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Integración de los modos de locomoción terrestre y aéreo en sistemas robóticos bioinspirados

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Presenta
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Integration of aerial and terrestrial locomotion modes in a bioinspired robotic system

Thesis

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Presents
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1. Abstract

In robotics, locomotion is a fundamental task for the development of high-level activities such as navigation. For a robotic system, the challenge of evading environmental obstacles depends both on its physical capabilities and on the strategies followed to achieve it. Thus, a robot with the ability to develop several modes of locomotion (walking, flying or swimming) has a greater probability of success in achieving its goal than a robot that develops only one.

In nature, Hymenoptera insects use terrestrial and aerial modes of locomotion to carry out their activities. Mimicry the physical capabilities of these insects opens the possibility of improvements in the area of robotic locomotion. Therefore, this work seeks to generate a bio-inspired robotic system that integrates the terrestrial and aerial modes of locomotion.

The methodology used in this research project has considered the anatomical study and characterization of Hymenoptera insects locomotion, the proposal of conceptual models that integrate terrestrial and aerial modes locomotion, the construction of a physical platform and experimental testing of the system. In addition, a gait generation approach based on an artificial nervous system of coupled nonlinear oscillators has been proposed. This approach has resulted in the generation of a coherent and functional gait pattern that, in combination with the flight capabilities of the system, has constituted an aero-terrestrial robot.

The results obtained in this work include the construction of a bioinspired physical platform, the generation of the gait process using an artificial nervous system and the experimental tests on the integration of aero-terrestrial locomotion. This research project led to the production of a journal paper and a divulgation one.

2. Introduction

This work arises from the limitations of robotic systems restricted to a single type of locomotion and is motivated by the opportunity to emulate multimodal navigation systems of hymenoptera insects as a path to transcend these limitations. The main problem addressed in this research project is to integrate the modes of terrestrial and aerial locomotion into a zoomorphic robotic system.

In the field of robotics, the shortcomings of the existing machinery and tools are a permanent motivation for the seeking of improvement possibilities. For example, aerial robots, despite having achieved social impact due to its numerous applications, still show multiple limitations in terms of dexterity and mobility that represent improvement opportunities [1, 2]. In terrestrial robotics, the systems driven by legs have shown dexterity when navigating in closed and rugged environments [3, 4], but show deficiencies to reach objectives on high ground.

A paradigm for addressing robot design problems is biomimicry. This work strategy is based on the imitation, learning or copying of certain attributes present in nature as a path to solve technological problems [5]. Under this scheme, it is possible to propose solutions to the current limitations of robots, such as locomotion and navigation, based on the methods developed by evolution.

In nature, insects of the order Hymenoptera, a group to which bees, wasps, bumblebees and ants belong, are characterized by highly developed navigation skills. The motion performance of these insects is mainly due to the multifaceted and intrinsically multimodal nature of their locomotion. This multimodal locomotion strategy integrates the ability to cover large spaces by aerial locomotion, i.e. flying, with the virtues of the arthropod terrestrial locomotion for the displacement in narrow environments. Therefore, in order to solve locomotion problems and to enhance the skills of robotic navigation, Hymenoptera insects are good candidates for mimicry.

This research has the goal of integrating two modes of locomotion, one terrestrial by legs and another aerial based on rotating propellers, in a robotic system under a design approach based on the mimicry of insects of the Hymenoptera order. This research does not formally contemplate the applications that may be given to the final generated prototype.

This document is organized as follows. Section 3 corresponds to the research proposal and addresses the set of theoretical concepts that support this work. Some concepts about robotics are introduced along with some notions about Hymenoptera insects, while presenting a structured review of those technological developments that constitute the state of the art. In addition, the hypothesis, objectives and methodology used in this work are addressed. Section 4 introduces the scientific article entitled “Nonlinear oscillator-based gait generation for a novel aero-terrestrial bioinspired robotic system”. This paper focuses on the proposal of a physical-experimental robotic system with the ability to fly and walk. A strategy for the coordination of the gait, based on a network of non-linear oscillators bioinspired by the nervous system of insects, is presented. Finally, Section 5 covers the general conclusions and a reflection about future work.

3. Research proposal

3.1. Bibliographic review

3.1.1. Theoretical framework

This section introduces the most relevant concepts used throughout this research. First, basic concepts of robotics and some general classifications of robots are introduced. Next, a section is devoted to the explanation of the area of biorobotics and the locomotion systems used by mobile robots.

Other issues related to robots are also addressed, such as the environments in which they operate, as well as the sensors that make them up. Finally, a section is devoted to relevant concepts about Hymenoptera insects.

Robotics and robot classification

Robotics is a widely applied scientific discipline in the fields of industry, education and research. The ISO (International Organization for Standardization) defines a robot as an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks" [6]. These can be classified in two main categories:

a) **Industrial robots.-** They are reprogrammable multifunctional manipulators with 3 or more degrees of freedom, whose objective is to perform tasks such as positioning materials, parts, tools or special devices through defined paths [6].
b) **Mobile robots.-** They are autonomous systems with the ability to change their position within their work environment without, necessarily, being operated by human beings [7]. Autonomy is an inherent characteristic of these systems and their research efforts focus on problems such as route planning, perception and navigation [8].

Based on their degree of autonomy robots can be classified as follows:

c) **Teleoperated robots.-** These systems are remotely controlled by a human operator, which performs complex control tasks, through a computing device [9]. These robots can have manipulative arms and certain degree of displacement capacity.
d) **Semi-autonomous robots.-** They are characterized by working on repetitive tasks within structured industrial environments with a limited perception [3]. In addition, they require human supervision to perform their tasks.
e) **Autonomous robots.-** This kind of robotic systems execute their tasks with minimal or no intervention of human beings [8].

Biorobotics, biomimetic and zoomorphic robots

The term inspiration could be defined as “someone or something that gives ideas for doing something” [10]. Nature, in its variety of biological systems, presents solutions to the problems addressed by robotics, motivating it to consider design, morphology or control alternatives. Thus, biorobotics has emerged as an area that takes advantage of biological systems and is inspired by its operating principles for robot design. The robots developed under this premise are known as bio-inspired or biomimetic robots [5, 11]. This mimic paradigm can manifest itself in different areas of a robot, these areas can be physical (mechanisms, morphology, structures) or computational (software). Robots that mimic biological systems in tangible aspects, specifically animals, are known as zoomorphic.

Locomotion systems for mobile robots

The word locomotion expresses the idea of having capability to move from one place to another [10]. For a mobile robot, the locomotion system provides the ability to change its position within an environment. The choice of a locomotion system will depend mainly on the type of terrain on which the robot will navigate and the type of tasks it will perform. In addition, the locomotion system depends on other aspects such as energy expenditure, control or mechanical complexities [3].

According to the environment in which they work, mobile robots can be classified as terrestrial, aquatic or aerial [12]. A different classification, which should not be confused with the previous one, is given by the amount of locomotion systems present in a robot. In this way, a robot can remain in the terrestrial category and have two locomotion systems, for example wheels and legs.

Robots that only use one type of system for their movement are known as mono-modal locomotion robots [12]. On the contrary, those robots that combine two or more locomotion systems for mobility are known as multi-modal locomotion robots or simply as hybrid robots. This last design paradigm arises from the need to improve characteristics such as adaptability to the environment, versatility in locomotion and operational flexibility of the robot [13, 14].

Land mobile robots

Land mobile robots and UGV (Unmanned Ground Vehicle) are characterized by performing their tasks with minimal intervention of human beings supported on some surface, mainly the ground. These can be classified according to their locomotion system in the following categories [3].

a) **Wheeled robots.-** Robots based on this type of locomotion are used in environments with relatively flat surfaces and are popular due to their simplicity, efficiency and intrinsic stability [15].

b) **Tracked robots.-** This type of robots, commonly used on irregular terrains, are conformed by a pair of sliding actuated tracks which are responsible for propulsion and orientation [8].
c) **Legged robots.-** They have a locomotion system based on open kinematic chains that support the body using only discrete points of contact with the ground. These robots are especially capable of crossing terrain with obstacles [7, 8].

Aerial mobile robots

Aerial robots and UAV (Unmanned Aerial Vehicles) evolve in the air as work environment and do not need to rest on any surface to move. They are also characterized by having a morphology similar to small airplanes or helicopters [2, 16]. Developments in recent decades have resulted in a variety of configurations and morphologies in aerial mobile robots. According to their morphological characteristics, these can be classified into the following categories [17].

a) **Fixed-wing aerial robots.-** They are unmanned airplanes that need to make a run or be catapulted to get their take off.
b) **Rotating-propeller aerial robots.-** They are based on propellers with the particularity of performing vertical take-offs. There are single-rotor, multi-rotor, coaxial or tandem rotors. They have greater maneuverability than fixed-wing ones.
c) **Robotic airships.-** Their morphology resembles a balloon and they are characterized by being light and making long flights at low speeds.
d) **Flapping-wing aerial robots.-** They have flexible or convertible wings, similar to those of birds and insects, which allow them to take off vertically or glide.

Aquatic mobile robots

The mobile aquatic robots move above or below the water and are equipped with specialized sensors for the environment such as sonars or radars. They arise from the interest in inspection, data collection or maintenance applications in places of difficult access for the human being [8].

Work environments for mobile robots

The environment make reference to a place or surroundings in which a person or animal performs its activities [10]. This definition can be extrapolated to the field of robotics to indicate the environment in which a robotic system operates. It is necessary to define the types of environments according to their relationship with the robot and its degree of certainty. Under this condition the types of environment are classified below [18, 19].

a) **Structured environment.-** This is fully defined for the robot and whose characteristics have been adequating to benefit its operation. They are predictable and invariant.

b) **Semi-structured environment.-** It is characterized by knowledge and partial adaptation of its characteristics. The robot knows in advance and with certainty the behavior of a few aspects of the environment, but unforeseen elements may arise.
c) **Unstructured environment.-** The robot has a minimum knowledge of its environment, manifesting itself in high uncertainty in the variables that characterize it.

Sensors

In the field of robotics, a general classification of the sensors arises with reference to the origin of signals to be measured, in this sense the sensors can be proprioceptive if they measure variables within the same robot or exteroceptive if their function is to get data from the environment [15].

Regarding the energy requirements, the sensors can be divided into active sensors if they need an external power supply for its operation or passive sensors if they can work without one. In addition, if the measured value can be represented unambiguously for any moment in time it is said that it comes from an absolute sensor, otherwise, if the measured value only indicates the magnitude change of a variable for a certain period, it is said that a relative sensor has been used [8, 15].

There is a set of characteristics that determine the performance of a sensor and serve to evaluate it. One of these characteristics is linearity, which indicates whether the correlation between the measured physical variable and the values obtained at the output of the sensor has a linear relationship or not. The smallest value in the measurement variable that the sensor can acquire is determined by its resolution, precision is the dispersion of the values obtained in different measurements, while the ability to perform measurements of a variable with the same states obtaining the same results is known as repeatability. Sensitivity refers to the ability of the sensor to detect small variations in the measured signal. Hysteresis is a difference in measurements when they are performed with the variable increasing or decreasing [8].

Most sensors can be classified according to the nature of the measured variable as follows [8, 15]:

a) **Linear and rotational displacements sensors.-** Potentiometers, optical encoders, magnetic encoders and resolvers.
b) **Linear and angular speed sensors.-** Tachometers, tachogenerators and gyroscopes.
c) **Presence and proximity sensors.-** Limit switches, inductive, capacitive, Hall effect, optical and ultrasonic. Force and torque sensors such as strain gauges.
d) **Navigation sensors.-** Compasses, magnetometers, accelerometers, IMU (Inertial Measurement Unit), GPS (Global Positioning System) and cameras.

Hymenoptera insects

Insects belonging to the Hymenoptera class include varieties such as ants, bees, wasps and bumblebees. Despite presenting variations in size and shape, these insects are characterized by maintaining a common morphology which consists of: two pairs of membranous wings, mouth structures of the chewing and licking type, segmented antennas and poisonous stingers in the most evolved groups [20].

Their locomotion systems are formed by six legs which these insects use to move on almost any surface, and their wings by means of which they can flee from threats or move to look for food. They stand out for their social capabilities that allows them to meet in large colonies in order to carry out productive activities and ensure their survival [20].

3.1.2. Background

Locomotion in robots and animals

In both natural and robotic systems, the form of locomotion defines the level of performance when moving in a certain environment and is a success factor in tasks that require changing from one position to another. In nature, millennia of evolution have resulted in a vast amount of solutions to the problem of locomotion in multiple environments, a subject of study by biologists and naturalists.

Biorobotics emerges as a synergy between biology and robotics that benefits both areas; in robotics, it provides inspiration models for biomimetic designs [14, 21, 22], while in biology it contributes with devices capable of emulating the behavior of animals that allow them to approach studies closer to reality [11, 12]. In order to generate bioinspired models, it is necessary to carry out studies on the biological system to be emulated, so that its behavior, advantages and limitations can be characterized. Fulfilling the previous premise, in robotics the problem of bioinspired locomotion has been addressed primarily with the study of locomotion in biological systems.

Lock R. y Vaidyanathan R. [12] conducted a study from a structural approach on the mechanisms of locomotion in various biological systems to determine their individual and group performance levels. This work shows the tendency of biological systems towards multimodal locomotion, qualitatively addressing the various terrestrial, aerial or aquatic locomotion systems present in animals according to their membership in the classes: bird, reptile, amphibian, fish, mammal, arthropod or cephalopod.

Authors in [12] propose and evaluate a set of elements present in aerial, aquatic, underwater, terrestrial and underground environments that affect performance in animal locomotion. Some of these elements are resistance to movement, ability to stop and passive support of the body in the environment. This shows the contrast between the different characteristics and complications in each environment, justifying the presence of multiple locomotion systems in a wide range of animals as a way to overcome these complications.

In biorobotics, frequent questioning arises regarding which animals have locomotion systems with a higher level of performance. Also in [12] this question is addressed by grouping animals into three categories according to their mode of locomotion. The first group includes aerial and terrestrial animals, the second group aquatic and aerial animals while the third group considers terrestrial and aquatic animals. The research shows that birds and insects are the animals with the highest locomotion abilities for the first two groups, while reptiles and mammals are the most prominent in the last.

