





Analysis of Robotic Manipulation Technologies Applied to the Cleaning/Extraction of FOD from Fighter Aircraft Air

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Abstract—In the aerospace industry, maintenance protocols are in place to ensure the safety of personnel and the integrity of aircraft. Air intakes are difficult to access, making it challenging to clean them and perform Foreign Object Debris (FOD) extraction. This paper presents a technical-economic analysis of robotic handling technologies, aimed at identifying the most suitable technology for cleaning and FOD removal operations in fighter aircraft air intakes. First, a research team from the Universidad Nacional de San Agustín de Arequipa (UNSA) in collaboration with maintenance personnel from the Fuerza Aerea del Peru (FAP), conducted a review of recent technologies in manipulation robotics focused on cleaning and removing FOD from fighter aircraft air intakes, classifying them into 12 types of manipulators according to the end effector, to rate their performance in FOD cleaning and/or extraction activities, while also meeting the needs of FAP personnel. Nine indicators aligned with the requirements were determined, each manipulation technology was rated, and these values were operated with relevance factors calculated for each indicator by the Mudge diagram. Micro-gripper handling technology obtained the highest score for both technical analysis and technical-economic analysis, with weights of 25.7 and 30.1, respectively. This result makes it the technology best suited for cleaning and FOD extraction in air intakes. These results were based on an assessment by FAP expert staff, and no experimental validations or tests with actual prototypes were performed. The results of this study will be corroborated in future work through advanced simulations and experimental laboratory tests.

Keywords—aircraft, manipulation, robotics, cleaning, extraction, Foreign Object Debris (FOD), air intakes

I. INTRODUCTION

Currently, the aeronautical industry has maintenance protocols designed to ensure pilot safety and aircraft integrity. Foreign Object Debris (FOD) is the leading cause of structural damage [1], even leading to engine failure and rendering aircraft inoperable [2]. For this

reason, FOD research has received increased attention in recent years [3]. Fighter jets are typically supersonic, feature variable-geometry air intakes, and have a complex structure with multiple cavities and compartments that regulate airflow to the engines for optimal aircraft performance [4, 5]. This area, due to its structural complexity and small space, makes maintenance operations difficult, since FOD is located in areas of the air intake with poor visibility for technical personnel, which can be overlooked and consequently be sucked in by the engines [6], causing damage to the blades that impairs the performance of the aircraft, and even causing catastrophic losses and putting personnel at risk [7–9].

In response to this, robotic technology has made significant advances in the aeronautical industry in recent years. Adair *et al.* [10] incorporated borescopes to detect structural failures in engine blades and FOD in air intakes. Madison *et al.* [11] presented a portable device, “HANNDI,” to detect FOD in fuselage rivets. Zhao *et al.* [12] developed the hexapod robot “Hbot” for exploring internal aircraft areas such as air intakes. In 2022, the Universidad Nacional de San Agustín de Arequipa (UNSA), in collaboration with the Fuerza Aerea del Peru (FAP), conducted an analysis of robotic technologies applied to locomotion in air intakes [13]. Meneses *et al.* [14] designed three wheel-type robots, testing three suspension systems to determine the one best suited to air intakes. Mamani *et al.* [15] developed and implemented the ALLQU robot in the air intake maintenance protocol for fighter jets. These studies show the development and implementation of robots capable of entering air intakes and inspecting the internal surface for FOD; however, they still lack the capability to extract and eliminate FOD, so the risk of FOD aspiration into the engine persists, potentially causing millions of dollars in losses to the aircraft and endangering the safety of FAP personnel.

On the other hand, robotic manipulator technology has been developed and implemented in modern industry for handling objects of varying sizes and shapes, such as FODs. It has been classified into two groups: soft

