative aerial manipulator, the distributed and the centralized. In the first one is considered the independent control of each vehicle to maintain a pre-established formation by the union of the elements of transmission. To deal with that, methods denominated in the literature as consensus or formation control [173], [174], are used. Here each aircraft must worry about achieving its

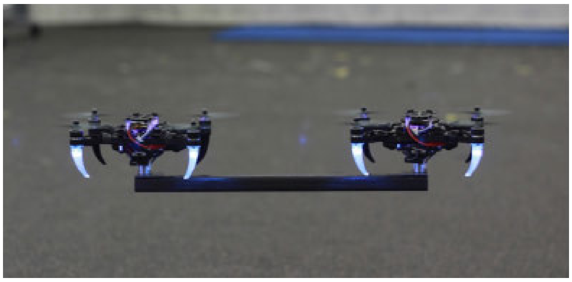

FIGURE 10. Cooperative transportation, Loianno-2018.

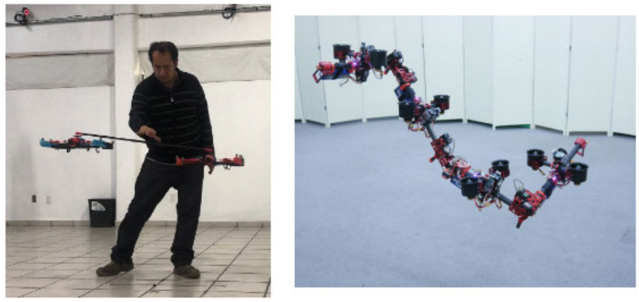

FIGURE 11. Omnidirectional Serial Manipulators, J.Mendoza-Mendoza-2015,M.Zhao-2018.

own position and orientation such that an stable common formation is maintained, similar when two or more individuals move a piece of furniture.

On the other hand, at centralized interaction, the whole system is considered as a single dynamic entity and each multicopter or propeller is modeled as a thruster that generates torques and forces with a common effect in a virtual point of the system called center of gravity, center of masses, geometric center, center of flotation, etc, It is said to be virtual, because this point could or could not be physically placed over the system depending on its geometric configuration, inertial properties, as well as rotational and translational velocities and accelerations achieved. In the centralized way of flight, all aircrafts must worry about achieving a common dynamic and not just a geometrical formation [23]. Even more, most of the approaches are concerned with obtain propeller arrays called allocation matrices [150], [175].

Concerning the ways of cooperation, there are also flight modes to achieve them, also known as planning methodologies. Using drones terminology, and the distributed way, a cooperative aerial manipulator can be programmed as this example: an aircraft or propeller must act as a waist having to maintain a fixed mode of spatial and rotational location by using loitter, guided, post hold, etc flight modes, and the multicopters or propellers that are part of the arms should operate in althold, sport, stabilize, or similar flight modes, because they must maintain their height and orientation but their planar position is variable [176]. On the other hand, in the centralized manner, each multicopter changes its own mode of operation continuously, adapting by itself according to the condition of mobility that is required.

According to our investigation, all the flight modes are variants or combinations among the next three kinds:

1 Almost pure translational approaches: In spite of being complete dynamical approaches, they focuses on the postulate of bringing the aircraft angles and their respective angular velocities to a zero reference (except for the yaw angle). The main objective is to achieve smooth translational movements. At present, they are the most extensive methodologies for UAV controllers [146], [177]–[179]. They have application in snake aerial manipulators take-off and landing phases (see forward sections). Their basic control tools concerning with nonlinear standard control can be found at [180], [181].

2 Kinodynamic approaches: They are relatively new approaches [67], [94]. Currently they are based on backstepping techniques, and the idea is to disengage translational and rotational models, giving dynamic quality to the translational model and quasi-static character to orientation. They could find their application during the aerial manipulation phase (look at next sections). Their control foundations are related with nonlinear backstepping and the references about can be found at [182], [183].

3 Geometric approaches: Those approaches are also fully dynamical, but the aircraft orientation is designed to achieve rude, complex, aggressive and acrobatical movements [17], [30], [147], [184]. They can be really useful at the transformation phase, and long-flight to the workspace phases (see forthcoming sections). Their elementary control design concerning with nonlinear geometric control can be found at [148], [149].

