Analysis of Robotics Applied to Mobility in the Air Intakes of a Fighter Aircraft

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***Abstract*—For the correct operation of aircraft in the aerospace industry, maintenance and inspection protocols were designed to safeguard the safety of the pilot and the integrity of the aircraft, one of the spaces difficult to access for technicians responsible for the inspection of the aircraft are air intakes, That is why the maintenance area of the Peruvian Air Force (FAP) in collaboration with the National University of San Agustin (UNSA) conducted a review of the latest technological advances in robotics applied to mobility in confined spaces similar to the air intakes of a fighter plane, classifying them according to their locomotion system in wheel robots, caterpillar, adherent and contactless, in order to qualify their possible performance in the inspection work in compliance with the requirements requested by the institutions. Two values were assigned to each technology, the first one qualifies how well it complies with the requirements based on the results exposed in the literature and the second one evaluates the importance of each requirement calculated with the Mudge diagram based on the experience of the maintenance technicians, being the final qualification the product of both values; obtaining the highest score the mobility technology of the tracked robots, which in conclusion is the technology that could be better adapted for the work environment that in the future will be corroborated with the laboratory tests.**

***Index Terms*—Aircraft, robots, mobility, air intakes, caterpillar, wheel, suction cup, vortex, electro-adhesive, continuous, UAV**

I. Introduction

Robotics applied to mobility technology is currently used by the industry for inspection tasks in order to increase their efficiency, effectiveness and reach so that they can ACCESS places that are inaccessible to humans, as in the case of air intakes whose geometry depends on the requirements of fighter aircraft, these were designed for optimal engine performance, maintaining subsonic air speed at the inlet and optimal flow distortion levels [1-4], the type of air intake for fighter aircraft in this work is in the variable geometry classification. In the Peruvian Air Force (FAP) in ORDER to safeguard the integrity of the fighter aircraft and the safety of the pilot from the danger posed by the presence of Foreign Object Damage/Debris (FOD) in the air intakes which have the capacity to cause damage with costs in the millions of dollars, so it is subjected to various pre-flight controls. In the aeronautical industry inspection, there are solutions such as the use of unmanned aerial vehicles (UAV) by the Spanish Air Force and Airbus for the inspection of their aircraft [1]; on the other hand, in recent research, there is the Vortex and the suction cup robot applied in the inspection of the external fuselage of commercial aircraft, the continuous and electro adhesive robots applied in the inspection of aircraft engines; however, these proposals are only focused on the revision of air intakes.

On the other hand, in the piping, boiler, heating, ventilation and air conditioning (HVAC) duct industry, we find a similar solution to the inspection problem in air intakes. See Fig. 2, for a better analysis, they have been conveniently classified according to their mobility technology as follows: Wheel Robot, Crawler Robot, Adhesive Robot and Non-contact Robot. The wheel type is applied in the inspection of pipes, boilers and HVAC ducts, is mobilized by wheels with different configurations, being able to vary the number of wheels, location of these, form of action and the customized structure of the vehicle that allows to improve the traction capabilities of the robot and that can be adjusted to the inspection terrain [5-14], the caterpillar type is applied in the inspection of pipes, boilers, HVAC ducts, however, it has better qualities compared to the wheel type, it is mobilized by caterpillars, and can also be found in several configurations [15-21], the adhesive type is applied in the inspection of pipes, engines and aircraft fuselage, these robots have capabilities that allow them to move on surfaces with horizontal, vertical and inverted orientation, since the different types of locomotion mechanisms normally used such as legs, caterpillars and wheels are associated with suction cup adhesion systems, vortex and electro adhesion

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[22-36], finally, the non-contact type is applied in the inspection of HVAC ducts, engines and aircraft fuselage, referring to continuous robots and UAVs which have no contact with the environment while moving [37-43].

This document has developed a review of the latest advances in robotics applied to mobility in confined spaces and seeks to perform an evaluation oriented to the mobility in the air intakes of a fighter aircraft, under technical criteria supported with a mixed analysis (qualitative-quantitative) and in the company of FAP maintenance technicians. Section II presents the characteristics of the air intake work environment and the tasks in which the robot would have to perform for a satisfactory inspection and detection of FOD, whose results will be the basis for the design of a robot with the ability to move effectively and efficiently in that environment. Section III classifies according to the mobility of the reviewed robots that work in confined spaces similar to air intakes, in addition to a prospective of each model oriented to mobility in the mentioned work environment, later in section IV each type of robot is compared according to its mobility technology to then express those that are best suited to inspect air intakes.

II. Working Environment: Fighter Aircraft Air Intake

The variable geometry air intakes of fighter aircraft are located downstream of the cockpit, right in the middle part of the aircraft as shown in Fig. 1.a; they have the function of regulating the air flow as required by the aircraft engine to achieve optimum performance in flight.

These air intakes have the particularity of having a "Y" shape and variable geometry in almost all its path, it is composed as follows, see Figure 1.b:

-Air inlet: There are 2 air inlets, located on each side of the cabin, this has the shape of a circular trapezoid as shown in Fig. 1.c and the available space is 16 cm.