grippers and rigid grippers. For better understanding and analysis, it has been subdivided as follows: Rigid grippers into three subcategories: simple, micro-gripper, and magnetic structure; and soft grippers into nine subcategories: passive structure, fluidic elastomer, granular, electro-adhesive, active materials, membrane-less suction cups, membrane-bound suction cups, origami, and flexible strips. The simple rigid gripper is the most widely used in industry. It is used in industrial assembly and even in space exploration. These grippers have different configurations in the number of rigid joints, allowing for variations in their geometry to grasp objects of different shapes and in hard-to-reach places such as air intakes [16, 17]. The rigid micro-tweezer is used in the medical field for surgery. It has a simple design with few joints and is small in size, allowing for precise manipulation in even tighter spaces without damaging the surrounding environment [18–21]. The rigid magnetic gripper is used in industry to manipulate metallic objects [22, 23]. In experimental projects, it has been combined with soft robotics to manipulate even non-metallic objects [24, 25]. The soft passive gripper, used in industrial robotics, is composed of flexible structures and designs with patterns that adapt to the different geometries of objects [26–30]. The fluidic elastomer gripper is used to manipulate objects of varied and delicate shapes, requiring low clamping pressure. It is actuated by an internal pneumatic or hydraulic system [31–34]. Research has been conducted on granular jamming grippers, which operate using a granular material inside a flexible membrane. When a vacuum is generated by a pneumatic system, the granules are compressed, and the gripper adapts to the shape of the objects [35–37]. Electro-adhesion as a manipulation method has been studied in recent years as an alternative for handling smooth, flat, lightweight surfaces, regardless of the material [38–40]. Grippers with active materials are also being investigated. These are small, similar in size to micro-grippers, and are composed of thermally sensitive materials that change their dimensions in response to temperature variations, gripping the object to be manipulated [41]. Membrane-less suction grippers are already used in industry, most notably in warehouse logistics, food handling, and automotive and electronics assembly and manufacturing. Their system consists of suction cups that, through a pneumatic system, generate a vacuum between the objects and the suction cup to hold them [42, 43]. In addition, membrane suction cup grippers are being investigated for more precise handling of fragile objects [44, 45]. Soft origami grippers are being studied in the laboratory for gentle manipulation; their foldable structure, based on origami geometry, is ideal for adapting to confined environments such as air intakes [46–50]. Finally, flexible strip grippers are another type of manipulation device that has been recently studied for precisely holding a variety of delicate objects [51, 52].

This article presents a techno-economic analysis of the latest advances in robotic manipulation in modern industry to identify the technology best suited for

cleaning and removing FOD from fighter jet air intakes. First, the working environment of the air intakes, the characteristics of the FOD, and the tasks that the manipulator system should perform to clean and extract the FOD, according to the FAP maintenance personnel, are studied. Next, the reviewed robotic manipulators, which work with objects similar to FOD, are classified according to the type of end effector, with a focus on their applicability in FOD cleaning and removal operations in fighter aircraft air intakes. Finally, the Mudge matrix is used to compare the technologies based on technical and economic criteria to determine which technology is best suited for cleaning/extracting FOD from the air intakes of fighter jets.

II. WORK ENVIRONMENT

This chapter explains the characteristics and components of the working environment called the air intake of fighter jets and the FOD commonly found in the air intakes according to the maintenance personnel of the FAP, as well as the critical areas where they are usually located.