Similarly, Ijspeert A. [11] analyzes the problem of locomotion from a functional approach, starting by classifying the forms of displacement according to the way they run, swim, fly, craw, climb and walk. This study emphasizes the use of robots for the emulation and analysis of locomotion in biological systems.

Swimming, as a mode of locomotion, shows a strong relationship with the nature of the environment in which it is performed. Results indicate that complex interactions of water movement with the deformable and undulating nature of swimming are responsible for the level of performance achieved. The effects of these complex interactions are manifested in the so-called periodic vortices of Karman. These vortices are produced by the wave movement of the fish tail and serve as an additional boost that increases the maneuverability and speed capabilities [11].

Also in [11], a phenomenon of relevance for swimming and flight known as Gray's paradox is addressed. This paradox originates from raising the inconsistency between the pushing capacity of the rear fin and the dolphin muscles with the swimming speeds that they achieve. Today it is known that this inconsistency is due to the flexibility and undulating movement of the fins that allow the fishes to generate thrust forces with complex dynamics such as the aforementioned vortices of Karman.

Due to the similarity between the dynamics of air and water fluids, these concepts can be extrapolated to the flight of birds, insects and robots with a locomotion system based on folding wings. In these systems, factors such as synchronization of movements and undulating trajectories of the wings determine the nature of the flight. According to Ijspeert A. [11], a change in the synchronization of the undulating movements of the wings alters the direction of the thrust forces allowing to modify the direction of the flight in height and orientation.

In [11] it is warned that animal locomotion is not necessarily optimal but sufficient from an evolutionary perspective, so the developers of bioinspired robots should be careful to mimic only the relevant aspects to avoid incurring redundancies in the design.

Terrestrial locomotion systems

Bruzzone L. and Quaglia G. [3] carry out a study of qualities and limitations of locomotion systems used by terrestrial robots in order to generate a comparative analysis of them. Initially, robots are classified according to their way of movement in a basic set that includes systems that use wheels, tracks and legs to subsequently extend to systems that combine two or three of these elements.

In the first instance, land-based locomotion systems based on wheels are analyzed. These stand out for their ability to reach relatively high speeds with low energy consumption, reduced mechanical complexity and relative ease of control. [3, 15]. Among the disadvantages in the use of these systems are, its limited ability to overcome obstacles or navigate irregular terrain and, in vehicles with more than three wheels, the need to include a suspension system that ensures wheel contact at all time with the ground as stated in [3, 7].

According to [3], the number of wheels used in robotic vehicles is decisive in their performance. Vehicles with three or more wheels are inherently stable and convenient in unstructured environments, while robots with two wheels require complex control systems to stabilize. Robots with two actuated and one passive wheels, are used in structured environments with flat surfaces due to their ability to rotate on a vertical axis and their ease of control. This configuration shows poor performance on irregular surfaces or unstructured environments. Vehicles whose orientation and number of wheels allow them three or more degrees of freedom, are characterized by maximum maneuverability, known as omnidirectionality, that gives them the ability to move in any direction [7].

Bruzzone L. y Quaglia G. in [3] classify robots with wheels, according to the mobility of their structures, in articulated and non-articulated. The non-articulated robots have little mobility due to fixed positions between their wheels. Robots with articulated structure are able to adapt to the terrain and overcome obstacles more easily.

Authors in [3] analyze the locomotion systems based on caterpillars. These systems are distinguished by their ease of movement in soft terrain and their ability to overcome obstacle while its main disadvantages are: reduced speed, energy inefficiency and susceptibility to vibrations. These robots may have articulated or non-articulated caterpillars. When their tracks are not articulated, these systems remain structurally simple and are capable of turning thanks to the possibility of generating a speed difference between their tracks. In the articulated systems, passive tracks, that increase the complexity of the system, are added in order to improve the displacement of robots on irregular surfaces. This difference increases their ability to adapt to the terrain and overcome a obstacles.

Also in [3] terrestrial locomotion systems based on legs are analyzed. Robots with these kind of systems are characterized by a high mobility that makes them suitable for navigation in unstructured environments with uneven terrains. Its main disadvantages are its low speed, its high consumption of energy and the requirement of multiple actuators with complex control systems.

Legged robots are intrinsically bioinspired and may have static or dynamic gait [3]. Static gait robots are always balanced because their center of gravity is within the polygon formed by the contact of the legs with the ground, allowing them to stop or advance at any time without going out of balance. Kinematic models are generally used in these types of robots and have the advantage of magnify their travel speed simply by increasing the speed of their legs without varying the paths followed by them.

Otherwise, robots with dynamic gait require more complex structures, mathematical models and control strategies because they are not inherently stable in balance. These robots exhibit complications such as the need to modify the trajectories of their legs in order to magnify their travel speed, the necessity to compensate external disturbance forces and the requirement for multiple actuators per limb. Despite this, they have considerable advantages such as the ability to isolate the body from the ground to compensate for external disturbances and irregularities of the terrain, and a greater energy efficiency due to the minimum loss of kinetic energy in their movements.

Quadruped robots have good capacities in unstructured environments, with obstacles and sloping terrain. An example of this is the Bigdog robot shown in Figure 1. This robot has been developed for military purposes by Boston Dynamics and it is capable of traveling on slopes with obstacles carrying up to 50 kg with three hydraulic actuators per leg [23]. Another example is the Tekken 2 shown in Figure 2, which seeks the greatest displacement capacity in rough terrain with four actuated joints per leg and implementing an adaptive gear scheme [4].

Figure 1. Bigdog climbing a 35° slope on an uneven terrain *[23]*

Figure 2. Tekken 2 walking in an open environment *[4]*

Multi-legged robots, generally hexapods and small in size, are used in tasks such as recognition and monitoring in which the transport of loads is minimal or negligible. It should be noted that the decrease in size also reduces the mechanical and control complexity of the system without compromising the performance of the robot [3]. The use of a greater number of legs has allowed these robots to perform tasks such as climbing steep slopes, overcoming obstacles of large dimensions in proportion to the robot, climbing vertically and even walking head-down while holding nets.

An example of a robot with multiple legs and a dynamic gear pattern is ASTERISK. This hexapod robot is capable of using its members as walking legs or as manipulative arms. With four degrees of freedom per member, it stands out for its ability to climb vertical stairs [24]. Otherwise, the RHex hexapod robot exhibits a lower structural complexity since it has a single actuator per leg and a static gait pattern. It has demonstrated considerable abilities to walk, run, overcome obstacles and climb stairs [25]. These robots are shown in Figure 3 and Figure 4, respectively.

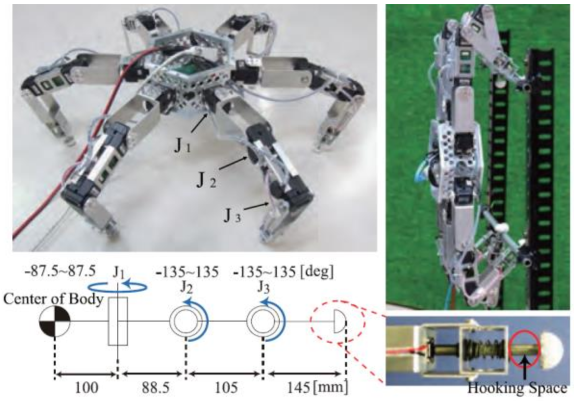


Figure 3. Leg mechanism of ASTERISK *[24]*

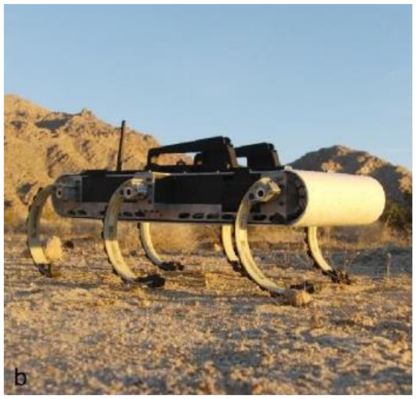


Figure 4. RHex robot *[25]*

In [3], the next ten characteristics evaluated for the analysis of each locomotion system are reported: maximum speed, ability to cross obstacles, ability to climb stairs, ability to climb slopes, ability to walk on soft terrains, ability to walk on uneven terrains, energy efficiency, mechanical complexity, control complexity and technological feasibility. Table 1 shows the degree of performance of land locomotion systems that use wheels, tracks or legs with respect to the 10 characteristics mentioned above.

Table 1. Comparison of terrestrial locomotion systems (modified from *[3]*)

	Wheels	**Tracks**	**Legs**
Maximum speed	high	medium /high	low (static gait) medium (dynamic gait)
Ability to cross obstacles	low	medium /high	high
Ability to climb stairs	low	media	high
Ability to climb slopes	low / medium	high	medium / high
Ability to walk on soft terrains	low	high	low/medium
Ability to walk on uneven terrains	low	medium/ high	high
Energy efficiency	high	medium	low (static gait) medium (dynamic gait)
Mechanical complexity	low	low	high
Control complexity	low	low	high
Technological feasibility	high	high	medium (dynamic gait) high (static gait)

3.1.3. State of the art

Robots whose mobility is limited to a single type of environment (terrestrial, aerial or aquatic) are known as mono-modal locomotion robots [12]. In contrast, those with the ability to move through different environments using two or more modes of locomotion are known as multi-modal locomotion robots or hybrid locomotion robots [13, 14].

In robotics, the study of the integration of two or more modes of locomotion emerges as an option to improve mobility in unstructured environments with obstacles. The approach of multimodal locomotion is based on the fact that each locomotion strategy allows overcoming different obstacles, so having several of these in a single robotic device will allow an easier adaptation to the environment [26].

The coupling of two or more modes of locomotion implies problems such as the increase in the complexity and weight of the system. Thus, robots with the characteristic of using the same actuators and structures in various modes of locomotion have emerged, considerably reducing their weight and complexity. In general, robot design approaches with multimodal locomotion can be classified as follows [13]:

- **Additive approach. -** The robot uses different actuators and mechanisms for each locomotion mode. Each system adds additional weight and there is a potential loss of performance.
- **Semi-additive approach. -** Locomotion modes are executed using the same actuators, but different mechanisms.

- **Integrative approach. -** In this approach, the same actuators and mechanisms are used to perform all modes of locomotion. It generates systems of less complexity and weight than the previous ones, but with a greater difficulty of integration.

Next, a revision is presented referring to some of the current work on robots that integrate both the terrestrial and the aerial modes of locomotion. This revision is made in 3 parts, classifying the developments according to their morphology in: quadcopters with legs, terrestrial roller and winged morphologies.

Legged quadcopter morphology

DUCK [27] is a semi-additive proposal of aerial and terrestrial locomotion based on a quadcopter with legs. As Figure 5 shows, its structure combines a four-rotor flight platform with active-passive gait legs. On inclined surfaces the passive gait is used to descend due to gravity and with a minimum energy consumption, while the active gait uses the thrust force of the propellers as an impulse to climb those slopes.

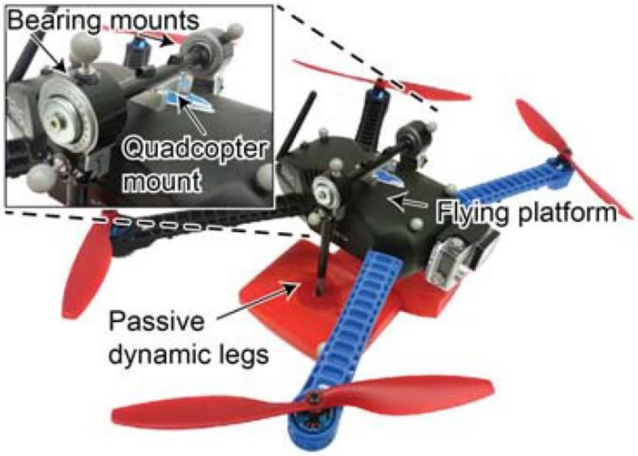


Figure 5. Prototype of DUCK robot *[27]*

The mechanical and structural design of DUCK was based on mathematical modeling and simulations previously carried out by the authors of [27]. The structure of the flying part was a commercial quadcopter developed by the company 3D Robotics, while the legs were built with aluminum and coupled to 3D printed feet made of (Acrylonitrile Butadiene Styrene).

The experiments performed with DUCK [27] showed that the robot is capable of executing passive walking on slopes with angles between -0.6° and -3.1°, since outside of this range of inclination, the robot is not able to walk or falls. In addition, it is possible to use the force of the rotors to brake the passive gear or to stabilize it.

As for the active gait, DUCK [27] can reach a speed of up to 0.15 m/s without being destabilized. However, in flight mode it is energetically less efficient (between 13% and 56% depending on whether or not the legs are installed). Another disadvantage is the presence of strong swings in the legs that make landing difficult.

The integration of multimodal locomotion in quadcopters of small size presents difficulties mainly related to energy autonomy, since the addition of locomotion systems demands a greater energy consumption. In Figure 6 Flying Monkey is shown, a quadcopter of 30 g developed under the additive paradigm, capable of flying, walking and holding objects [28].

It consists of eight legs based on a mechanism of folding sheets inspired by origami designs. The legs move in two groups with a phase shift of 180° and are activated by the movement of a single axis. A direct current motor coupled to the base is responsible for activating all the legs. In each phase of the march, the robot maintains four legs on the ground, which improves symmetry and distributes weight more evenly than designs based on six legs.

Figure 6. Flying Monkey *[28]*

The legs are coupled to a four bar mechanism that restricts its movement to a single degree of freedom. However, the robot is able to walk in curved trajectories moving its orientation thanks to the yaw force (rotation force around a vertical axis that passes through the center of gravity of an aircraft) produced by the rotors. Thanks to its multimodal locomotion it is capable of ridding multiple obstacles flying and moving in confined spaces such as pipes.