Finally there are control techniques, each flight mode can achieve a task, through a huge variety of existing control techniques, from a simple PD to a neuro-fuzzy control. For example, a loiter mode can be achieved by using a PID control or in the same way by using intelligent algorithms or sliding modes. The effect of the control technique employed is not in the task but in the performance of the task (faster, more violent, softer, more natural with respect to a living being, optimal in energy consumption, optimal in the runtime etc) [178], [185]–[190].

In summary, the operation of a collaborative aerial manipulator is a choice between two ways of vehicle collaboration, even their combination: centralized and distributed. Where each vehicle operates with a considerable variety of flight modes (loitter, guided, pos hold, acro, etc) and also each flight mode is achieved through a variety of control techniques (PD, sliding, intelligent, fuzzy, etc.). This way, the final result of operation has a wide range of algorithms whose selection depends on each user and the desired application. This will determine which cooperative way, flight method and control technique to use or maybe a mixed sequence of operations (as in a blender keypad or in an car gearbox)

Reading of orientation, planar position and altitude sensors: The way to do this is by using IMUs, magnetometers, barometers, accelerometers and GPS units, all of them operating with different communication protocols and sampling frequencies, in some cases by design of the sensor and in others by priority of the measurement [191], [192].

Command to the propellers and execution servomechanisms: This consist in the direct propeller control (e.g brushless motors) and also in the use of auxiliary motors (e.g servomotors) for performing secondary tasks during the flight. For example, camera stabilizers, ailerons and mechanisms of thrust vectoring [75], [141], [144]. In general, propeller action must be faster than auxiliary motors (e.g 490Hz and 50Hz respectively)

Feedback control of attitude, planar position and altitude: In general, UAV control is divided into these three modes of execution, the priority is to maintain a height of operation also known as hovering, the intermediate priority range is to control the orientation or attitude of the aircraft and finally its planar position, also known as steering [76], [108], [146], [150], [160].

Image Processing: This task becomes necessary in conditions where satellital positioning are not available [9], [169], [188], [191]–[195].

Internal communication of data: This is usually performed through serial topology buses. It is the way in which the data of the sensors are shared and processed towards the main processor and at the same time, the way in which the processor decides how to write to the actuator systems.

Storage data and telemetry: It is the way in which the system stores and shares the data among flying units for their use and interaction including the wireless communication among the aircraft.

Reading of remote control commands: It consists in reading the remote control units, which establish the link among the aircrafts and the ground base. As can be seen, together with the telemetry, there are two different wireless modules. The challenge here is to ensure that they operate accurately at different frequencies and also with multiple channels.

Reading of analog and digital ports: It consists of the habilitation, interaction, reading and writing of analog ports, and general purpose input / output digital ports.

Signal filtering: The addition of noise to the UAVs is implicit with the mechanical vibration of the motors and their electrical interaction with the environment. In this way, a filtering algorithm is necessary, which is usually done by means of Kalman techniques.

Sensor fusion: When the task environment changes constantly, it is necessary to use a combination of geolocation sensors. An example is between tasks where the drone passes from an external environment to an internal and a switch between an artificial vision system and a GPS must be done.

Tasks planning: It is necessary to obtain velocities and acceleration data for smooth movements, and also there are authors who indicate and show that it is necessary to include the snap (the acceleration second derivative) [184], as the sensors are restricted to read velocities, positions and accelerations, and in most of the cases this is done partially or inaccurately. It is necessary to include estimators that involve mathematical observers, neuronal estimation, fuzzy estimation and also algorithms of trajectory planning. All these operations implies the need for developing even better matrix optimization algorithms.

Real time task priority: Given the different operating frequencies of the sensors, actuators, systems and control loops, it is necessary to prioritize the execution of tasks, those of higher priority are usually the individual motor control, the attitude control, and the altitude reading; the intermediate ones are those of planar reading, and finally in a lower range are the tasks of serial communication, reading of remote control commands and storage of flight data. On the other hand within the priorities related to control, the hierarchies are attitude, altitude, steering and three-dimensional trajectory. For our purposes is enough with the capabilities of the Pixhawk autopilot which has an RTOS system able to assign priorities and execution times. However, in the case of designing a new flight controller or task, it is necessary to establish a real time system scheduler for the correct execution of the desired events.