-Critical section: It is the section with the smallest available space, this is 14 cm, its shape is also that of a circular trapezoid and it is located 30 cm from the air inlet.

-Peripheral damper 1: There are 2 peripheral dampers, located on each side and are located at the bottom of the air intake, despite being closed in the pre-flight, these have a narrow cavity as shown in Fig. 1.e, where the detection of FOD would be complicated.

-Peripheral damper 2: There are 2 peripheral dampers, located at the intersection and they are located at the bottom of the air intake, the shape of their cavity is observed in Fig. 1.f.

-Intersection: It is the part where the circular trapezoid shaped air intakes connect and result in the shape of a circle with a diameter of 78 cm as seen in Fig. 1.d

-Air outlet: There is only 1 air intake outlet and it is also where the fighter jet engine starts.

In order for a robot to move through the air intakes performing the inspection and FOD detection tasks successfully, an evaluation of various mobility technologies is first required, outlined in the next chapter.

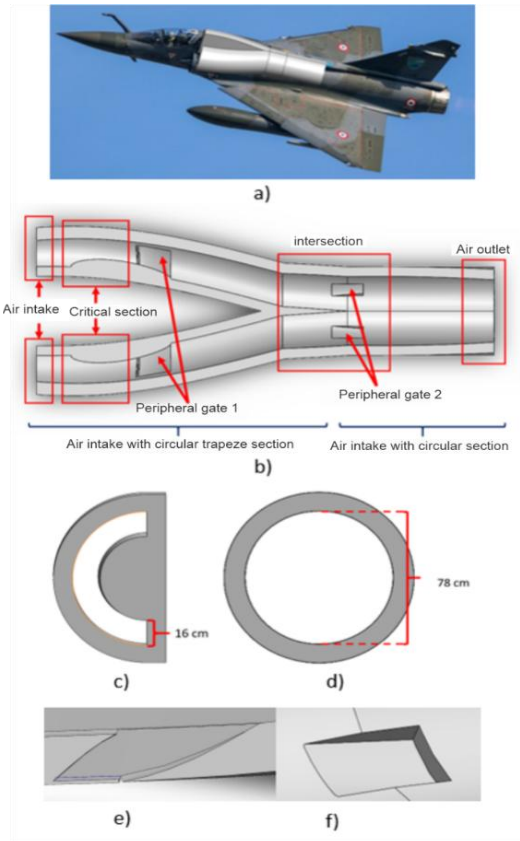


Figure 1. (a) Location of air intake on fighter aircraft [44] (b) Components of air intake (c) Section at air intake inlet (d) Section at air intake outlet (e) Peripheral damper 1 (f) Peripheral damper 2.

III. Classification of Robots According to the Technology Applied in Their Locomotion

Regarding robotic inspection in confined spaces, there is a large number of robots, these have been conveniently classified according to the technology applied in locomotion as shown in Fig. 2, to perform a better analysis of the inspection of air intakes of a fighter plane.

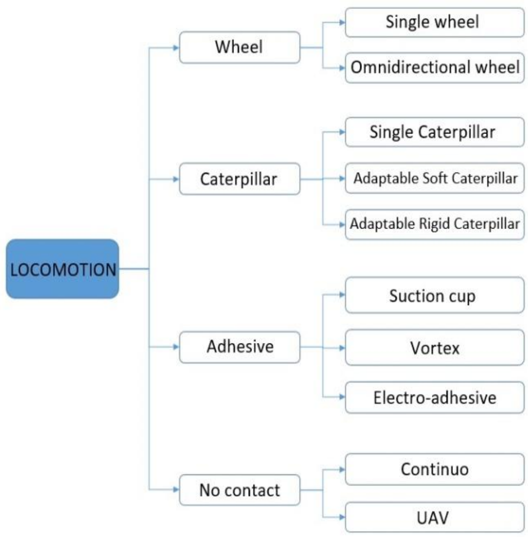


Figure 2. Classification of robots according to their locomotion

A. Robots with Wheels

According to the work of R. Ramakrishman [45] the mobility of a robot is mainly related to its size, surface of movement and the way the wheel propagates; on the other hand, the interaction of the wheel topography depends directly on the load capacity of the ground and the traction performance of the wheel; so for a design with this technology it becomes necessary to take these variables into account to obtain the best possible performance.

Classified in this section are robots that use wheels to move, this classic technology offers different configurations that can be adjusted to the terrain and the task to be performed by selecting the number, type of wheel, location, performance and structure of the vehicle; in addition these have variations of the traditional model improving their traction and adaptability capabilities according to the work environment for which they were designed.