In [29] another model that integrates terrestrial locomotion in a quadcopter has been proposed. Following an approach based on the integrative paradigm, a single group of actuators is used to achieve two different types of locomotion. The morphology of this device consists of a quadcopter with passive legs coupled at the bottom of each rotor. The developers have called this device "walking quadcopter" and it is shown in Figure 7.

The legs have two linear degrees of freedom, one vertical and one horizontal. They are constituted by a four-bar mechanism and a sliding crank mechanism which, when subjected to a crushing force perpendicular to the surface with which the leg is in contact, can elongate to achieve a displacement. The required force is provided by the rotors activated in the reverse direction and when it disappears. The leg mechanism is able to return to its original configuration thanks to a set of articulations that act as springs.

Figure 7. Walking quadcopter prototype *[29]*

The process of walking, in this robot, requires a phase of flight in which the leg is not in contact with the ground, this has been achieved through the use of nitinol cables as shape memory actuators or SMA (Shape Memory Alloy) able to pull the leg to raise it.

Another proposal based on an additive approach is the robot presented in [30]. This robot has been designed to inspect steel bridges in order to find structural failures in environments that are not suitable for human access.

Its structure consists of a hexapod robot with 3 degrees of freedom per leg for the terrestrial structure. A brushless motor with a propeller is attached to each femoral segment with the intention of providing aerial locomotion. This model of 18.5 cm in length, has been manufactured using a 3D printer. Figure 8 shows the model previously described.

Figure 8. Hybrid robot for bridges inspection [30]

It should be highlighted the presence of unwanted vibrations due to the lack of rigidity of the joints that support the engines responsible for the flight and their rotational speed. To attenuate these oscillations, a Gaussian quadratic linear control was proposed.

Another work with a very similar scheme is presented in [31]. The structural design of this robot consists of a hexapod of 3 degrees of freedom per leg for terrestrial locomotion and 4 motors with propeller coupled to the legs for air locomotion as shown in Figure 9. This robot has an estimated weight of 4800 g and has been manufactured using a 3D printer in PLA (PolyLactic Acid) and ABS.

To start the flight process, it is necessary that the robot adopts a predetermined posture that allows him to place the propellers in the proper position. Once this position is adopted, the folding propellers are placed horizontally with respect to the ground and since there is no mechanical interference it is possible to start rotating [32].

Figure 9. Hexapod robot with flight capability [31]

Terrestrial wheeler morphology

DALER (Deployable Air Land Exploration Robot) is presented in [33]. It is an aerial and terrestrial locomotion robot designed under the integrative approach. As seen in Figure 10, it has an adaptive morphology that gives it the ability to use its wings as rims to move on the ground. Planned to perform search tasks in disaster areas giving priority to long-range flight, its morphology resembles that of a small airplane capable of flying at a speed of up to 14 m/s for 30 minutes.

The prototype with a weight of 450 g and a length between the wings of 60 cm has been manufactured using a 3D printer in a plastic material. It has a single propeller in the central part of the body for the flight, a motor in each wing for the movement as a wheel and servomotors to change the position of the ailerons. It excels its capacity to withstand impacts to the landing and its capacity to move on lands with snow, grass, carpets and cement.

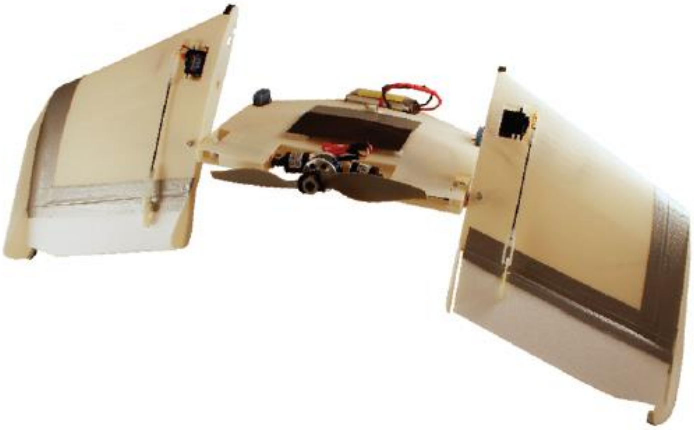


Figure 10. Prototype of DALER *[33]*

Another device that uses the same set of actuators to achieve a terrestrial and aerial locomotion (semi-additive approach) is ATR (Aerial Terrestial Robot) [34]. This characteristic results in a simple and lightweight design (35.24 g) oriented to search, rescue and surveillance tasks.

Structurally, the ATR consists of a quadcopter of reduced size (135 mm between the tips of the rotors) surrounded by a circular exoskeleton, as shown in [34]. The quadcopters are attached to the exoskeleton by means of a central axis around which it can rotate freely, which allows the system to orient its inclination angle. The exoskeleton consists of a circular cage completely open to drafts, so that the quadcopter can fly freely.

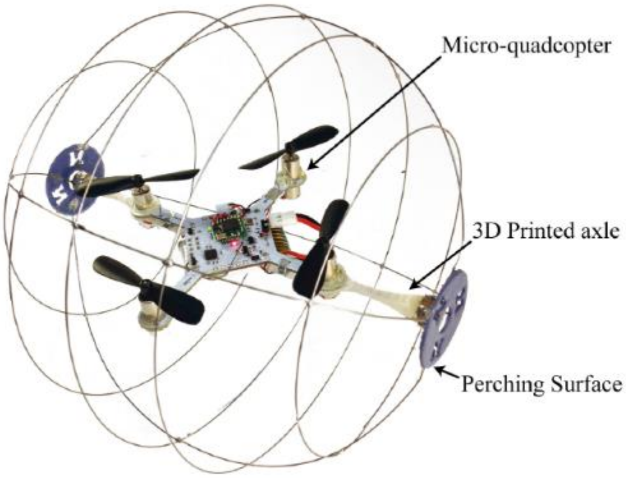


Figure 11. ATR: Aerial Terrestrial Robot *[34]*

For terrestrial locomotion, the quadcopter rotates with respect to the central axis and is positioned almost vertically to the ground generating a thrust force that allows it to move. This ability allows the robot to easily move into pipes and other types of ducts. The exoskeleton is made of steel cable and the body is completely composed of a printed circuit board.

Results indicate a higher energy efficiency of the ground locomotion over the aerial one. Rolling is able to travel a distance of 1.7 km in 12 minutes while flying is only able to stay 4.82 minutes achieving 469 m. Using only a land locomotion strategy, this system is 256% more efficient than the quadcopters average. However, its efficiency with respect to them is 39% lower when it uses only an aerial locomotion strategy.

Flapping wing and gliding morphologies

Research into the forms of multimodal locomotion integration has not been restricted to robots with rotating propellers. In [35] BOLT (Bipedal Ornithopter capable of both aerial and terrestrial Locomotion) is introduced, a robot under the semi-additive approach, with flapping wings and bipedal terrestrial locomotion that is shown in Figure 12. This robot of 11.4 g and 17.5 cm in length is capable of reaching a land speed of up to 0.5 m/s in quasi-static gait (wing beating has no significant effects on the gait) and 1.85 m/s in dynamic gait (the beating of the wings has considerable effects).

Figure 12. Bipedal Ornithopter capable of both aerial and terrestrial locomotion *[35]*

Its mechanical structure uses the commercial ornithopter V-wing Avenger of the company Air Hogs ®, to which a support structure and a pair of legs developed by the researchers have been added. The support structure is made of carbon fiber and has the functions of holding the elements, protecting the controller and maintaining an appropriate angle of the wings so that they generate enough vertical momentum for the flight. The legs have been manufactured in PET (PolyEthylene Terephthalate) and carbon fiber, they are coupled to the motor by means of a four-bar mechanism in such a way that one revolution of the motor equals one step with each leg and one flutter. The electronic components are reduced to only those essential for reasons of weight saving and consist only in a processor, a wireless transceiver and an accelerometer.

With a single motor it is able to activate both the wings and the legs to navigate through complex three-dimensional terrains and switch between both modes of locomotion when necessary. For walking, the movements of the legs are 180° out of phase, while the wings give stability when running bipedally.

In the static gait, the wings generate minimum and insufficient forces to provide significant impulse to it, leaving the work to the traction generated by the legs. On the contrary, in the dynamic march the wings generate a significant contribution to the whole movement. For the transition between gait and flight, the robot must run along the ground at a speed of 1.75 m/s that allows it to get enough aerodynamic momentum to take off. At a speed of 3 m/s, the robot is able to enter a vertical flight position in which the tail swings below the body.

In [36] MultiMo-Bat is introduced, it is a 115.6 g robot that, inspired by the bats' locomotion strategies, is able to gliding and perform jumps of up to 3 m. Developed under the semi-additive paradigm, it is composed of only 20 mechanical parts of which the 6 simplest were machined using CNC (Computer Numerical Control) tools while the more complex ones were manufactured by replicating polyurethane models previously printed in 3D.

MultiMo-Bat is shown in Figure 13. Structurally, it is constituted by 3 parts: body, legs and wings. In the part of the body a gearmotor and a pulley system are embedded, the 2 legs consist of mechanisms of 4 bars coupled by springs and attached to the gearmotor by a tensed cable. When the motor is activated, the cable will wind through the pulley system, folding the mechanism of the legs and compressing the springs.

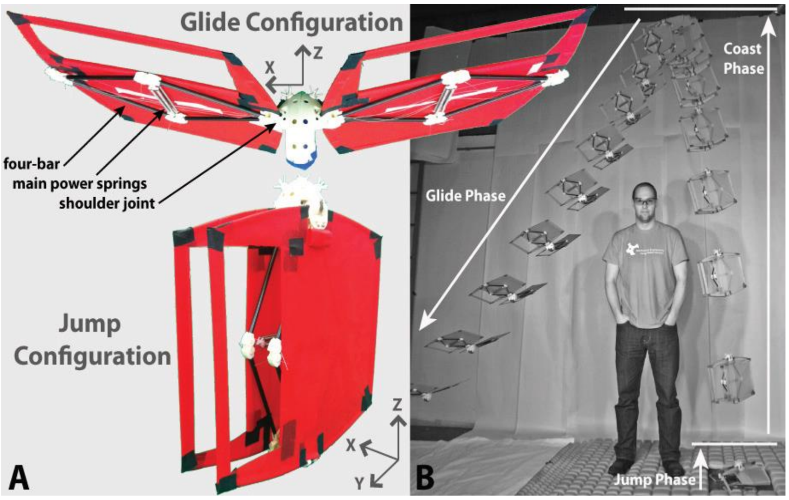


Figure 13. MultiMo-Bat performing a jump and glide sequence *[36]*

On the other hand, the wings consist in a membrane made of ripstop coated nylon that is attached to the outside of the leg mechanism. The previously mentioned material was selected to ensure a reduced weight and durability against the constant folding of the wings.

The locomotion process takes place in several phases. In the first phase the gearmotor is activated to fold the legs and store energy in the springs, in the second phase the energy of these springs is released which causes the robot to jump almost vertically, the third phase starts at the maximum point of the jump where the robot opens its wings to glide smoothly during its descent and until its landing.

The previously collected information shows the virtues, variety of designs and limitations of each system. It is convenient to pay specific attention to novel designs and solutions with the purpose of using them as a basis in future developments. Regarding the limitations, it is possible to interpret them as opportunities for improvement, which naturally allow the proposal of solutions and even new systems.

Table 2 shows the technical aspects of the system developed in this research and of similar systems found in the literature.

Table 2. Technical aspects of the aero-terrestrial prototypes

System	Ratsamee et al. [30]	Pitonyak et al. [31]	This work
DOF/leg	18	18	12
Propellers	4	6	4
Mass (kg)	4.8	1.5	2.1
Material	PLA/ABS	PLA	PLA/Aluminum
Dimensions (cm) L – W - H	Not specified	18.5 - 14.5 - 3.5	30 - 20 - 13
Gait generation	Inverse kinematics	Inverse kinematics	Central Pattern Generator
Electric source	2 x Li-Po battery 11.1 V – 6.2 A	Not specified	1 x Li-Po battery 11.1 V – 3 A
Leg servomotor	Dynamixel AX-12A	Dynamixel XL-320	TowerPro MG996

3.2. Problem statement

Currently, the developments of science and technology have allowed humanity to achieve more comfortable lifestyles and with greater facilities characterized, among other things, by the ease of transport over long distances, fast communication and an increase in the life expectancy. These characteristics, combined with production and consumption, have triggered problems such as uncontrolled population increase in urban areas, environmental deterioration or the growth in the demand for resources.

In response to these challenges, engineering has provided a paradigm shift on traditional technological development approaches. Disruptive technologies such as vertical aeroponic crops for urban areas [37], autonomous flying robots [16] or soft robots [38], arise as a reaction to the need to transcend our limited tools to ones with a greater degree of versatility, adaptability and dexterity.

In spite of the advances achieved at present, the premise of perfectibility of our tools is still categorical. As an example in robotics, the development of drones has had a social impact due to their numerous applications, despite the fact that they have limitations in terms of dexterity and mobility that represent improvement opportunities. In contrast, leg locomotion robots, although they appear limited in applications, have demonstrated dexterity when navigating in closed and rugged environments [3, 4].

A proposal for the improvement of systems created by engineering is biomimetics, which consists of the copy, learn or imitation of certain attributes present in nature as a way of solving specific problems [5]. Biomimetics seeks to improve the effectiveness of the tools by adding or optimizing certain features, for example, the development of scaling robots with Gecko-inspired technology for surface adhesion [39] or the use of flip-wing systems inspired by bats in aerial robotic systems [40].

In nature, insects of the order Hymenoptera (bees, wasps, bumblebees and ants), generally characterized by grouping in densely populated societies, fulfill tasks of collection, care, monitoring and construction that demand a high skill for navigation in diverse environments. The success in the performance of these tasks is mainly due to their social skills and the multifaceted nature of their locomotion. This intrinsically multimodal locomotion integrates the ability to cover large spaces by aerial navigation with the virtues of displacement of arthropod locomotion in narrow and confined environments.

This research emphasizes the limitations of systems restricted to a single type of locomotion and is motivated by the opportunity to emulate the successful multimodal locomotion systems of Hymenoptera insects. Therefore, the problem that is addressed in this project is to integrate two modes of locomotion into a robotic system with animal morphology.