Discussion: This section has dealt with various problems commonly found at UAV designing, with emphasis on real-time task scheduling and planning methodologies. Addressing generalities about the individual engine components of a snake aerial manipulator. In the particular case that they are composed of multicopters, the relevant difficulties have been already investigated and developed. However, it is insisted on the restrictions of a team of aircraft with morphing capabilities and interdependent physical linkages, so there are 4 priorities and subjects of research:

Reduction in the weight and size of the sensors and actuators: while using just an aircraft maybe such parameters are not so relevant for the execution of a task, but as in this case an aircraft team and their components are required, the weight and volume is multiplied, reducing operating times and demanding better and huge power supplies.

Reduction in their electrical consumption: this point is linked to the previous paragraph, although it could be independent, that is to say, while the motors do not consume so much power, it is possible for a system with greater size and weight to have a longer duration flight. Even, it could be feasible to reduce batteries or other power elements and just to transport the required equipment.

Better real-time processing systems: it is known for example, than certain processing units, have difficulties in order to control a quadcopter, so pretending to use them with six or more engines means migrating to more expensive or not so intuitive equipment. This way, it is necessary to develop more technology in autopilots or development cards that allows at least to 10 brushless motors, a minimum of 6 servomotors, a minimum of 4 analog inputs, a set of GPIO ports for digital inputs and outputs, and wireless and wired reading and writing with at least 2 serial ports to operate at the same time, considering also to store data flight as, position and orientation while filtering at least 8 signals (orientations and altitude plus their derivatives) and carrying out multiple calculations. As already indicated, autopilots such as the Pixhawk [167] are quite versatile, but they could deal with a limited number of engines, and in the case of a snake aerial manipulator, they become overdemanded.

Finally it is ideal to develop mixed or intelligent control schemes that determine when an action is more relevant than others for each one of the engine elements that form part of the general structure, and that are able to identify certain parameters such as the location of the gravitational center (or any other). In addition, it is also necessary to consider the execution of the global task and the effect on each individual engine element (as already said, a controller suitable for knowing how to decide between the hierarchy of manipulation, free flight, take off, transformation or landing tasks and their corresponding subprocesses). Also is ideal to develop controllers that do not require biasing or positive translation and work directly on the positive space of the actuators (which implies the use of numerical methods, and computational and optimization algorithms instead of classical fully mathematical control schemes) [34], [53], [87].

B. DESIGN CONSIDERATIONS OF FLIGHT TO THE WORKING AREA AND TRANSFORMATION SEQUENCE

1) COORDINATION AND PARALLEL PROGRAMMING IN PHYSICALLY RESTRICTED FLIGHT OF MULTIPLE UAVs

This can be centralized if a single processor is used and the system it is viewed not as a set of collaborative UAVs but as a set of propellers with full-body interaction. In this case a novel and complex model of equations is needed and a first approach was recently developed by [39], [55], [70], [85]. On the other hand, the flight can be decentralized (multiprocessor) if each UAV uses its respective processor and in this way, the whole system is viewed as a coordinated group of autonomous UAVs. The Pixhawk autopilot is capable of performing both modes of operation with aerial manipulators having up to 8 propellers (i.e 2 quadrotors or either 4 coaxial aircrafts or maybe eight single-copters). The problem of centralized operation is the surcharge of data-processing and control tasks for a single processor unit, and also the modeling and control. The main problem of decentralized control is regarding with coordination and consensus [173], [174], [196]–[199].

2) ONLINE DISTURBANCE ESTIMATION

Although the whole flight has disturbances, one of the critical parts is that of long duration movement or the aircraft mode, where it becomes necessary to estimate and counteract the effects of wind and pressure just to mention the most common perturbations. This is computationally complicated at open air because the wind represents a turbulent flow and its variations are modeled with partial differential equations that impacts over a beam (the aircraft is considered as a beam with multiple supports on their propellers). A more feasible option is to design robust flight control schemes [200]–[206].