1) Single wheel robots

Simple wheel technology is considered in this paper to be the discs that rotate on their own axis like the one in Fig. 3.a; this technology by having small modifications acquires properties that are used to adapt to the diverse catalog of possible scenarios that the user could encounter, as is the case of the AVAQUS-based wheeled pipeline robot [5] that thanks to the terramechanics-based design using the finite element software AVAQUS is prepared to overcome muddy terrain. Another similar design is the robot with wide wheel for soft terrain, which was designed using the modeling method, ground contact (SCM) the work of Saeed Ebrahimi [6-7] managed to make an optimization algorithm based on the optimal maneuvering shape of the rovers, for this design was considered the effect of self stability against a rigid obstacle that makes it able to overcome rough and rigid surfaces with the proposal of a new type of self-adjusting wheel shape; the objective is to obtain a reduction of the required torque using the SCM method, an easier maneuvering turn and an adequate control of the wheel sinkage.

Single wheel technology could be useful due to its simplicity and low manufacturing cost, however, several technological adjustments are needed to meet the requirements satisfactorily proposed in section II.

2) Omnidirectional wheel robots:

The fundamental design of this technology is shown in Fig. 3.b. and as can be inferred from its geometry, more sophisticated controllers, software and sensors are required to take into account the displacement of the center of gravity, stability, etc. to fully exploit the capabilities of this technology, different variations have been designed with successful applications such as the ObBuRo robot [11], designed to enter into confined spaces with the ability to move longitudinally and laterally balancing using the principle of the inverted pendulum with dual-axis wheels inspired by unicycles, has the ability to follow routes pre-established by researchers without the need for the robot chassis to rotate on its axis; another variant of this technology are the mecanum wheels that have the characteristic of having the rollers at 45 º with respect to the circular edge of the wheel end, in the model of Changlong Ye [13] , who in order to find an optimal structural design for the wheels, analyzes the relationship between motion accuracy and error with the number of rollers installed on the wheels, at the end of the tests indicates that these are still unstable in motion due to the problems of impact and vibration caused mainly by the discontinuity of the design leaving way for future improvements in later models; Jesus H. Lugo's tetrorail variant seeks to acquire all-terrain capability. A comparative study was carried out to evaluate its performance, resulting in an advantage of the design over the Mecanum wheels when rotating on its own center; Finally, the wheels of Vaibhar Nand Kumar Kadam's design [14] has a notably superior advantage over the omnidirectional wheel models due to its unrestricted maneuverability; it is composed of three coordinated Sphero mini spherical robot modules that allow it to maneuver easily in flat confined spaces; this technology has problems with friction due to the design of its wheels. The different problems that this technology could have are mainly related to the complicated control for the user, but this could be solved with a control software and a more friendly and simple user interface using mathematical models and computer simulations [8-10].

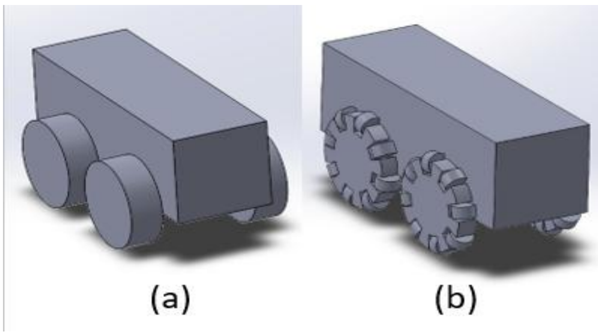


Figure 3. (a)Single wheel robot, (b) Omnidirectional wheel robots

B. Caterpillar Robots

This category includes robots that use tracks to move and perform the tasks for which it was designed, this technology has the property of adapting to the terrain where they work while maintaining greater stability and traction due to its greater contact surface; in this document this technology has been classified by the arrangement of the tracks in three variants: Simple Caterpillar, Adaptable Soft Caterpillar and Adaptable Rigid Caterpillar. In the following, tracked robots working in environments similar to those considered in Section II are presented.

1) Simple caterpillar

This classification considers those robots that perform their functions with two sets of tracks without extra support arranged on the sides as shown in Fig. 4.a; robots with this technology are able to move on uneven terrain with stability, maneuverability and good traction. Mohd Zafri Baharuddin's LS-01 robot [15] is designed to optimize the inspection of the boiler heads of Tenaga

Nasional Berhad (TNB) thermal power plants, it is equipped with a probe capable of obtaining the necessary images to determine their condition by going into the narrow path where the operator used to do it manually, these checks are frequently performed to verify that the boilers present signs of possible failures due to their thick-walled design and exposure to adverse service conditions. As a sample of the all-terrain capabilities of this technology is evidenced by the application in agriculture where a robot with the ability to increase the efficiency of inputs and labor required to increase production in this area, the work of Sania Afreen [17] offers a solution consisting of a tracked robot that can traverse without problems the multiple surfaces encountered in agricultural work, this robot also has compatibility with a wide arsenal of interchangeable tools and sensors that make it the best in its field improving by 46% the manual work, With the technology of interchangeable tools a robot can greatly increase its capabilities for the conditions for which it will be designed, also the stability offered by the single track technology allows it to perform its tasks and overcome the rough terrain of agriculture, demonstrating satisfactorily that this technology is a strong candidate to be applied in the inspection of the air intake.