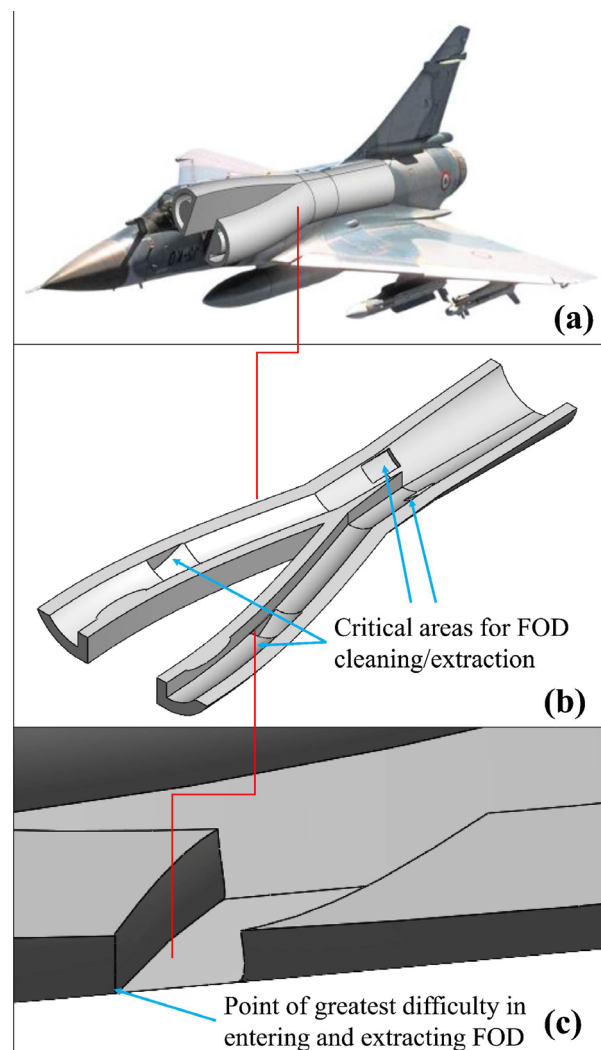


Fig. 1. Working environment: (a) air intake location on fighter jet; (b) critical areas for FOD cleaning/extraction; (c) point of greatest difficulty.

Supersonic fighter jets have a structure called an “air intake,” which allows for the control and redirection of airflow to the jet engines. Air intakes are characterized by their variable geometry, allowing for the intake of redirected air and the flow required by the engine. They also have peripheral hatches that allow for the intake of auxiliary air, enabling supersonic aircraft to achieve optimal performance during flight. These characteristics make the air intake a complex and difficult-to-access environment for FAP maintenance personnel. The air intake is located just behind and below the pilot’s seat, as shown in Fig. 1(a). Fig. 1(b) shows a cross-section of the air intake, identifying the peripheral hatches as the critical areas and the most difficult to access, including for cleaning and removing FOD. The peripheral hatches have a cavity-like structure with an acute angle at their deepest point, which is the most challenging area for FOD removal, as shown in Fig. 1(c).

On the other hand, FOD consists of objects of varying shapes, sizes, and materials that pose a potential danger to aircraft integrity. These are commonly found on runways at aeronautical facilities and in aircraft air intakes. This study focuses on FOD located in air intakes. Through technical discussions organized with FAP maintenance personnel, it was found that the most common FOD found in air intakes, and those that pose a high risk to aircraft integrity, are bolts, nuts, washers, rivets, tools such as wrenches and screwdrivers, and aluminum or steel clipboards.

III. CLASSIFICATION OF ROBOTIC MANIPULATORS ACCORDING TO THEIR END EFFECTOR

This chapter presents a classification of robotic handling technologies currently used in industry, followed by a detailed analysis of each technology, focusing on its applicability for cleaning and removing FOD from the air intakes of a fighter jet. This classification aims to identify the manipulation technology with the greatest potential for application to operations in this working environment in the aerospace industry.

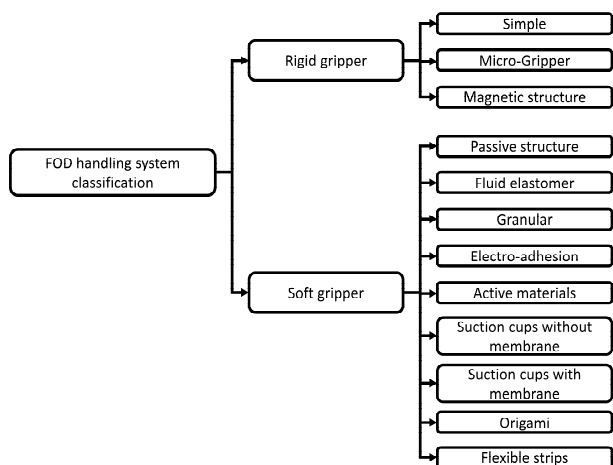


Fig. 2. Classification of robotic manipulators according to their type of end effector.

Regarding object handling, modern industry employs a variety of robotic handling technologies. For the purposes of this study, and to better analyze the handling and extraction of FOD from fighter jet air intakes, the technologies have been classified according to the type of end effector, as shown in Fig. 2. Initially, they were divided into two groups: rigid grippers and soft grippers. Subsequently, they were subdivided into 12 groups. The rigid gripper group includes simple grippers, micro-grippers, and magnetic structures, while the soft gripper group includes passive structures, fluidic elastomers, granular materials, electro-adhesion, active materials, membrane-less suction cups, membrane-containing suction cups, origami, and flexible strips.