3.3. Aim of the project

The integration of two modes of locomotion, one terrestrial through legs and another aerial, in a robotic system inspired by hymenoptera insects.

3.4. Objectives

3.4.1. General objective

Generate a bio-inspired robotic system prototype that integrates the terrestrial and aerial modes of locomotion.

3.4.2. Particular objectives

- Characterize the modes of terrestrial and aerial locomotion of the Hymenoptera insects.
- Identify the specifications of each type of locomotion that show the most relevant elements for the mimicry.
- Propose a set of conceptual designs of each mode of locomotion for the integration of a robotic system inspired by Hymenoptera.
- Generate conceptual designs of mechatronic devices that mimic the characteristics of each selected mode of locomotion.
- Select a conceptual design of each type (terrestrial and aerial) based on its feasibility of development and compatibility with other designs.
- Integrate selected conceptual designs into a single robotic or prototype system.
- Build a bio-inspired robotic system prototype of Hymenoptera insects with terrestrial and aerial locomotion.

3.5. Scope and limitations

This research will focus on the integration of two modes of locomotion into a robotic system. It will only consider aerial and terrestrial capabilities, delving specifically into locomotion using legs for the land mode and based on rotating propellers or folding wings for the aerial mode.

This work will follow a design approach based on the biomimicry of insects of the order Hymenoptera and its main objective will be the development of a robot with zoomorphic characteristics. It is not the intention of this work to carry out systems identical to the natural ones, so that discrepancies in the design such as size, weight, number of legs or mechanisms of action between the proposed system and its natural counterpart could be considered.

This research will be fully oriented to the study, characterization, evaluation and mimicry of the Hymenoptera insects, locomotion for their subsequent integration into a robotic system and does not formally contemplate the applications that may be given to the generated prototype.

3.6. Proposed methodology

The realization of this project was based on different stages that constituted the methodology that was followed to achieve the general objective.

Literature review.- Bibliographic sources that address the current research about the integration methodologies of multiple locomotion systems in robots were reviewed. The knowledge achieved at this point served as the basis for the development of the project, so the literature review was carried out throughout all the research process.

Identification of the modes of locomotion.- The different forms of locomotion used by Hymenopteran insects were identified. In this process, those modes with variations in their execution were classified as different ones, regardless if they take place in the same environment.

Anatomical description.- It consisted of the recognition of the physical structures that make up Hymenoptera insects. Special emphasis on the study, from a structural and functional perspective, of those organs or systems that are directly related to locomotion was made.

Locomotion characterization.- The qualities and characteristic features of locomotion of Hymenoptera insects were detailed. The study of the trajectories, kinematics and dynamics of aerial and terrestrial locomotion was addressed.

Selection of locomotion modes.- Locomotion modes were classified based on their performance impact. Only those that present indispensable or outstanding characteristics were selected according to the information collected through literature. Likewise, replaceable and expendable characteristics were also recognized in each of the modes.

Design specifications.- This stage discarded secondary aspects in the Hymenoptera locomotion and focused on the presentation of the most relevant dynamic and kinematic features, as well as on the definition of simplified structural elements. This stage served in later tasks marking the elements of greatest relevance for the mimicry

Identification of previously developed robotic systems.- Bibliographic review that focused on the study of methodologies, designs and technologies used in past research for the development of bio-inspired robotic systems. This review allowed knowing key and problematic points of previous works with the purpose of adopting or avoiding them.

Proposal of conceptual models.- The design specifications as well as the previously developed robotic systems were considered in the proposal of conceptual designs and locomotion strategies needed to define the aero-terrestrial system.

Generation of technological proposals.- Based on the conceptual model, mechatronic systems based on the locomotion mechanisms of Hymenoptera insects were proposed. The proposals were considered as part of a larger system, but these were worked individually for each mode of locomotion.

Evaluation of technological feasibility.- The viability of construction of the technological proposals were studied based on the availability and development state of current technologies and tools.

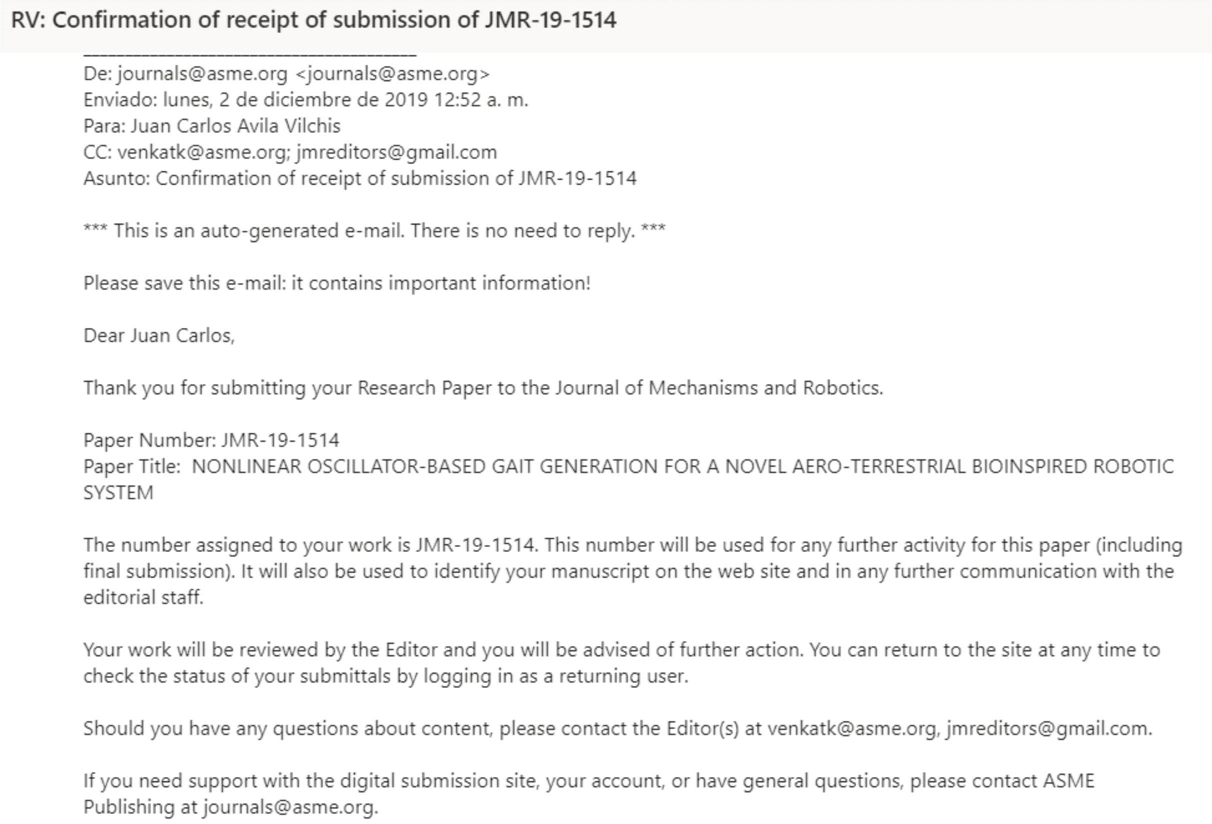
Selection of the proposals.- In this process the technological proposals that were used for the integration of the final system were determined. Criteria such as complexity, feasibility of development, compatibility with other proposed systems and possible future improvements determined the acceptance or rejection of the proposals.

Integration of the selected proposals.- It consisted in the integration of the selected proposals in a single robotic system.

Writing of the research report.- The writing of the document that reports this work was carried out throughout all the research process.

4. Scientific papers

The scientific paper entitled " Nonlinear oscillator-based gait generation for a novel aero-terrestrial bioinspired robotic system", with DOI: https://doi.org/10.1115/1.4047269, was submitted and accepted by “The Journal of Mechanisms and Robotics of the ASME” as shown in Figure 14 and Figure 15.



RV: Confirmation of receipt of submission of JMR-19-1514

De: journals@asme.org <journals@asme.org>
Enviado: lunes, 2 de diciembre de 2019 12:52 a. m.
Para: Juan Carlos Avila Vilchis
CC: venkatk@asme.org; jmreditors@gmail.com
Asunto: Confirmation of receipt of submission of JMR-19-1514

*** This is an auto-generated e-mail. There is no need to reply. ***

Please save this e-mail: it contains important information!

Dear Juan Carlos,

Thank you for submitting your Research Paper to the Journal of Mechanisms and Robotics.

Paper Number: JMR-19-1514
Paper Title: NONLINEAR OSCILLATOR-BASED GAIT GENERATION FOR A NOVEL AERO-TERRESTRIAL BIOINSPIRED ROBOTIC SYSTEM

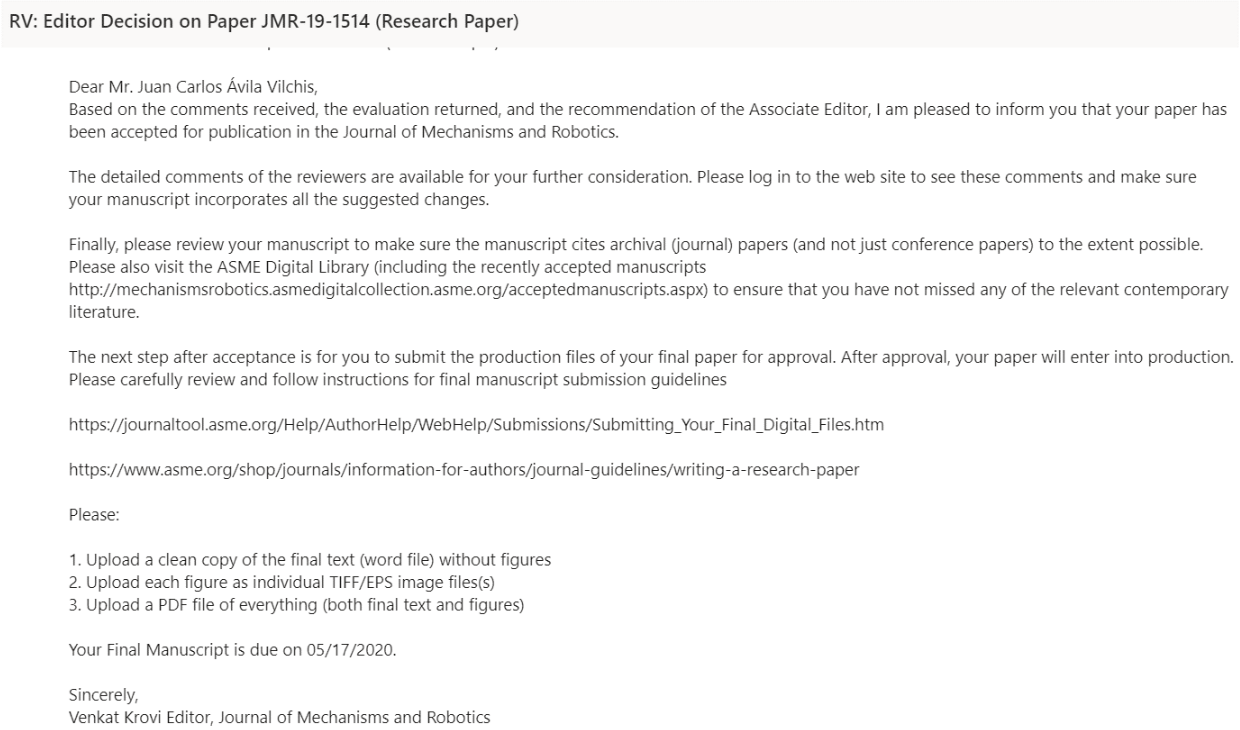
The number assigned to your work is JMR-19-1514. This number will be used for any further activity for this paper (including final submission). It will also be used to identify your manuscript on the web site and in any further communication with the editorial staff.

Your work will be reviewed by the Editor and you will be advised of further action. You can return to the site at any time to check the status of your submittals by logging in as a returning user.

Should you have any questions about content, please contact the Editor(s) at venkatk@asme.org, jmreditors@gmail.com.

If you need support with the digital submission site, your account, or have general questions, please contact ASME Publishing at journals@asme.org.

Figure 14. Paper submitted to “The Journal of Mechanisms and Robotics of the ASME”



RV: Editor Decision on Paper JMR-19-1514 (Research Paper)

Dear Mr. Juan Carlos Ávila Vilchis,
Based on the comments received, the evaluation returned, and the recommendation of the Associate Editor, I am pleased to inform you that your paper has been accepted for publication in the Journal of Mechanisms and Robotics.

The detailed comments of the reviewers are available for your further consideration. Please log in to the web site to see these comments and make sure your manuscript incorporates all the suggested changes.

Finally, please review your manuscript to make sure the manuscript cites archival (journal) papers (and not just conference papers) to the extent possible. Please also visit the ASME Digital Library (including the recently accepted manuscripts http://mechanismsrobotics.asmedigitalcollection.asme.org/acceptedmanuscripts.aspx) to ensure that you have not missed any of the relevant contemporary literature.