Single tracked robots prove to be very competent in the area of inspection of confined space similar to the one to be worked on as seen in Fig. 1.b with the difference of the change in diameter of the air inlet and the lower opening, being these obstacles surmountable by this technology. Adding further that according to the work of O.O Pavlovskaya's team [46] an automatic system is required that with the feedback provided by the sensors installed on the robot that compensates for the spontaneous deviations caused by the change of properties of the working floor thus achieving a substantial improvement to the maneuverability of the robot in its inspection tasks.

2) Adaptable soft caterpillar

The elastic crawler technology in this paper is considered those with the property of imitating the movement of amoebae, compared to the previous ones they have the ability to adapt to the environment where they are located by deforming their tracks that are bent outward using the elastic force of the crawler belt to apply pressure to the walls of the working surface as seen in Fig. 4.b. The simple and compact mechanism proposed by Fumika Fukunaga's team [18], has technology with the ability to mobilize multiple crawler belts in a cylindrical environment driven by a worm gear, the model is very compact compared to the other models.

The elastic force of the belts in the model, in addition to its small size, gives it the capacity to work in chemical, water and gas plant pipelines, where it yielded satisfactory results with respect to locomotion and maneuvering.

This technology is promising for the work of inspection of air intakes for its adaptability in variable environments and its simple mechanism that promise low cost in maintenance and manufacturing, however, this technology is so little developed that adapting it to the needs of the FAP would raise development costs considerably by the different iterations between materials and configurations for testing.

3) Rigid caterpillar adoptable

Rigid crawlers are considered to be those that maintain their shape thanks to the extra modules used for locomotion; they adapt to the environment by exerting force on the working surface, as shown in Fig. 4. c, they are mainly used in pipelines with complicated routes with diameters that can vary, they have the ability to climb and in addition to a maneuverability that allows them to pass smoothly through pipes, elbows and T fittings; as in the design of Yoon Gu Kim's equipment [19] which is intended for the inspection of pipes in industrial and practical installations, its technology makes it capable of moving multiple caterpillars that are pressed from the central module to the contact surface, it has the property of having self-sufficiency in its inspection tasks, in addition to the ability to navigate in its working environment and circumvent the obstacles that it could encounter while maintaining its stability and avoiding slippage. On the other hand, the work of Ajit Salunke's team [20] is a robot mounted on a hexagonal housing and has three tracks of rubber tracks with a shock absorption system, this model is controlled by an integrated ATMEGA32, the work for which the model was designed is abrasive cleaning of circular pipes maintaining its stability and route thanks to the detection of obstacles by the installed ultrasonic sensors. In order to solve the problem that is the inspection of subway pipes, Rohit Kashyap's team [21] seeks with its two design versions of the SAPER robot of multiple tracks to solve them preventing future disasters produced by any malfunction in these systems.

The technology used by the adaptable rigid robot is very similar to the robots with simple tracks, with the marked difference that they have the extra support of a third track on the robot designed to give greater traction to the robot offering adaptability to the variable diameter in the pipes and a robust model with the ability to mount a tool, extra equipment and proximity sensors; technology that could be very useful to circumvent the obstacles shown in Fig. 1.b and offer extra services in addition to just inspection without sacrificing stability.

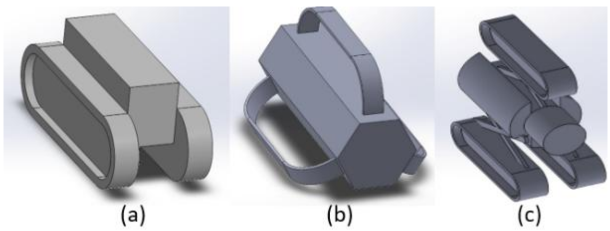


Figure 4. (a) Simple caterpillar, (b) Adaptable soft caterpillar, (c) Rigid caterpillar adoptable

C. Adhesive Robots

Adhesive robots have the ability to move on different surfaces in horizontal, vertical and inverted orientation, because they have adhesion systems that are classified as suction cup, vortex and electro-adhesive.

1) Robot suction cups

The suction cup robots usually use limbs to move, and in each one there are suction cups with which the robot adheres to the surfaces, see Fig. 5.a. It is generally used in the aerospace industry for the inspection of the internal and external fuselage of aircraft.

Wang [22-24] developed a robot for the inspection of the external fuselage of airplanes, it has 8 extremities to move, and at the end of each extremity it was installed suction cups driven by a pneumatic adsorption system with which it adheres to the fuselage. Tests were carried out on a commercial airplane to inspect the rivets.

Shang [25] designed a climbing robot to inspect the fuselage of airplanes, it has 2 sets of extremities that make its movement more flexible, equipped with suction cups which are driven by a pneumatic system and adhere to the surface, it was tested on a curved aluminum plate to simulate the inspection on an airplane.