A. Rigid Gripper

Rigid grippers are the most widely used in modern industry, with applications in industrial assembly, automotive manufacturing, micromanipulation, space exploration, and robotic surgery [16]. They are characterized by their rigid structure and links. According to Hernández *et al.* [17], rigid grippers are classified into three groups: completely rigid, semi-rigid, and deformable. The first two groups are further subdivided into compression mechanisms and rigid linkages, while the deformable group is subdivided into single-mass grippers and single-mass finger grippers. Rigid grippers are those with few joints and a robust structure. They typically hold objects firmly in a single position and have considerable gripping force. In this case, their compression mechanism is achieved with springs that provide a degree of deformation to grip objects, increasing their gripping force. On the other hand, rigid linkage grippers have an improved joint configuration for greater versatility in gripping a wider variety of objects. Semi-rigid grippers have a greater number of joints and are made of deformable materials. In this case, the compression-mechanism type has a structure with cavities that allows it to deform and adapt to the objects being handled. Rigid-link grippers also have a significant number of joints, giving them the ability to adapt better to various object shapes. Deformable grippers have structures made of materials with greater deformation capacity, combined with a greater number of internal cavities, either throughout the entire gripper (as in single-mass grippers) or only in the fingers (as in single-mass finger grippers). These grippers have the ability to adapt to diverse objects, a superior characteristic to the other types of grippers presented previously. However, their load capacity and gripping force are much lower.

Although these studies presented a classification of rigid forceps, they also end up describing forceps with characteristics similar to soft forceps, and do not even consider other types of rigid forceps such as the magnetic type [22]. Therefore, in this section, rigid forceps are classified into 3 subcategories applicable to FOD manipulation in air intakes as shown in Fig. 3: simple rigid grippers, micro-grippers, and magnetic structure. These are explained below:

1) Simple

Simple rigid grippers are all those that in their design have rigid links and joints as seen in Fig. 3(a), they normally use 2 fingers and their entire opening and closing mechanism is operated by a single motor or actuator.

From the study by Hernández *et al.* [17], in this category would be considered the completely rigid gripper with compression mechanism and rigid link and of the semi-rigid clamp only the one with rigid link.

Rigid grippers are a good option as they allow for the secure attachment of any FOD detected in air intakes. Their superior load capacity even allows for the handling of large and heavy FOD items such as steel tools or clipboards. However, their bulky size and the space required to open them make them difficult to operate in confined spaces, such as the deepest corner of the air intake's peripheral flap. Furthermore, their typically rigid construction could damage the air intake surface.

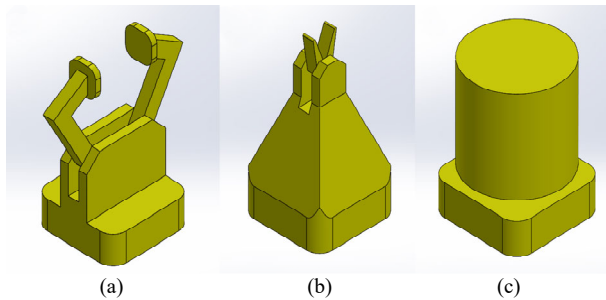


Fig. 3. Rigid grippers: (a) simple; (b) micro-gripper; (c) magnetic structure.

2) Micro-gripper

Micro-gripper has a design similar to that of simple rigid forceps, with the difference that they are much smaller in size and have fewer joints; they are high-precision manipulators and are mainly used in the medical sector for robotic surgeries [18, 19].

Typically, surgical micro-gripper has a 1 DoF. Samuels *et al.* [20] designed a multi-DoF micro-forceps for improved surgical manipulation performance, as well as the ability to be miniaturized and inserted into smaller spaces, thus promoting less invasive surgeries. Kim *et al.* [21] designed the SurgGrip, a micro-forceps with a higher load capacity, for manipulating surgical instruments.

Because of their small size, micro-gripper can access hard-to-reach spaces such as the deepest part of peripheral gates with sharp angles. Also, because they require little space to manipulate objects and have a high degree of surgical precision, they are ideal for extracting FOD from the critical section of the air intake without damaging the surface. However, their load capacity is lower and they may have difficulty handling heavier FOD.