The next step after acceptance is for you to submit the production files of your final paper for approval. After approval, your paper will enter into production. Please carefully review and follow instructions for final manuscript submission guidelines

https://journaltool.asme.org/Help/AuthorHelp/WebHelp/Submissions/Submitting_Your_Final_Digital_Files.htm

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Please:

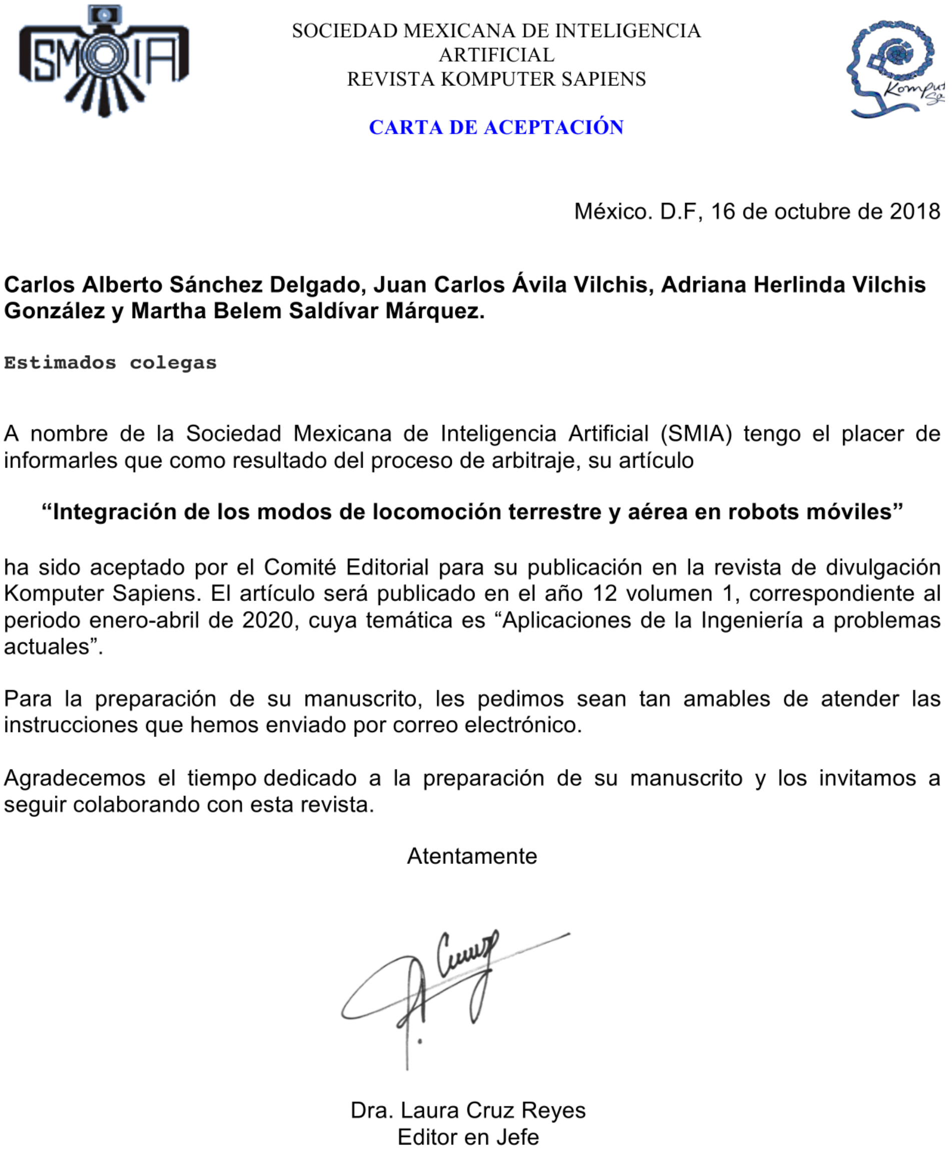
1. Upload a clean copy of the final text (word file) without figures
2. Upload each figure as individual TIFF/EPS image files(s)
3. Upload a PDF file of everything (both final text and figures)

Your Final Manuscript is due on 05/17/2020.

Sincerely,
Venkat Krovi Editor, Journal of Mechanisms and Robotics

Figure 15. ASME acceptance letter for publication

Another paper entitled “Integración de los modos de locomoción terrestre y aérea en robots móviles” was submitted and accepted for publication in the disclosure magazine of the Mexican Society of Artificial Intelligence KSapiens as shown in Figure 16. The paper was published in the year XII volume I with ISSN 2007-0691.



SOCIEDAD MEXICANA DE INTELIGENCIA
ARTIFICIAL
REVISTA KOMPUTER SAPIENS

CARTA DE ACEPTACIÓN

México. D.F, 16 de octubre de 2018

Carlos Alberto Sánchez Delgado, Juan Carlos Ávila Vilchis, Adriana Herlinda Vilchis González y Martha Belem Saldívar Márquez.

Estimados colegas

A nombre de la Sociedad Mexicana de Inteligencia Artificial (SMIA) tengo el placer de informarles que como resultado del proceso de arbitraje, su artículo

“Integración de los modos de locomoción terrestre y aérea en robots móviles”

ha sido aceptado por el Comité Editorial para su publicación en la revista de divulgación Komputer Sapiens. El artículo será publicado en el año 12 volumen 1, correspondiente al periodo enero-abril de 2020, cuya temática es “Aplicaciones de la Ingeniería a problemas actuales”.

Para la preparación de su manuscrito, les pedimos sean tan amables de atender las instrucciones que hemos enviado por correo electrónico.

Agradecemos el tiempo dedicado a la preparación de su manuscrito y los invitamos a seguir colaborando con esta revista.

Atentamente

Dra. Laura Cruz Reyes
Editor en Jefe

Figure 16. KSapiens acceptance letter for publication

This thesis is orientated to obtain a master degree, through the specialized article graduation option. Considering the articles 57, 59 and 60 bis of the REA (Reglamento de Estudios Avanzados) of the UAEM (Universidad Autónoma del Estado de México). The first sheet of ASME and KSapiens articles are shown below.

NONLINEAR OSCILLATOR-BASED GAIT GENERATION FOR A NOVEL AERO-TERRESTRIAL BIOINSPIRED ROBOTIC SYSTEM

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ABSTRACT

This paper focuses on the design of a novel aero-terrestrial robotic system based on the morphology of the Hymenoptera order insects and, particularly, on a strategy based on nonlinear oscillators for the coordination of its 12 terrestrial DoF (Degrees of Freedom). The ability of this new aero-terrestrial robot to, successfully, perform the walking process is validated through numerical simulations and tests performed on an experimental platform in which the gait speed was varied from 0.04 to 0.2 m/s. Some of the most important qualities of this robotic system are: a relatively simple design with only 2 DoF per leg and a versatile terrestrial locomotion with the ability to vary its speed and direction in real time with smooth transitions. Furthermore, unlike existent similar systems, the robot is designed to initiate flight phase in any position without adopting particular postures avoiding undesirable interferences with the walking configuration.

Keywords: multimodal locomotion, bioinspired design, mobility enhancement, nonlinear oscillators.

1. INTRODUCTION

The research effort on versatility improvement over the mobility of robots has led to the integration of several modes of locomotion (terrestrial, aerial or aquatic) into a single system. The development of designs and algorithms that control and link modes of locomotion is a research area of growing interest [1,2]. In both animals and mobile robots, locomotion is a fundamental activity for the tasks development. The ability to move through an environment empowers the systems for undertaking activities such as navigation or cooperation. An important branch in mobile robotics research is devoted to the development of systems capable of moving despite physical barriers. The success in this, depends on the physical capabilities of the robot and on the strategies proposed to evade obstacles. A robot with mono-modal locomotion, will find the navigation task more difficult than a robot with several modes [1,2].

Insects have the virtues of multimodal locomotion in the development of complex tasks. Hymenoptera insects excel by the use of their locomotive capabilities in complex tasks such as construction, collection and cooperation. These tasks are not trivial in robotics research and represent challenges as coordination or aero-terrestrial tracking, for instance. Therefore, the study and mimicry of biological mechanisms could promote advances in the field of locomotion and robotic navigation [3].

Integrating several modes of locomotion into a single system, faces some difficulties such as the weight and complexity increase. In [4], some paradigms are introduced to address these problems in three ways: a) The additive approach in which each locomotion mode uses a greater number of mechanisms and actuators. b) The semi-additive approach in which the same actuators are used for different mechanisms. c) The integrative approach where the same actuators and mechanisms are used in different modes, decreasing performance and versatility due to a reduced number of DoF.

Currently, there are several proposals regarding the integration of land and aerial modes of locomotion into a single robotic system. Based on morphology aspects, robots can be grouped in three categories:

1) The union of a ground rolling structure and a flight system. In [5], the Deployable Air Land Exploration Robot system is designed under the integrative approach. It consists of an airplane structure that accomplishes the aerial mode of locomotion while on the ground uses its wings as rims to move. The Aerial Terrestial Robot system [6] uses a semi-additive approach and consist of a quadcopter attached to an exoskeleton by means of an axis around which it can rotate freely, generating a thrust force that allows it to roll on the ground.

2) The union of a multicopter and a legged walker. In nature, locomotion by legs is extensively used even in animals with the ability to fly as in [7-12]. A semi-additive proposal is presented in [7] where, for walking on inclined surfaces, the system descends due to the gravity effect. To climb slopes, the device uses the thrust force of the propellers as impulse. The Flying Monkey [8] is an eight-legged quadcopter based on an origami-inspired folding mechanism developed under an integrative paradigm. Although its legs limit its mobility to one degree of freedom, the system is able to turn thanks to the yaw force produced by the rotors. The Walking Quadcopter proposed in [9], under an integrative approach, employs crawling legs for terrestrial locomotion. Each of its legs consists of a four-bars-sliding-crank mechanism which, subjected to a crushing force provided by the propellers, elongates to achieve displacement. The legs return to their original configuration when the crushing force disappears. Other system suggests the addition of an 18 DoF-hexapod with a multicopter as the robot in [10] that attaches a propeller to each femoral segment to

ARTÍCULO ACEPTADO

Integración de los Modos de Locomoción Terrestre y Aérea en Robots Móviles

Carlos Alberto Sánchez Delgado, Juan Carlos Ávila-Vilchis, Adriana H. Vilchis González y Belem Saldivar

Resumen

En el campo de la robótica, el estudio de la integración de dos o más modos de locomoción surge como una opción para mejorar la movilidad en entornos no estructurados y con obstáculos. El enfoque de la locomoción multimodal se fundamenta en que cada estrategia de locomoción permite superar obstáculos distintos, por lo que contar con varios de estos en un sólo dispositivo robótico permitirá adecuarse al ambiente con mayor facilidad. Este articulo presenta una revisión de algunos trabajos de actualidad sobre robots que integran los modos de locomoción tanto terrestre como aérea. Dicha revisión se realiza clasificando a los desarrollos de acuerdo con su morfología, para finalmente concluir con una reflexión sobre los aportes de estos trabajos y tendencias en el área.

Introducción

Los robots cuya movilidad se limita a un solo tipo de ambiente (terrestre, aéreo o acuático) son conocidos como robots de locomoción mono-modal. En contraste, aquellos con la capacidad de desplazarse mediante dos o más modos de locomoción a través de distintos ambientes son conocidos como robots de locomoción multi-modal o como robots de locomoción híbrida.

En robótica, el estudio de la integración de dos o más modos de locomoción surge como una opción para mejorar la versatilidad de desplazamiento en entornos no estructurados y con obstáculos. El enfoque de la locomoción multimodal se fundamenta en que cada estrategia de locomoción permite superar obstáculos distintos, por lo que contar con varios de estos en un sólo dispositivo robótico permitirá adecuarse al ambiente con mayor facilidad [1].

El acoplamiento de dos o más modos de locomoción supone problemáticas como el aumento en la complejidad y peso del sistema. Por ello han surgido robots con la característica de emplear los mismos actuadores y estructuras en varios modos de locomoción, reduciendo considerablemente su peso y complejidad. En general, los enfoques de diseño de robots con locomoción multimodal pueden clasificarse de la siguiente forma [2]:

- **Enfoque aditivo.** El robot emplea tanto actuadores como mecanismos distintos en cada modo de locomoción.
- **Enfoque semi-aditivo.** Los modos de locomoción se ejecutan empleando los mismos actuadores, pero distintos mecanismos.
- **Enfoque integrativo.** En este enfoque se emplean los mismos actuadores y mecanismos para desempeñar ambos modos de locomoción.

A continuación, se presenta una revisión referente a algunos de los trabajos de actualidad sobre robots que integran los modos de locomoción tanto terrestre como aérea. Dicha revisión se realiza en 3 partes, clasificando los desarrollos de acuerdo con su morfología en: cuadricóptero con patas, rodador terrestre y otras morfologías. Finalmente, se realiza una reflexión sobre los aportes de los trabajos realizados y tendencias en el área.

Trabajos recientes en la integración de locomoción terrestre y aérea en sistemas robóticos

Morfología de multicóptero con patas DUCK [3] es una propuesta semi-aditiva de locomoción aérea y terrestre basada en un cuadricóptero con patas. Como muestra la Figura 1, su estructura combina una plataforma de vuelo de cuatro rotores con piernas de marcha activa-pasiva. En superficies inclinadas la marcha pasiva es empleada para descender por efecto de la gravedad con un consumo energético mínimo. La marcha activa emplea la fuerza de empuje de las hélices como impulso para subir dichas pendientes.

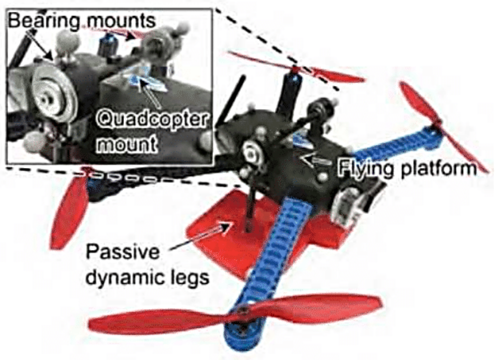


Figura 1. Prototipo de DUCK [3].

The article sent to the ASME Journal of Mechanisms and Robotics has 4 videos of supplementary material. These videos illustrate the experimental tests carried out on the gait process and can be found on the article page. A description of the hardware, software, and experimental tests performed on the aerial part has been included in the appendix section.

Table 3 summarizes the technical aspects of the experimental physical platform developed in this research.