The suction cup robots are the ones that have been used for the inspection of aircraft for the longest time, however, due to their robust adhesion system, their application is limited to the external fuselage, therefore, an inspection of internal parts of the aircraft such as the air intakes would be complicated.

2) Vortex robot

Vortex robots are characterized by using a mini turbine that keeps them adhered to the surfaces, see Fig. 5.b, they were designed to inspect at a higher speed surfaces of complex shape such as the fuselage of airplanes.

Ramalingam [26] developed a climbing robot to inspect aircraft fuselage. The main feature of this robot is that it is divided into 2 modules, and each one has its own mini-turbine to adhere to the surface, this configuration allows it to move in more pronounced changes of direction. Inspection tests were performed on the external fuselage of a Boeing 737 and compact airplanes.

The VRP robot [27-32] was developed as a better alternative to the suction cup robot for external fuselage inspection of airplanes. The Vortex robot adheres to surfaces because it is propelled against them by a mini-turbine located in the middle part of its structure. It moves on wheels and locomotion tests were performed on Boeing 737 airplane fuselage, pipes, and vertical and inverted flat surfaces.

Liu [33] designed a bio-inspired climbing robot for signal collection on bridges, search and rescue at disaster sites, and mine inspection. This robot is characterized by having a mixed adhesion system (vortex-suction cup) in addition to having micro-spine-like wheels inspired by the legs of flies to be able to move on various types of surfaces. The robot was tested on a variety of rough wall surfaces demonstrating stability with additional loads.

The Vortex robot is a recently developed technology, however, from the tests performed it shows a clear advantage over suction cup robots in adhering to surfaces. On the other hand, on its application for inspection in the air intakes of a fighter plane there is a potential drawback, since, due to the suction effect of the mini-turbine, it could end up hindering the work of FOD detection and even damaging the robot's propellant.

3) Electroadhesion robot

The electroadhesion robots, see Fig. 5.c, use an adhesion technique that consists of using an electrode film to adhere to the surface by electrostatic forces, this works on conductive and non-conductive materials [36]. They were mainly designed to inspect difficult to access spaces, such as the internal fuselage and engine of an aircraft.

Rivaz [34] designed a novel adhesive microrobot, to climb and inspect in complex workspaces (vertical surfaces, inverted and confined environments). This microrobot is a quadruped that adheres to surfaces by means of electro-adhesive pads. Tests were performed on a commercial aircraft engine demonstrating its potential in industry, however, the robot was unstable when moving on non-conductive surfaces.

Wang [35] developed an adhesive robot to move on complicated surfaces. The robot is driven by an electrostatic motor and adheres by electroadhesion technique to the surfaces, 2 models were developed, the first has a rigid structure and was tested on flat vertical aluminum surfaces, the second has a flexible structure consisting of several joints, which allow its adaptation to changing aluminum surfaces (horizontal floor-sloping floor).

Yamamoto [36] developed a robot with a novel electroadhesion mechanism for wall climbing. He built 2 models, the first one consists of 4 limbs with electroadhesion pads and was tested on a wall made of conductive material, the second model consists of an electroadhesion belt that moves like a caterpillar, increasing the adhesion capacity to move on non-conductive surfaces, as occurred in the test on a glass surface.

The electroadhesion robot is a promising option, since its design was made thinking of inspecting very small spaces, such as the air intakes of a fighter plane, however, being a recent technology, it is in the experimental stage and its main problem is its load capacity, since in the latest research it has not yet been possible to install an inspection device on the robot.

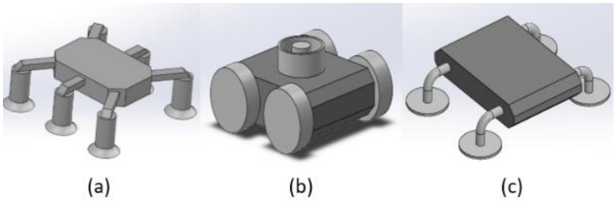


Figure 5. (a) Robot suction cup, (b) Robot vortex, (c) Electroadhesion robot

D. Non-contact Robots

This category includes robots that are designed not to come into contact with the work surface; these technologies are more adaptable than those mentioned above due to their independence from the surface. They can be classified into continuous robots and UAVs.

1) Continuous robot

This technology is designed based on the anatomy of snakes and has the main feature of not using wheels to move and being composed of several modules driven by internal tendons driven by external actuators, this technology can maneuver without having contact with the walls of the work environment, additionally some designs have an end effector to perform repair operations, see Fig. 6.a.

Tang [39] developed a hyper-redundant continuous robot driven by cables and validated experimentally as part of a continuous robot design methodology. On the other hand, models applicable to the aeronautical industry were developed, such as the work of Wang [37-38] who developed a thin, dual-structured continuous robot for the inspection of the combustion chambers of commercial aircraft engines. Likewise Dong [40] developed a thin continuous robot for the inspection and repair of the blades in the first stages of the compressor of commercial aircraft engines.