3) Magnetic structure

Magnetic grippers have a solid and usually bulky structure, with a permanent magnet or electromagnetic magnet end effector, and are normally used in the

production industry such as metalworking for transporting metal and automotive parts during assembly.

Ruo *et al.* [22] propose the development of a robotic gripper with an electromagnetic end effector, designed with an additive manufacturing structure. This allows for a lightweight design, customizable gripper size, and better adaptation to the available space. Schorr *et al.* [23] design and manufacture a prototype magnetic gripper based on the Halbach matrix, which allows the electromagnet to have a variable intensity adjustable to the weight of the metallic objects being manipulated in a complex environment such as outer space.

Magnetic gripper are an excellent option for removing metallic FODs; however, some FODs are non-metallic, and their structure is often robust, making it difficult to access critical areas of the air intake.

B. Soft Grippers

Soft grippers, also known as “soft robotics,” are a technology that has been implemented and developed in recent years, with applications focused on the food, agriculture, logistics, and medical sectors [53]. These technologies have a lower load capacity and gripping force than rigid grippers, allowing them to hold delicate objects without damaging them. They are also characterized by having materials and designs in their structure that provide flexibility to adapt to the geometry of the objects being manipulated [30]. According to Shintake *et al.* [41], soft robotic gripper technology has evolved from 1980 to the present, now reaching its peak technological development and beginning its incorporation into various industrial sectors. They also propose a classification into three categories: actuation, rigidity control, and adhesion control. The actuation category is further subdivided into four groups; Passive structures with motors, Fluidic Elastomer Actuators (FEAs), electroactive polymers with Dielectric Elastomer Actuators (DEAs) and Ionic Polymer-Metal Composite (IPMC) actuation, and Shape Memory Alloys (SMA). The stiffness control category was subdivided into four groups: granular jamming, Low Melting Point Alloys (LMPA), Electrorheological (ER) and Magnetorheological (MR) fluids, and Shape Memory Polymers (SMP). The adhesion control category was subdivided into two groups: electroadhesion and gecko adhesion. Actuation-type grippers are characterized by being systems that deform upon contact with objects to adapt to their geometry. They also use actuators or actuation systems to deform. Within this category, passive structure grippers with motors have a structure with cavities that allow them to deform, adapting to the object's geometry. Then, FEAs type grippers also have internal cavities, but these are closed cavities into which a fluid-air, water, or oil is injected. The pressure of this fluid deforms the gripper's structure, allowing it to adapt to the shape of the objects being handled. DEAs and IPMC electro-active polymer grippers are plastic structures, or even alloys with metals, that deform in a limited way to hold objects when electrical voltage is applied. SMA grippers deform when heat is applied, allowing longitudinal expansion and enabling the gripper

to generate a gripping effect. Rigidity control grippers are characterized by a deformable structure with greater control of their deformation through an actuation system. This type adapts even more closely to the shape and geometry of objects than the previously presented gripper types. The granular jam gripper has a flexible membrane that envelops granular materials. Upon contact with objects, this membrane deforms, conforming to their exact shape. Subsequently, the system, usually pneumatic, is activated, generating a vacuum between the granules and creating pressure on the object being handled. LMPA and SMP grippers are actuated either electrically or thermally, deforming to adapt to the geometry of the objects. This type of gripper is also quite compact and allows for the careful gripping of very small objects. Adhesion-control grippers are characterized by systems that utilize the adhesion generated between two surfaces. They control adhesion through electrical systems and sometimes employ systems based on gecko-like movements. Their grippers are thin, flexible blades that allow them to hold objects of various materials with great delicacy. Of all gripper types, this one has the lowest load capacity but offers the best adaptation and precise gripping of objects. The adhesion gripper uses a drive mechanism that electrifies the blades, generating static electricity that attracts the surface of the objects, creating sufficient electro-adhesive force to lift them. Finally, gecko-adhesion grippers are inspired by the way lizards climb smooth surfaces. They also have blade-shaped grippers, but with micro-scales added to the surface so that they adhere to the objects being handled through Van der Waals forces.