Table 3. Technical aspects of the physical experimental platform

Mechanical features	**Electrical features**	**Software features**
Material: PLA/Aluminum Mass: 2.1 kg Leg morphology: 4-bar linkage Dimensions: 30L – 20W – 13H Propellers: 1045	Leg servos: TowerPro Mg996 Head servos: TowerPro MG90s Battery: Li-Po 11.1 V – 3 A Servos regulator: Xl4016 Computer regulator: LM2596 Main board: Raspberry Pi 3 B+ Flight board: Crius SE 2.5 Camera: Pi Camera version 1.3 Brushless motors: A2212/13T Servos board: PCA9685	Operating system: Raspbian Strech Python version: 3.6 ROS version: Kinetic Kame Multiwii version: 2.4

5. General conclusions and future work

This research delves into the proposal, design, construction and implementation of a robot with aero-terrestrial locomotion, bioinspired by Hymenoptera insects. As a final product, a physical-experimental platform, which contains the mechanical, electronic and software elements sufficient for the successful integration of both modes of locomotion, has been generated. The bioinspired nature of this robotic platform is manifested in the hardware through mechanical structures that resemble the morphology of Hymenoptera insects, and in the software, through algorithms based on neural structures that coordinate the locomotion of these insects.

The scientific article written during this research addresses a detailed description of the mechanical structures and electronic architecture that make up the system. Furthermore, it focuses on the proposal of a terrestrial locomotion strategy based on the design and implementation of an artificial nervous system composed of coupled nonlinear oscillators. The robotic platform was subjected to experimental tests in order to validate the operation of the proposed locomotion strategy.

The advantages of the robotic system include, but are not limited to, those presented by multimodal robots over monomodal ones. In the mechanical part, the combination of a four-bar mechanism and two actuators as constituent elements of the legs has allowed the generation of a system that uses the same structures for flight and walking. In addition, the robotic system is capable of taking off without adopting predetermined postures and, based on the information provided in Table 2 and Table 3, it can be established that shows a better relationship between complexity and weight than similar systems found in the literature. In the algorithms, the proposal of an artificial nervous system based on CPG (Central Pattern Generator) provides versatility on the gait, since it allows the online modification of its speed and direction by adjusting a small group of parameters.

The proposal, construction and experimental validation of this platform opens up new research possibilities. Following the bioinspired scheme, the structures that coordinate locomotion in insects are related to other activities such as sight and smell by neuronal centers in the brain. Since the robotic platform generated in this research already has the necessary hardware elements, future research, based on high-level brain structures of insects, could be oriented to propose vision and learning algorithms aimed to achieve autonomous navigation and collaboration between several robots.

References

[1] F. Ruggiero, V. Lippiello and A. Ollero, "Aerial Manipulation: A Literature Review," *IEEE Robotics and Automation Letters,* vol. 3, no. 3, pp. 1957-1964, 2018.

[2] G. Cai, J. Dias and L. Seneviratne, "A Survey of Small-Scale Unmanned Aerial Vehicles: Recent Advances and Future Development Trends," *Unmanned systems,* vol. 2, no. 2, pp. 175-199, 2014.

[3] L. Bruzzone and G. Quaglia, "Review article: locomotion systems for ground mobile robots in unstructured environments," *Mechanical Sciences,* no. 3, pp. 49-62, 2012.

[4] H. Kimura, Y. Fukuoka and A. Cohen, "Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts," *The International Journal of Robotics Research,* vol. 26, no. 5, p. 475, 490.

[5] Y. Bar-Cohen, "Biomimetics—using nature to inspire human innovation," *Bioinspiration & Biomimetics,* vol. 1, no. 1, 2006.

[6] ISO 8373:2012, Geneva, Switzerland: International Organization for Standardization, 2012.

[7] S. Tzafestas, "Introduction to mobile robot control," Primera ed., Athens, Elsevier Inc., 2014, p. 689.

[8] A. Ollero Barturone, Robótica Manipuladores y robots móviles, Barcelona: Marcombo, 2001.

[9] A. Barrientos, L. F. Peñin, C. Balaguer and R. A. Santoja, Fundamentos de Robótica, Segunda ed., Mc Graw-Hill, 2007.

[10] "Cambridge dictionary," Cambridge, [Online]. Available: https://dictionary.cambridge.org/us/. [Accessed 11 12 2019].

[11] A. Ijspeert, "Using robots to emulate and investigate agile animal locomotion," *Science,* vol. 346, pp. 196-203, 2014.

[12] R. J. Lock and R. Vaidyanathan, "Multi-modal locomotion: from animal to application," *Bioinspiration & Biomimetics,* no. 9, p. 18, 2014.

[13] L. Daler, Adaptive Morphology for Multi-Modal Locomotion, É. P. F. D. LAUSANNE, Ed., Lausanne, 2015.

[14] S. Mintchev and D. Floreano, "Adaptive Morphology: A Design Principle for Multimodal and Multifunctional Robots," *IEEE Robotics & Automation Magazine* , vol. 23, pp. 42-54, 2016.

[15] R. Sieward, I. Nourbakhsh and D. Scaramuzza, Introduction to Autonomous Mobile Robots, Massachusetts: The MIT Press, 2011.

[16] K. Noami, F. Kendoul, S. Satoshi, W. Wang and D. Nakazawa, Autonomous Flying Robots, Tokio: Springer, 2010.

[17] M. Hassanalian and A. Abdelkefi, "Classifications, applications, and design challenges of drones: A review," *Progress in Aerospace Sciences,* vol. 91, pp. 99-131, 2017.

[18] D. Dolgov and S. Thrun, "Autonomous Driving in Structured and Unstructured Environments," in *2009 IEEE International Conference on Robotics and Automation*, Kone, Japan, 2009.

[19] D. Dolgov, S. Thrun, M. Montemerlo and J. Diebel, "Path Planning for Autonomous Vehicles in Unknown Semi-structured Environments," *The International Journal of Robotics Research,* vol. 29, no. 5, pp. 485-501, 2010.

[20] C. Gillott, Entomology, Dordrecht: Springer, 2015.

[21] R. Bachmann, F. Boria, . R. Vaidyanathan, P. fju and R. Quinn, "A Biologically Inspired Micro-Vehicle Capable of Aerial and Terrestrial Locomotion," *ScienceDirect,* vol. 44, p. 513–526, 2009.

[22] L. D. Paulson, "Biomimetic robots," *Computer,* vol. 37, pp. 48-53, 2004.

[23] M. Raibert, K. Blankespoor and G. Nelson, "BigDog, the Rough-Terrain Quadruped Robot," in *The International Federation of Automatic Control*, Seoul, 2008.

[24] F. Shota, I. Kenji, T. Tomohito, M. Yasushi and A. Tatsuo, "Ladder climbing control for limb mechanism robot “ASTERISK”," in *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, Pasadena, 2008.

[25] R. Altendorfer, N. Moore, H. Komsuoglu, M. Buehler, H. Brown, D. McMordie, U. Saranli, R. Full and D. Koditschek, "RHex: a biologically inspired hexapod runner," *Autonomous Robots,* no. 11, p. 207–213, 2001.

[26] C. Nie, X. Pacheco and M. Spenko, "Robots on the Move: Versatility and Complexity in Mobile Robot Locomotion," *IEEE Robotics & Automation Magazine* , vol. 20, no. 4, pp. 72 - 82, 2013.

[27] C. J. Pratt and K. K. Leang, "Dynamic Underactuated Flying-Walking (DUCK) Robot," in *IEEE International Conference on Robotics and Automation*, Stockholm, 2016.

[28] M. Yash, B. Araki and J. Koh, "The Flying Monkey: a Mesoscale Robot that can Run, Fly,," in *IEEE International Conference on Robotics and Automation*, Stockholm, 2016.

[29] A. Kalantari and M. Spenko, "Design and prototyping of a walking quadrotor," in *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Chicago, 2012.

[30] P. Ratsamee, P. Kriengkomol, T. Arai, K. Kazuto , Y. Mae, K. Kiyokawa, T. Mashita, Y. Uranishi and H. Takemura, "A Hybrid Flying and Walking Robot For Steel Bridge Inspection," in *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR),* Lausanne, 2016.

[31] M. Pitonyak and F. Sahin, "A Novel Hexapod Robot Design with Flight Capability," in *System of Systems Engineering Conference (SoSE)*, Waikoloa, 2017.

[32] M. Pitonyak and F. Sahin, "Locomotion and Transitional Procedures for a Hexapod-Quadcopter Robo," in *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Banff, 2017.

[33] L. Daler, J. Lecoeur and B. P. Hählen, "A flying robot with adaptive morphology for multi-modal locomotion," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013.

[34] C. J. Dudley, A. C. Woods and K. K. Leang, "A Micro Spherical Rolling and Flying Robot," in *International Conference on Intelligent Robots and Systems*, Hamburg, Germany, 2015.

[35] K. Peterson and R. S. Fearing, "Experimental Dynamics of Wing Assisted Running for a Bipedal," in *IEEE IRSJ International Conference on Intelligent Robots and Systems*, San Francisco, 2011.

[36] M. Woodward and M. Sitti, "MultiMo-Bat: A biologically inspired integrated jumping–gliding robot," *The International Journal of robotics research,* vol. 33, no. 12, p. 1511–1529, 2014.

[37] D. Vitiello and L. Wolf-Powers, "Growing food to grow cities? The potential of agriculture foreconomic and community development in the urban United States," *Oxford University Press and Community Development Journal.,* pp. 1-16, 2014.

[38] C. Majidi, "Soft Robotics:A Perspective—Current Trends and Prospects for the Future," *SOFT ROBOTICS,* vol. 1, no. 1, pp. 5-11, 2013.

[39] C. Menon, . M. Murphy and M. Sitti, "Gecko Inspired Surface Climbing Robots," in *International Conference on Robotics and Biomimetics*, Shenyang, 2004.

[40] R. Alireza , S. Xichen , C. Soon-Jo and . S. Hutchinson, "Bat Bot (B2), a biologically inspired flying machine," in *Robotics and Automation (ICRA)*, Stockholm, 2016.

Appendix

A. Aerial locomotion

This appendix presents the elements developed for the aerial locomotion of the robotic system. Hardware and software aspects such as mechanical structures, electronic architecture and interconnection of the programs necessary for the flight are introduced. In addition, the experimental tests such as take-off, flight and landing carried out on the robot are described.

A.1 Hardware

Aerial locomotion is possible due to a set of 4 propellers actuated by brushless motors. The geometry in which these propellers have been coupled to the robot responds to the structure of the hexapod body, looking for a symmetrical distribution and considering a safe distance to avoid collisions when the motors are activated. In addition, this coupling geometry allows the motors to easily access the control boards and the power supply without interfering with other components of the system such as wireless tranceptors and a camera.

Figure A1 shows the attachment geometry of the 4 propellers mounted on the front and rear legs.

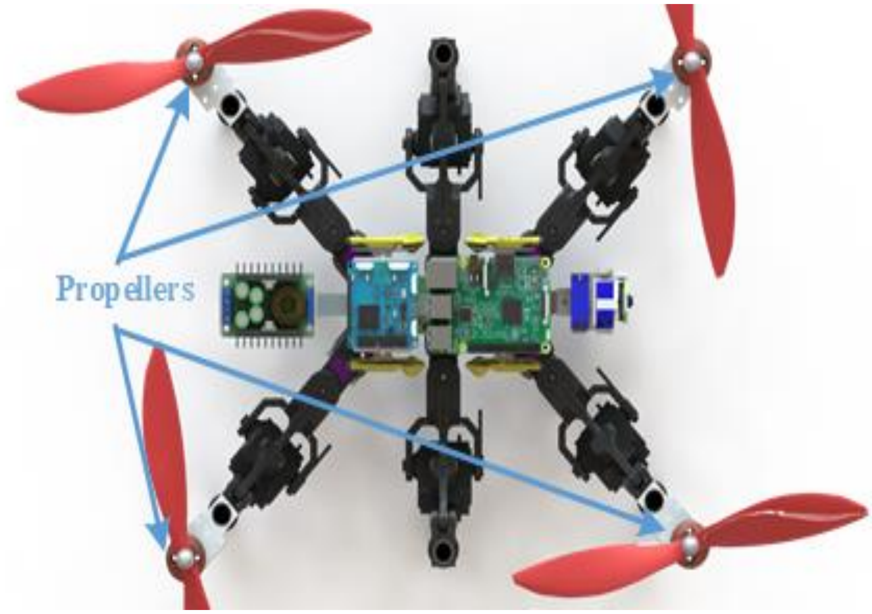


Figure A1. Propellers attached to the robot

This geometry in the positioning of the propellers does not limit the movement of the legs and does not interfere with the terrestrial locomotion process. Furthermore, aerial locomotion is also not compromised by the movement of the legs during the walking process under the tripod pattern. The 4-bar mechanism that constitutes the femur ensures that, regardless of the position of the joints, the propellers are always aligned in a configuration suitable for flight.

This implies that the robot does not has the necessity to adopt a specific position in order to start the take-off process.

Given the aforementioned advantages, a simple and light structure was used to attach the motors and the propellers to the FT (Femur-Tibia) joints as shown in Figure A2.

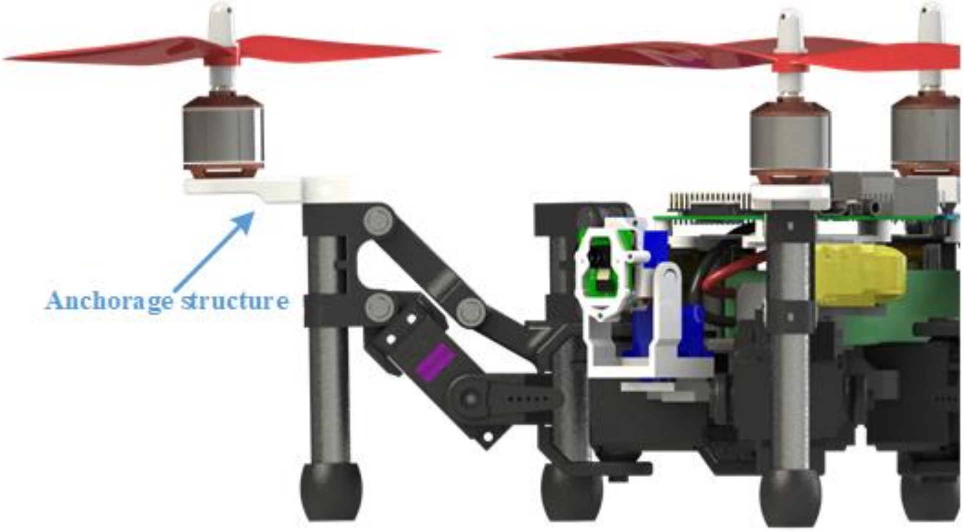


Figure A2. Propeller mounted on the FT joint

During the flight, the weight of the system is loaded on the 4 legs in which the brushless motors are anchored, causing the TC (Thorax-Coxa) joints to be subjected to stress. For this reason, it was decided to reinforce the union between the body and the TC joints by adding a structure as shown in Figure A3. This structure ensures that the weight does not deform or break the surrounding parts of the system.