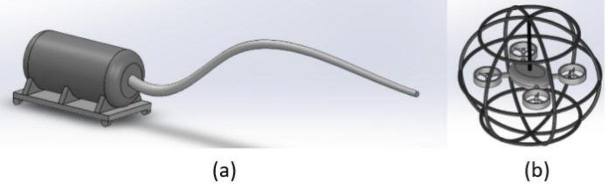
The presented continuous robots are a good option for inspecting the first meters of the air intake of a fighter jet, in addition to being able to adapt to the variation of the geometry of the duct, however, their range is limited compared to the length of the air intake (4 meters).

2) UAV robot

UAVs used in confined space inspection have the main feature of having a cage which protects its propellers as well as the integrity of the environment to be inspected. see Fig. 6.b.

Caroti [41] focused on extending the capabilities of commercially available caged UAVs to be able to perform photogrammetry in confined space environments (masonry tank and ventilation duct) and other conditions (low illumination, glare and dust) by experimenting with different photogrammetric processing procedures. Edgerton [42] presented a design methodology of spherical protective cages for UAVs, for this, cages of different materials were manufactured in 3D printing, Finite Element Analysis (FEA) simulation was performed to determine their mechanical characteristics, then a wind tunnel study was performed to determine the aerodynamic performance of the cage, and finally tests were performed in indoor environments. Ahmed Borik [43] developed a 3D printed caged UAV for HVAC duct inspection. Designed to move by rolling and floating in its cage, reducing energy consumption and extending inspection time, it is also remotely controlled and is able to navigate autonomously, its main function is to detect cracks and thermal leaks.

The UAVs presented are an alternative to be able to inspect in air intakes, however, the instability and low quality in the visualization of the environment ends up hindering considerably the detection of FOD.



(a) (b)

Figure 6. (a) Continuous Robot, (b) UAV Robot

IV. Information Analysis

In the present chapter we seek to perform the technical analysis and with mixed economic factor (qualitative-quantitative) to the locomotion technologies reviewed in the previous chapter, the Mudge diagram is used because it allows to evaluate in a practical and understandable way the relevance indicators of the locomotion technology of each robot reviewed, for its possible incorporation in the air intakes of a fighter aircraft. Although the Mudge diagram has limitations compared to other methods, this drawback was overcome with the collaboration of the FAP maintenance technicians of Air Group No. 4, who contributed with their evaluation criteria, obtaining accurate results.

For the evaluation of the robots, a scoring method was used based on research on the review of robots for inspection in pipelines, whose environment is similar to air intakes [47]. The scoring of each technology was done based on the results of the tests performed on the robots analyzed in Chapter III, the analysis used is qualitative and quantitative [48] and the indicators were evaluated with the Mudge diagram, taking into account the opinion of maintenance technicians, manufacturing and maintenance inputs of each technology in the international market.

A. Robot Requirements

1) For an adequate evaluation of the robot technology applied to the mobility in the air intakes of a fighter plane, 7 mobility indicators were used, which are the result of the demands that this task entails and what is required by the users of the maintenance area of the FAP, these are the following: Adaptability to the environment, measures the robot's ability to adapt to the different internal shapes of the air intake while moving.

2) Dimensions, refers to the dimensions of the robot that allow it to have the ability to enter the smallest part of the air intake.

3) Range, measures the ability of the robot to move away from the control point to the deepest part of the air intake and exit without mishap.

4) FOD detection effectiveness, measures the robot's ability to detect FOD without inadvertently interrupting FOD.

5) Stability, measures the robot's ability to move while maintaining balance.

6) Maneuverability, ability of the robot to perform the required maneuvers comfortably for the user in order to perform its tasks in the environment.

7) Speed, ability of the robot to move through the air intakes and inspect them quickly.

8) In addition to the 7 indicators mentioned above, 2 indicators that evaluate operation and maintenance costs have been added, as follows:

1. Cost, this indicator refers to the international market price of the parts required for the construction of the robot.
2. Availability, this refers to the ease of finding quality spare parts on the market.

PREFERENCE MATRIX MUDGE METHOD

FOD detection effectiveness	Dimensions	Adaptability to the environment	Stability	Maneuverability	Availability	Cost	Scope	Speed			
A	B	C	D	E	F	G	H	I	Sum	Percentage	Mobility indicators
A	B1	C1	A1	A1	F3	G3	H1	A3	5	7%	FOD detection effectiveness
	B	C1	B1	B3	F1	G3	B1	B3	9	13%	Dimensions
		C	C3	C3	F1	G1	C1	C3	12	17%	Adaptability to the environment
			D	D1	F3	G3	H1	D1	2	3%	Stability
				E	F3	G3	H1	E1	1	1%	Maneuverability
					F	G1	F1	F3	15	21%	Availability
						G	G1	G5	20	29%	Cost
							H	H3	6	9%	Scope
								I	0	0%	Speed
								Total	70	100%	

Importance	
Much more important	5
Moderately more important	3
Little more important	1

Figure 7. Mudge diagram to determine the level of preference of each mobility indicator.