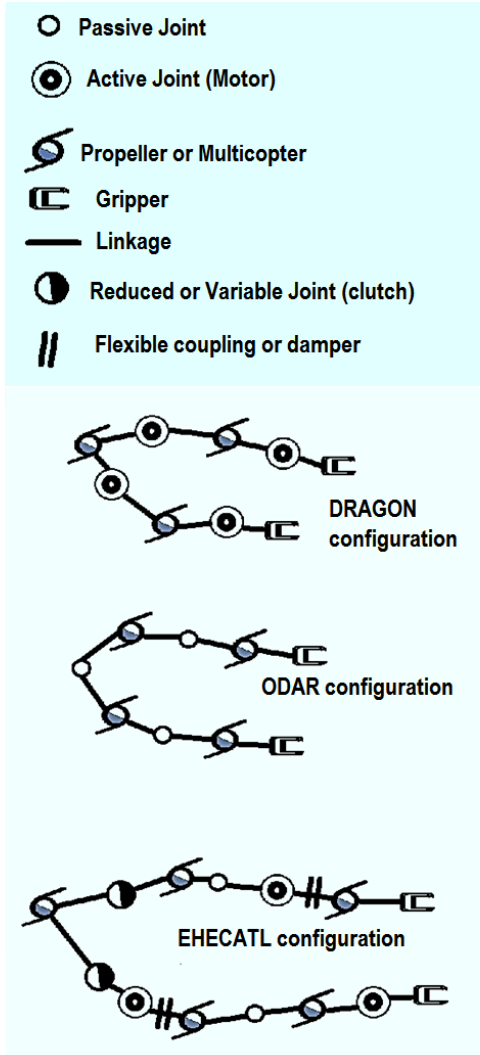

FIGURE 12. Aerial manipulators, waist configuration with at least two arms and a reference point.

3) ESTIMATION OF INERTIAL PARAMETERS AND CENTERS OF MASS OR GRAVITY

As these parameters are geometrically dependant on the aircraft shape, some algorithms for their calculation are described in [207]–[213], these algorithms involve calculating the inertial variations on each UAV and / or intermediate points of design, and transferring this data to a processing center, where the equivalent inertial point and centers of flight are calculated. This computationally implies the sending of simultaneous sensor data and also sending by wire or wireless protocols ensuring the correct transfer of data (for example the checksum protocol in the more basic level of verification).

4) TRANSFORMATION SEQUENCE

At this point, a method is required to transform the structure from an standard and coordinated flight mode (for example an helicopter or a tailsitter) to an aerial manipulator. The software implication is the right sequence of switching

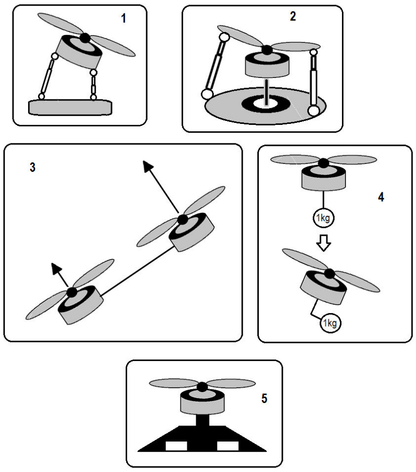

FIGURE 13. Common mechanical thrust-vectoring methods, 1 Full engine movement, 2 Propeller deflection, 3 Multiple engine interaction, 4 Center of mass deviation, 5 Flaps or main flow deviation.

frequencies of the engines, which must be turned off and on in a precise order as the full system keeps hovering in the air (helibot patent pending MX/a/2016/014595) see also [55], [72] **Fig. 6,8**.

Discussion: this section discussed about the main problems related to the tasks of free flight maneuvers to the workspace and the transformation sequence. The challenges related to cooperative control were highlighted, including the parameters and disturbances estimation either by centralized or decentralized modes. Finally the open problem of transition between the free flight mode and the aerial manipulation mode was stated.

As indicated in the previous sections, it is convenient to investigate the boundary conditions between the free flight and the manipulation flight, because said transformation stage and in general the manipulation stage, entails adverse aerodynamic effects. In this manner, concerning to the topics referred into this part of the article, it is convenient to develop sensors or mathematical estimators (observers) to recalculate the position and orientation of a reference point affected by these perturbations, not considered nonlinear dynamics, and the effect of the trajectories (the center of mass, the center of gravity, the center of floating, etc., or, several of these reference points).

On the other hand the coordination of the individual propulsion elements, implies the development of more efficient communication protocols in order to deal with data loss, and to incorporate selective or intelligent assignment of the event-based communication (for example by defining a leader according to whether or not there is a lot of wind concentrated at a specific part of the snake aerial manipulator), etc.