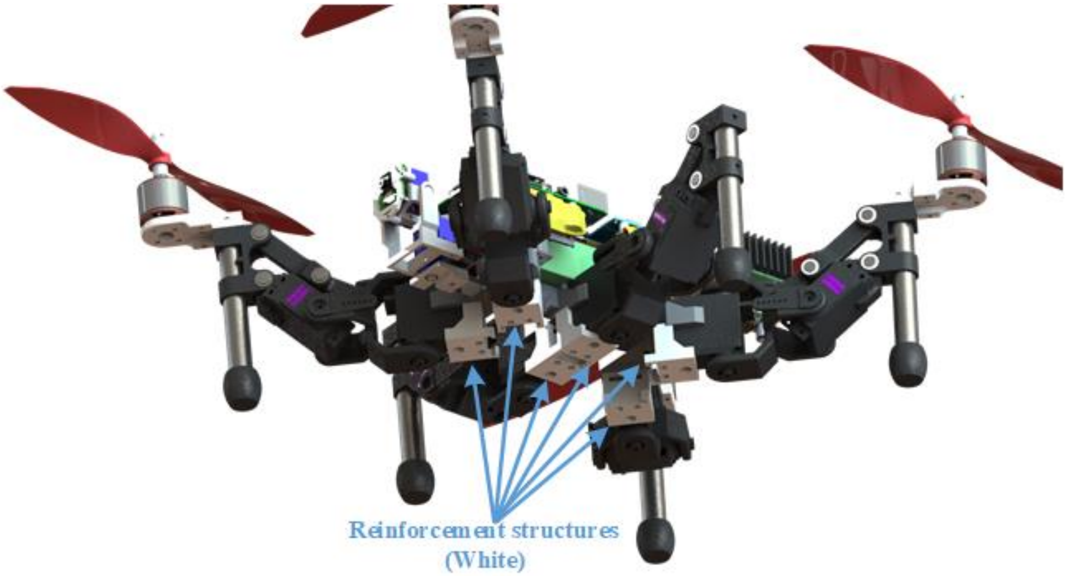


Figure A3. Reinforcement structures mounted on the system

Once the propellers were anchored, a set of electronic components was necessary to activate them. The Electronic Speed Controller (ESC) is an element capable of varying the rotational speed of the propellers based on a supplied input signal. For this application, it is desirable to use 4 ESCs, one per motor, capable of supplying a three-phase signal of at least 30 amperes in nominal use and being compatible with the 3-cell battery used in the system. For this reason, the use of the model ESC-30A of the company Readytosky has been considered.

Figure A4 shows the anchorage position of ESC on the lateral sections of the robot body. This position avoids interference of the set of ESC with the moving parts of the robot when the propellers are actuated and makes use of the flexibility and length of the wires that connect to the motors to facilitate the walking process. In addition, it allows easy connection with the battery and other electronic components.

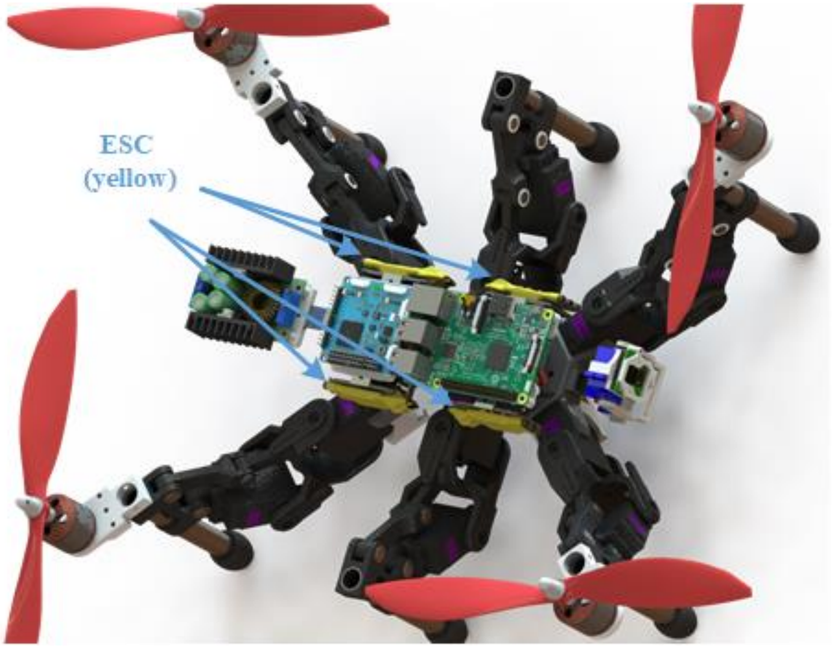


Figure A4. ESC mounted on the system

In order to ensure the flight, it is necessary to generate the appropriate signals for each ESC, keep electronic elements such as sensors and actuators in communication, in addition to monitoring variables such as height, inclination, acceleration and heading. The electronic board Crius SE 2.5 was chosen as Flight Controller Board in order to carry out the aforementioned tasks.

The Crius SE 2.5 card has built-in sensors such as an accelerometer, a barometer, and a electronic compass for monitoring the flight variables. It works with Multiwii, an open source firmware that implements and make possible to reprogram the processing, filtering and control algorithms necessary for the flight. In addition, it provides an I2C network, accessible to the user, that communicates all its components with each other and with the outside. This board provides the option to connect with other devices such as radio frequency transceivers, bluetooth modules or computers through a built-in serial port. Figure A5 shows the parts of the Crius mounted on the robotic system.

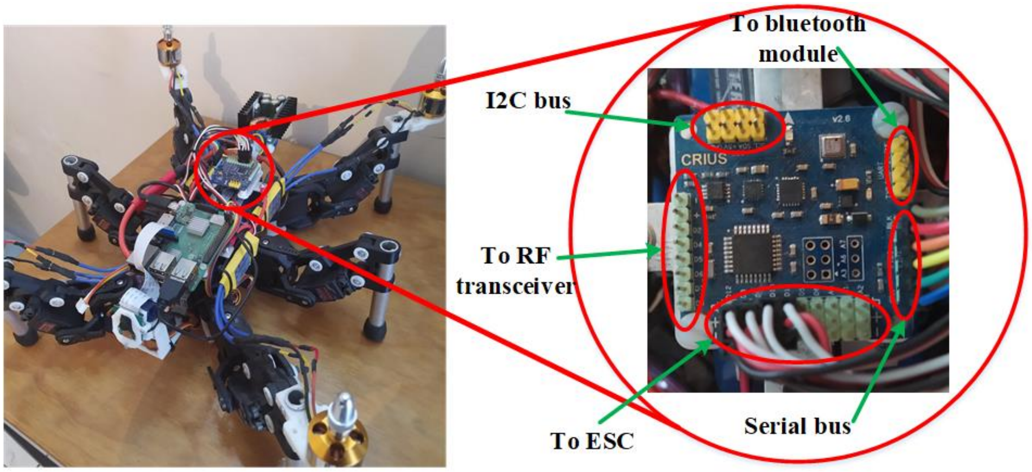


Figure A5. Crius mounted on the robotic system

A.2 Software

The Multiwii firmware can be configured according to the needs of the system through its serial port and following the MSP (Multiwii Serial Protocol). Features such as aircraft type (tricopter, quadcopter, hexacopter), sensors available in the hardware and speed range of the actuators can be adjusted. In addition, the MSP allows online modification of the 4 basic variables for teleoperation of an air vehicle. Figure A6 shows these variables, which are: roll, pitch and yaw angles that unequivocally define the orientation of the system and the throttle that refers to the vertical thrust necessary to vary the robot elevation during flight.

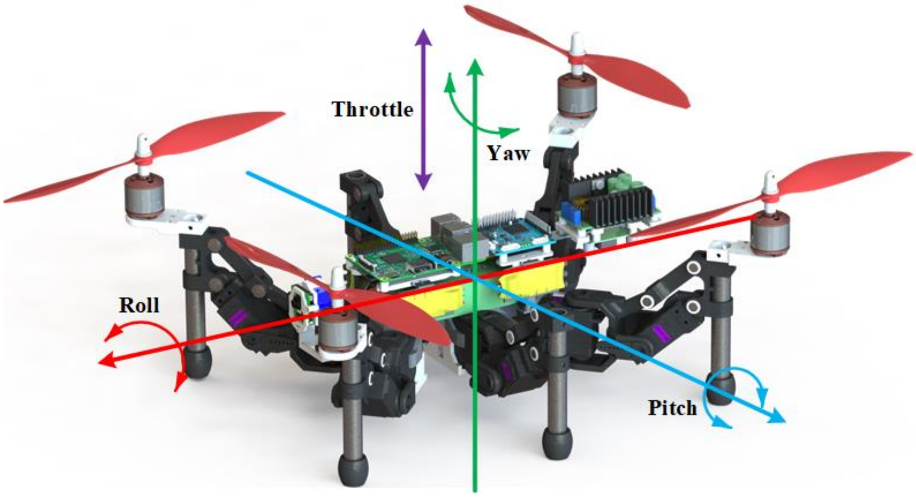
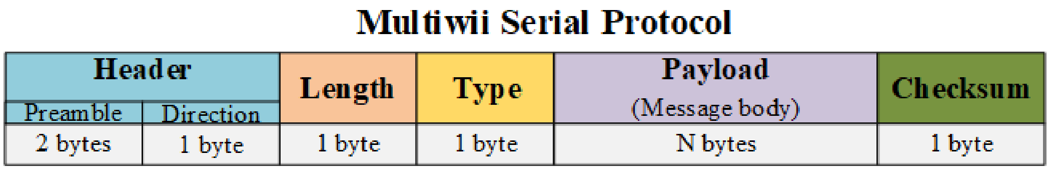


Figure A6. Roll, pitch, yaw and throttle

The MSP consists of a set of bytes sent through a serial format. The first part of the protocol, known as Header, is constituted of a 2-bytes preamble formed by the characters "$ M" that indicate the start of the transmission and of 1 byte that indicates the direction of the transmission as follows: if the character "<" is used then the Flight Controller Board receives the message, otherwise, if the character ">" is used the Flight Controller Board sends the message. The next byte describes the length of the message body, also called the payload. The fifth byte defines the type of the message between 2 categories: category "get" if data are being requested to the Flight Controller Board or "set" to modify some parameter of the Crius definitions. Finally, the payload is sent and is always followed by a checksum byte, whose function is to check whether the message was correctly transmitted or not. Figure A7 shows the structure of the data send through a serial port in the MSP format.

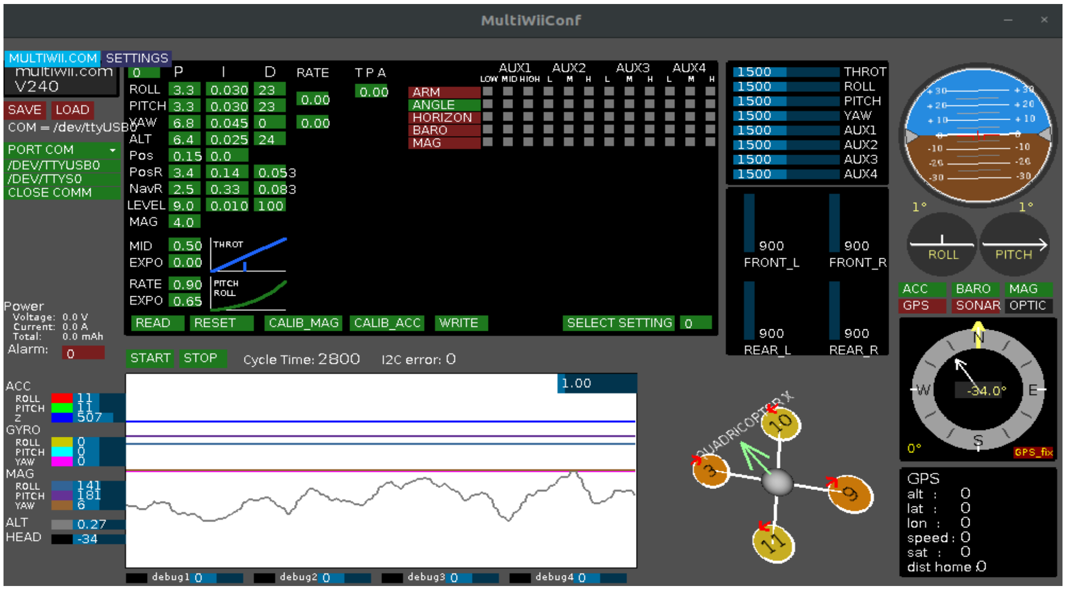


Multiwii Serial Protocol

Header		Length	Type	Payload (Message body)	Checksum
Preamble	Direction				
2 bytes	1 byte	1 byte	1 byte	N bytes	1 byte

Figure A7. Multiwii Serial Protocol

Before starting the flight process, it is necessary to tune the constants that define the control law that acts on the flight dynamics. Being a PID controller the one defined within the Multiwii firmware, the constants to be configured are the proportional (Kp) the integrative (Ki) and the derivative (Kd). The configuration of the flight parameters was done through the MultiWiiConf interface, which also allows monitoring the status of the sensors embedded in the Flight Controller Board. Empirical tuning of the control law constants is performed online and is possible by observing the propeller response during flight tests. Figure A8 shows the MultiWiiConf interface displaying graphics and values related to the flight.