The indicators were evaluated using the Mudge diagram, taking into account the opinion of the maintenance technicians, the manufacturing and maintenance inputs of each technology in the international market; This analysis can be seen in Fig. 7, which consists of assigning each indicator a letter, in this case it is from "A" to "I", the letters are placed at the top and on the diagonal of the diagram, then the importance of the indicators is evaluated in pairs, such as B is slightly more important than A so the score is B1, This means that the indicator B has 1 point, in this way the scores of the whole table are completed from left to right, in the Sum column is observed the accumulation of the scores for each indicator and on the right side is observed the column of percentages of each indicator. To determine the relevance factors, first the highest and lowest scores of the indicators in the Mudge diagram were assigned an equivalent factor of 2 and 0.5 respectively, then to obtain the other factors, a linear interpolation was performed; these results can be seen in Table I. This relevance factor will be used in the technical analysis and with the economic factor presented below.

TABLE I. REELEVANCE FACTORS

Item	Score
Cost	2
Availability	1.6
Adaptability to the environment	1.4
Dimensions	1.2
Range	1
FOD detection effectiveness	0.9
Stability	0.7
Maneuverability	0.6
Speed	0.5

B. Technical Analysis

For this section, the mobility technology was evaluated clearly, in the qualitative-quantitative analysis of each technology a scale from 1 to 4 was used, of ascending valuation, being 1 bad, 2 regular, 3 good, 4 very good; multiplying by the relevance factors of table I, obtaining as a result the final scores expressed in table II; being the mobility technologies that best adapt the following: adherent by electro-adhesion (20. 4), adaptable soft track (20.2), continuous (19.3), simple track (18.9), and adaptable rigid track (18.8), where we found that the tracked technology is the most reliable in the industry for this type of activities, noting superior in the average score (19.3), these results can also be visualized in a better way in Fig. 8.

C. Analysis with Economic Factor

In this section the technology is analyzed by adding 2 indicators to evaluate the operation and maintenance costs, the final score of these indicators is observed in the first 2 rows of Table II; being the best adapted technologies the following: single track (33.3), single wheel (31. 4), adaptive soft track (29.4), omnidirectional wheel (28.4) and UAV (27.4), where we find that the wheeled and tracked technologies are the most commercial, being their average score of (29.9) and (29.57) respectively, these results can also be better visualized in Fig. 9.

V. DISCUSSION

Different mobility technologies were reviewed and evaluated and conveniently classified into 4 categories (wheeled, tracked, adhesive and non-contact) from which the following were obtained as the best options: From the category of wheeled robots, the single wheeled omnidirectional one is recommended when looking for a low operating and maintenance cost solution. However, technologically, it could have many complications and difficulties when moving through air intakes. From the category of caterpillar robots, the simple caterpillar and adaptable soft caterpillar are recommended options, being economical and with acceptable technological characteristics to move in the air intakes, the adaptable rigid type robot is also a good option, however, it demands high operation and maintenance costs.

From the category of adhesive robots, the electro-adhesive type shows outstanding and promising results compared to the other categories of robots; however, being a recent technology, it is still in the experimental stage and its availability in the market is limited.

From the category of non-contact robots, the continuous type is recommended when looking for a solution with good technological characteristics, however, it is not economically viable, on the other hand, if a lower cost option is sought, there is the UAV robot, but this has technological shortcomings when moving through confined spaces such as air intakes.

TABLE II. FINAL SCORE

2-11	Wheels		Caterpillar			Adhesives			Non-contact robots	
Indicators	Simple	Omnidireccional	Simple	Adaptable soft	Adaptable rigid	Suction cup	Vortex	Electro adhesive	Continuous	UAV
Cost	8.0	6.0	8.0	6.0	4.0	4.0	6.0	2.0	2.0	6.0
Availability	6.4	6.4	6.4	3.2	3.2	4.8	3.2	1.6	4.8	6.4
Adaptability to the environment	2.8	4.2	4.2	5.6	5.6	5.6	5.6	5.6	5.6	4.2
Dimensions	4.8	3.6	3.6	3.6	2.4	1.2	2.4	4.8	4.8	2.4
Scope	2.0	2.0	3.0	4.0	3.0	3.0	3.0	4.0	1.0	2.0
Effectiveness of FOD detection	2.7	2.7	2.7	2.7	2.7	2.7	0.9	1.8	3.6	3.6
Stability	1.4	1.4	2.1	2.1	2.8	2.1	1.4	2.1	2.1	0.7
Maneuverability	1.8	0.6	1.8	1.2	1.8	0.6	1.8	0.6	1.2	0.6
Speed	1.55	1.5	1.5	1	0.5	0.5	2.0	1.5	1.0	1.5
Technical analysis	17.0	16.0	18.9	20.2	18.8	15.7	17.1	20.4	19.3	15.0
Average	16.5		19.3			17.7			17.2	
Analysis with economic factor	31.4	28.4	33.3	29.4	26.0	24.5	26.3	24.0	26.1	27.4
Average	29.9		29.6			24.9			26.8	