On the side of the controllers, developing tolerant schemes to the failure of one or more propulsion aircraft are needed(there are already some schemes for multicopters in the case of failure of one or more propellers [214]–[216], but in this case, the designer must remember that the thrusters could be full aircraft and not just individual propellers)

Also is needed the development of sensors capable of measuring planar positions and altitude with an acceptable resolution. This sensors should be reduced in noise and drift effects. This is mentioned because these problems are already present and they are really important in a single vehicle, in this way, they are increased while using a cooperative system of aircraft. Additionally, many of the experiments currently carried out with the exception of LASDRA [54], were done in the laboratory, under the comfort and reliability provided by external motion capture systems, but research must be done in the case of wanting to use snake aerial manipulators outdoors. It could be feasible to continue using external sensors, but by employing laser location systems, or specialized ultrasonic triangulation, or by developing passive or active ways of noise suppression so that the on-board measurements include less of the aforementioned inconveniences (here you could find specialized artificial vision algorithms, however, and since they require high processing, the reduction of weight, size and electrical consumption of these processing units, remains as a problem to be solved or improved)

C. TAKE-OFF AND LANDING DESIGN CONSIDERATIONS

The take-off is one of the simplest but dangerous part of the operation of an aerial system, this is because there is a bias in which the propellers turn on but the system does not get elevation. Even each propeller has its own starting value in dependence on the mechanical balance of the whole system or the adequate balance of each propeller. The software implication in this part is to ensure an optimal starting value for all the system without reaching the shutdown level, and also to establish a value where the system changes from one phase to another phase of operation.

The landing is another simple but significative operation, consisting on gradually turning off the motors but taking care that they stay in their mode of thrust support (that means,that they have enough force to ensure that the system does not fall). As it has been said, motors do not have a homogeneous bias, so orientational control takes higher priority in both modes of operation (it is the way to compensate the irregular bias of each propeller) and also in consequence is crucial to keep the sensors and actuators working in precise times that ensures a smooth and non-destructive landing or take off.

Discussion: It is well known that most aircraft accidents occur in this parts of the flight, and in the case of these snake aerial manipulators this is not the exception. Especially by considering those whose engines are multicopter teams, where this aircraft must not only worry about take off and landing themselves but also of the whole structure that they integrate, this implies a high precision individual and cooperative control of the attitude and altitude, then it is convenient to develop research in scenarios where:

The entire aerial manipulator system has an attitude with respect to the surface with angles equal to or tending to zero, but individual aircraft do not (ie slopes or irregular terrain).

Here is needed research on active control methods or passive landing (landing gear design for example) [217].

Take-off algorithms, as it was said, the propellers in general do not have immediate reversibility, so at the beginning of the snake-type aerial manipulation, the take-off was done with the aerial manipulator pre-held by a human or supported on stilts [53].

Like in many previous points, fault tolerance algorithms in the case that one or more propellers are burned or destroyed, are needed

Given that one of the problems is related with ''immediate'' or faster reversibility, it is appropriate to design thrust vectoring methods that allow or emulate this reversibility (as in the case of airplane braking by reverse thrust used in the turbines of passenger aircraft).

D. AERIAL MANIPULATION DESIGN CONSIDERATIONS

1) RESTRICTIONS ON THE ROTATION OF PROPELLERS

Once in the phase of aerial manipulation, three important computational implications arise, the first one is concerned to the rotation of the motors, this means that while the control can reach positive and negative bounds, some aircraft like multirotors require that their propellers do not change their preset direction of rotation in order to avoid effects of selfrotation, this is seen as an optimization problem and is described in [67], [70], [87]:

However, when it is possible to change the sense of rotation of the propellers, it can not be performed arbitrarily and follows negative resultant compensation procedures, one way is to add an additional motor that will counteract vectorially all the negative moments and forces generated by the rest of the thrusters [69].

2) ONLINE CONTROL CALCULATION AND HIERARCHY OF CONTROLLERS

The second consideration is to recalculate the control, and as it was said, this is divided into three categories, hovering, attitude and steering. However it is required to know in which situation it is appropriate to give more importance to one over the others. It is believed that the most important controller is the one related to the altitude, but paradoxically during the drone takeoff and landing, given the inequality in the activation bias of the thrusters, the most important variable to control becomes the attitude. Another example is in acrobatic tasks and aggressive maneuvers [147], [184] in this case it must be discerned and designed if the trajectory task has priority over the conservation of the angle or over the planar position [218].