COM = /dev/ttyUSB0

0	P	I	D	RATE	T P A
ROLL	3.3	0.030	23	0.00	0.00
PITCH	3.3	0.030	23		
YAW	6.8	0.045	0	0.00	
ALT	6.4	0.025	24		
Pos	0.15	0.0			
PosR	3.4	0.14	0.053		
NavR	2.5	0.33	0.083		
LEVEL	9.0	0.010	100		
MAG	4.0				

MID 0.50
EXPO 0.00
RATE 0.90
EXPO 0.65

Power
Voltage: 0.0 V
Current: 0.0 A
Total: 0.0 mAh
Alarm: 0

SELECT SETTING 0

Cycle Time: 2800
I2C error: 0

ACC
ROLL 11
PITCH 11
Z 507
GYRO
ROLL 0
PITCH 0
YAW 0
MAG
ROLL 141
PITCH 181
YAW 6
ALT 0.27
HEAD -34

debug1 0
debug2 0
debug3 0
debug4 0

1500 THROT
1500 ROLL
1500 PITCH
1500 YAW
1500 AUX1
1500 AUX2
1500 AUX3
1500 AUX4

900 FRONT_L
900 FRONT_R
900 REAR_L
900 REAR_R

GPS
alt : 0
lat : 0
lon : 0
speed : 0
sat : 0
dist home : 0

Figure A8. MultiWiiConf interface

The Crius SE board has taken the low-level tasks like sensor handling and dynamic control, so the high-level tasks, such as teleoperation through an user interface and a HMI (Human

Machine Interface), will be performed in the Main Controller Board. These boards communicate through an FTD232 board, which transmits the messages according to the MSP. Figure A9 shows the architecture used to connect the electronic elements necessary for the flight.

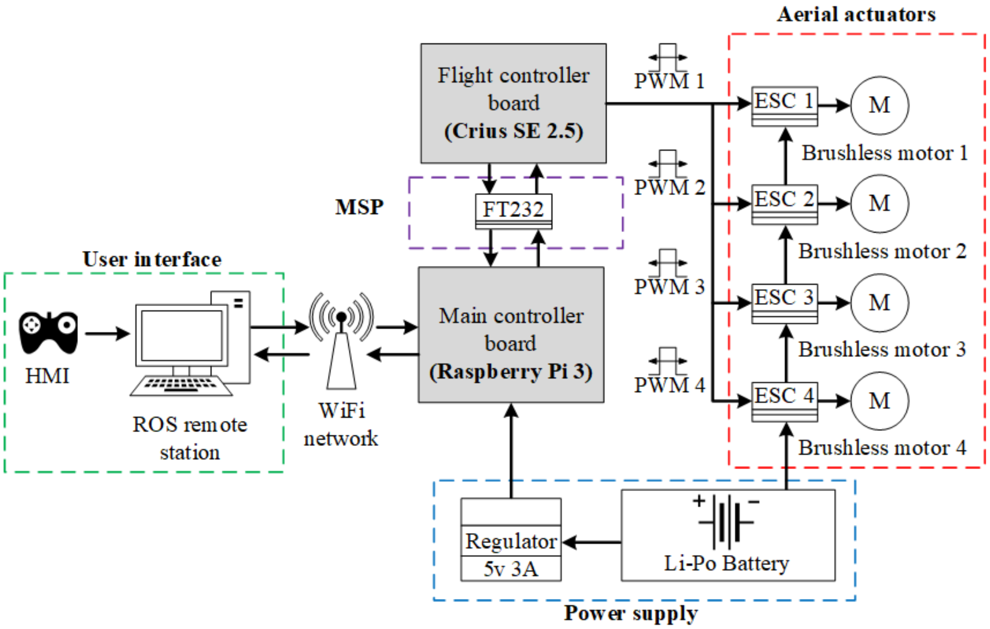


Figure A9. Electronic elements necessary for the flight

For the interaction between the Flight Controller Board and the Main Controller Board, a Python language module for the transmission of data via the serial port following the MSP was written. In addition, other scripts necessary for the teleoperation of the flight from a remote station through an HMI in the form of a manual remote controller were written. The necessary programs for the flight were organized in the form of nodes within a ROS network. The node that implements the MSP was executed in the Main Controller Board while the teleoperation and management nodes of the HMI were implemented in the remote terminal. Figure A10 shows the interconnection of nodes in the network.

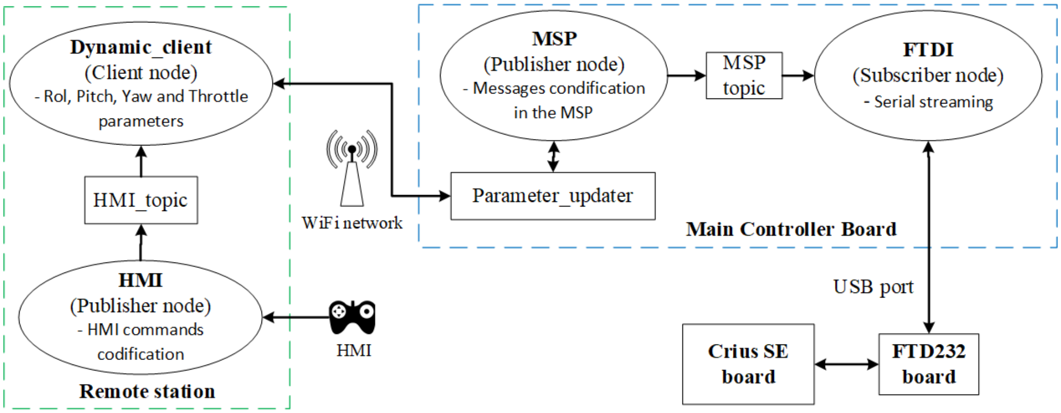


Figure A10. ROS nodes for the flight

A.3 Implementation

To carry out experimental tests, the flight process was divided into the take-off, subsistence and landing stages. Take-off and landing stages are mainly defined by the throttle variable. The subsistence stage, which depends on the stabilization of the aircraft, also depends on the roll, pitch and yaw variables.

A standardized action on quadrotor aircrafts is the "arm / disarm" process. The arm process enables the propellers to be commanded by the variables of roll, pitch, yaw and throttle sent by a higher control unit. Otherwise, the disarming process disables the propellers as a security lock to prevent unintended activations.

As mentioned in the previous section, the flight process considers its teleoperation by means of a remote terminal and through an HMI in the form of manual remote controller. The buttons and joysticks of this manual controller have been designated to modify the variables that govern the terrestrial and aerial locomotions of the robotic system as Figure A11 shows.

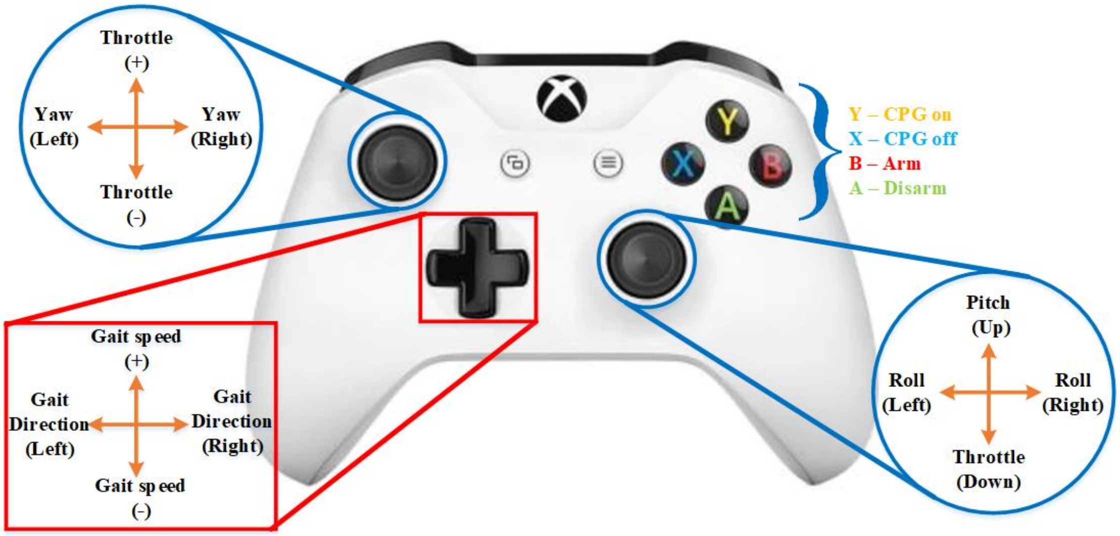


Figure A11. Manual controller used for teleoperation

In order to guarantee the integrity of the physical experimental model, the first flight tests in the take-off, subsistence and landing phases were performed separately and by stages. During take-off tests a gradual acceleration of the propellers was determined as a strategy to avoid overheating of the actuators and to avoid damage to the battery that would decrease its life cycle. Tests during the subsistence phase showed difficulties in stabilizing the system in flight due to the weight added by the structures for terrestrial locomotion. Therefore, the gradual variation of the roll, pitch and yaw variables was established as desirable in order to ensure smooth aerial movements. Figure A12 shows the robot during a take-off test.

Figure A12. Robot during a take-off test

Finally, during the landing tests 2 possibilities were studied: landing with the legs extended or retracted. The legs retracted option was chosen because it allows to distribute the impact of the landing between the legs and the body in order to reduce the risk of damage to the robot. Figure A13 shows a front view of the contact points of the system with the ground during landing with the legs retracted.

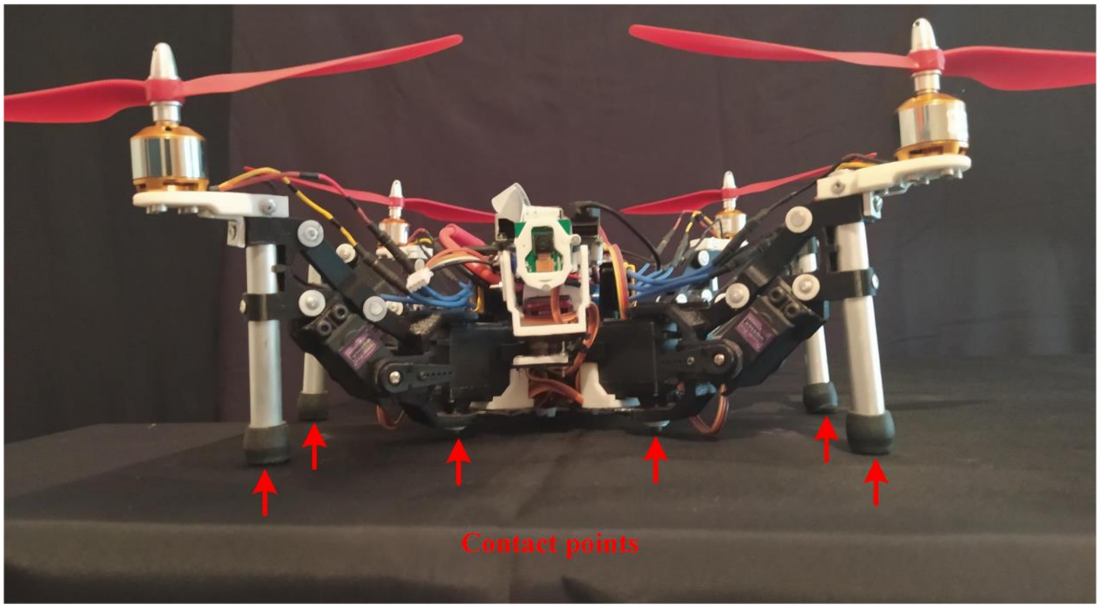


Figure A13. Front view of the contact points

With the take-off, subsistence and landing strategies determined during the previous tests, it was possible to carry out more experiments that involved the integration of the aerial and terrestrial locomotion modes. For the implementation of these experiments, a scenario with flat surfaces at 2 different height levels was designed and set up. As the Figure A14 shows, it is impossible for the robot, initially on the low surface, to move from the lower to the higher one only by means of its terrestrial locomotion.

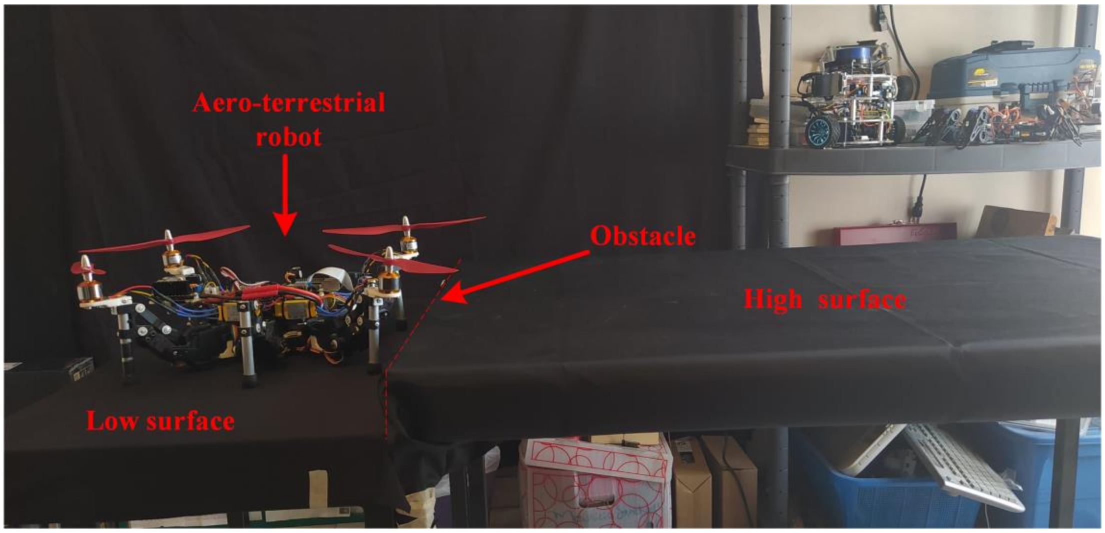


Figure A14. Scenario of the experimental tests

The strategy used by the robot in this scenario consisted in the transition to the highest surface through aerial locomotion. Once the obstacle had been evaded and positioned on the high surface, the robot was able to walk to the end of the terrain. Video-5 stages this transition process and can be consulted at the following link:

https://www.youtube.com/watch?v=VcLnfnzkvF8