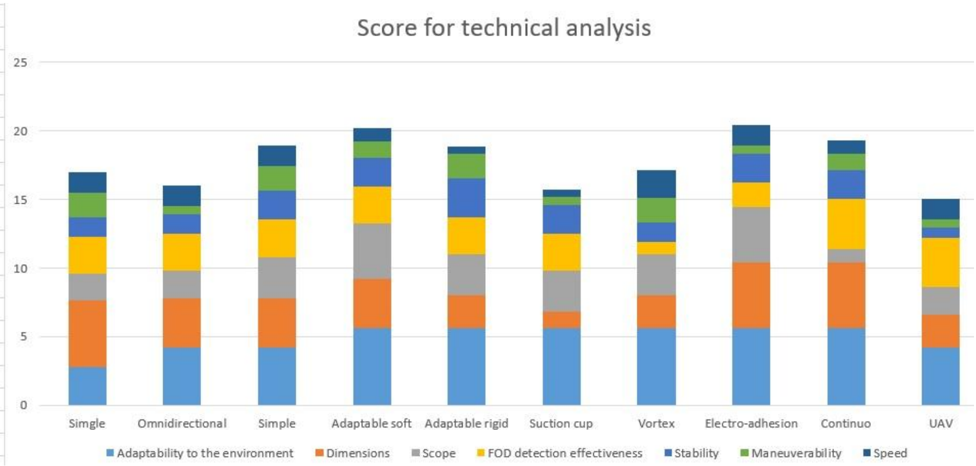


Figure 8. Stacked bar chart with robot scoring by technical analysis

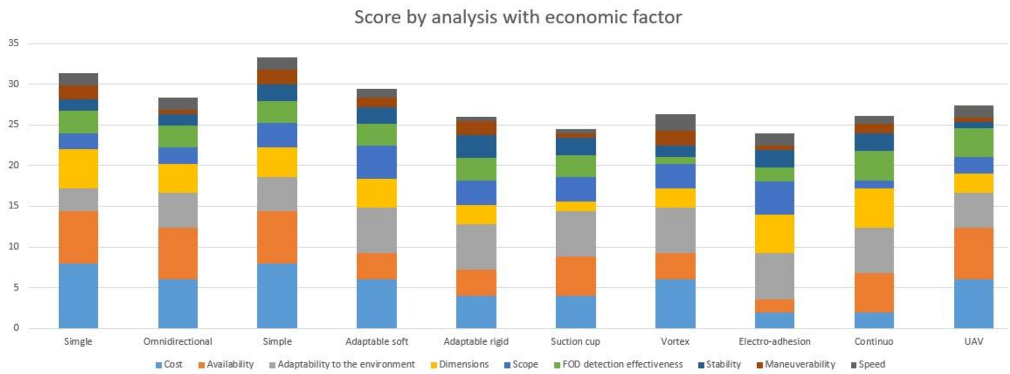


Figure 9. Stacked bar chart with robot score by analysis with economic factor.

From the information presented, not all the parameters considered for the qualification were exposed in the literature, so the missing values were assumed with an average taking as a reference the information provided by the documents that did have the missing data

From the above discussion and according to the technical analysis and with economic factor it was found that the caterpillar robot is the best adapted to move through the air intakes, this can be found in different configurations (simple caterpillar, soft adaptable and rigid adaptable), however in front of obstacles of the air intake, its adaptability to the environment, reach, maneuverability and stability could be affected, possibly requiring the implementation of support mechanisms as in the case of the FiRstLook caterpillar robot with support arms developed by Teledyne Flir [49].

It was also found that among the technologies currently applied in the aerospace industry, a robot capable of moving through the air intakes has not yet been developed, because aerospace robotics is one of the fields that has a low amount of research work [50], however, if we wanted to use a robot in this field, the best alternatives according to the technical analysis would be the electro-adhesive and continuous robot; and according to the analysis with economic factor, the UAV.

VI. Conclusions

A review of robotics applied to confined spaces was developed evaluating its possible advantages and disadvantages in the inspection of air intakes of a fighter aircraft with a mixed technical and economic analysis (qualitative-quantitative) and the following conclusions have been reached.

1. In the technical analysis, the mobility technologies that obtained the best results were: electro-adhesive, adaptive soft track, continuous, single track and adaptive rigid track.
2. In the analysis considering the economic factor, the best results are simple track, simple wheel, adaptable soft track, omnidirectional wheel and UAV.
3. The single tracked robots stand out in the analysis due to their reliability, availability and their compliance with the technical characteristics required to be able to move through the air intakes at a lower cost compared to the other technologies analyzed in the document. Being the tracked technology the one that has the best possibilities to perform the inspection of the air intakes of a fighter aircraft.

Future work is expected to corroborate these results with mobility tests using various robots available in the environment and also to design a robot that adapts to the needs of operators and users.

Conflict of Interest

The authors declare no conflict of interest.

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