3) OVERACTUATION OPTIMIZATION

Overactuation means to have more actuators than degrees of freedom, in this case the matrix that transfers the 6D cartesian control (3 dimensions of translation and 3 of rotation), must be transformed in order to speed-controlling each propeller, in this way, optimization methods such as those based on pseudoinverses are needed, and also this optimization must consider the restrictions described in the preceding paragraphs.

Discussion: when an aerial-arm robot is in the manipulator mode three problems related to motor operation arises: Hierarchy of controller in order to determine automatically which task is more important according to several situations of interaction (hovering, attitude or manipulation). Propellers sense of rotation restriction, where certain approximations have been made but they are not applicable to massive or bulky aircraft because of the implicit risk in changing the rotation of the propellers, and also the optimization problem if it is pretended an unidirectional thrust [87].

As indicated, this is the most complex mode of operation, since it implies the aerial mobility of a structure in variable configurations, many of which are not aerodynamically compatible, and with the risk to originate situations of vortexes or induced turbulence, in this way the investigation in this regard is suggested as follows:

Creation of simulation software and verification of vortex and turbulence conditions that should preferably be corroborated into wind tunnels. This software could help to a better development of control laws avoiding aerodynamic singularities

Sensor implementation to measure the effects of transmissibility, dissipation and efficiency of velocities, movements and forces, this could help to know the degrees of manipulability and dexterity

Create a research line on non-cartesian kinematics and dynamics in the case of snake aerial manipulators powered via tethered sources. For example, spherical spaces, having as a radius and reference angles the length of the power supply cable and the angles that this cable form with the plane where it is anchored, and similarly to develop compatible controllers with the aforementioned task space [219].

Determine the dynamical alterations suffered by using the different engine methods and indicate a performance index among the aircraft-team engine, the propeller-team engine and the set of valves and pumps engine.

Verify the effect of the previous points by using turbines. This could open the feasibility of spatial applications, but a radical change of behavior could be seen by the fact that the turbines unlike the propellers are designed to provide negligible torque compared to the thrust. This way the use of turbines would be more similar to the snake aerial manipulators based on valves and pumps.

Determine the working conditions in which a snake aerial manipulator is superior, inferior or coincident in performance with respect to the work that could be done with a classic aerial manipulator.

IV. CONCLUDING REMARKS

This document showed the most frequent mechatronical implications found in the design of snake aerial manipulators, this information was presented to the reader as a set of modules to consider and open problems to be solved if it is intended to perform coordinated and coupled aerial manipulation. Each section was accompanied by an extensive and informative discussion about the main research problems to be carried out, and when possible, the suggested hints for their resolution.

As was indicated, these are robotic arms made with aircraft (or propels) interconnected with each other and whose immediate applications are: design and test-benches for reconfigurable robotics, design and tests-benches for continuous robotics, test-benches for components of flying humanoids (arms and legs for example), test-benches for specialized controllers based on computational algorithms, numerical methods, optimization algorithms, simultaneously overactuated and underactuated systems (in reference to the task executed, for example simultaneous hovering and manipulation), aerospace applications (by means of turbines), test-benches for new thrust vectoring systems, and finally their corresponding extension to non-flying systems with the same configurations (aquatic snake manipulators for example)

For didactic purposes and from the computational and mechatronical points of view, this text was divided into two main sections dedicated to hardware, as well as electronics and software. Hardware section covered topics about structural dynamics, aerodynamics, power and energy, propulsion, thrust-vectoring and levels of autonomy of the propellers and the individual aircrafts. Electronics and software section offered a compilation based on the current state of the art and our own experience on computing, use of sensors, control methods and flight schemes. Also the main components of an snake aerial manipulator were presented along with their applications and drawbacks, their current global projects and their relation with classic aerial manipulators.

In summary, a survey on the design of different types of snake aerial manipulators was carried out, UAS, whose research is in huge growth and investment despite the short time of development of such technology. Partially developed topics were highlighted, some of them even with unclear results in this area of the research, these hints could be considered as future directions for their investigation. Examples are: robust control schemes of centralized and decentralized computing for their implementation in real time operating systems, techniques for calculating variable centers of gravity or mass in morphing-shape aerial-structures, energy and power consumption and their consequent need for researching on internal combustion or alternative methods of high density of power and energy, the creation of thrust-vectoring methods for huge size or massive aircraft, the development of fault tolerant schemes of control in the case of motor damage, and the comparative analysis among different kinds of snake aerial manipulators and classic aerial manipulators in order to determine their degree of efficiency and utility.

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