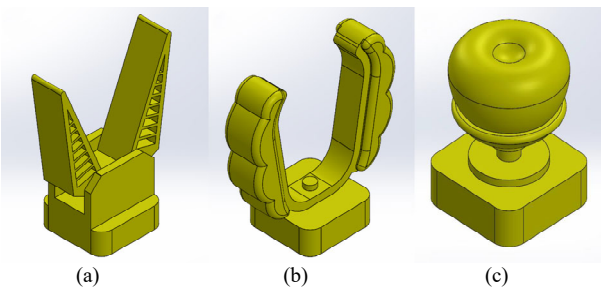


Fig. 4. Soft gripper: (a) passive structure; (b) fluidic elastomer; (c) granular.

As seen in this section, there are classifications for soft grippers that encompass a wide variety of gripper types. Unlike rigid grippers, soft grippers have demonstrated better adaptation to the shape of objects of different forms and materials than rigid grippers. This is why studies such as those by Maggi *et al.* [42] and Mehta *et al.* [44] seek to develop hybrid grippers that combine the strength and load-bearing capacity of rigid grippers with the broad adaptability of soft grippers to various objects in terms of material and shape. Studies of origami-inspired or flexible-strip grippers, which have gripping characteristics worth evaluating for this study, were also not included. Consequently, a classification of soft forceps is proposed, divided into 9 subcategories applicable to FOD handling in air intakes, as shown in

Fig. 4 with passive structure, fluidic elastomer, granular; in Fig. 5 with electro-adhesion, active materials, suction cups without membrane; in Fig. 6 with suction cup with membrane, origami, and flexible strips. These technologies are explained below:

1) Passive structure

Passive soft grippers have a design composed of structures with flexible materials and open cavities in a pattern as shown in Fig. 4(a). They are actuated by means of tendons or mechanical or electric actuators. When an object is to be held, the gripper structure closes and deforms, adapting to the geometry of the object. In this way, pressure and greater gripping force are generated by the deformation. This technology is for applications that require delicate handling, such as in the food industry [30].

Arachchige *et al.* [26] designed a novel gripper that combines two types of soft robotics technology: active materials with a passive structure. This gripper has variable stiffness, with rigid columns in its fingers. In this case, the gripper's deformation and movement are controlled by adjusting the material's stiffness, allowing for more adaptive gripping of objects. Xiang *et al.* [29] developed a passive structure gripper with pneumatic actuation and a novel multimodal geometry based on an inflatable toroid. This design allows it to manipulate objects with three types of movement: wrapping around the object, applying controlled pressure, and expanding to grasp larger objects. This provides greater adaptability to objects than its predecessors.

The passive structure gripper, due to its deformable characteristic, can handle more varied objects in shape and size. Also, being flexible, it would not cause damage to the air intakes. However, for its operation, it requires a space similar to that of rigid grippers for the opening of the gripper fingers, which can cause complications for the passive structure gripper in the narrowest part of the critical zone.

2) Fluidic elastomer

Fluidic elastomer soft grippers have a design composed of a highly flexible material and closed cavities, as shown in Fig. 4(b). They require a fluid to enter the cavities, filling the gripper and creating a closure to grasp objects of various shapes. They generate a gentle clamping pressure, making them ideal for handling delicate objects. They typically employ a pneumatic or hydraulic system. This technology is increasingly used in the food industry [32] and in delicate handling and packaging [34].

While soft fluid elastomer grippers can adapt to the shape of various objects, they do not have the same load capacity as rigid grippers. To address this, Peng *et al.* [31] developed a standard fluid elastomer gripper with an integrated rigid structure on the outside. This structure provides support and increases the gripper's load capacity, allowing it to lift heavy, metallic objects such as tools or machined parts. El-Sayed [33] designed a hybrid robotic gripper that combines fluid elastomer technology with a granular

operating principle. This resulted in a gripper with finger stiffness adjustable to the type of object being handled.

Fluidic elastomer clamps are a good option for handling FOD, taking care not to cause surface damage to the air intakes during operation, as they have a flexible and adaptable structure. Although they can adapt to a wide variety of objects, their expansive principle makes it difficult to grip very small or mainly flat objects such as washers or the steel clipboard; this is especially problematic in the critical area of the air intake.

3) Granular

The soft, granular grippers, as shown in Fig. 4(c), have an external membrane made of flexible material. Inside, they store granules of rigid or soft particles. A pneumatic system is used to actuate them, creating a vacuum between the particles. This causes the object to be gripped to become trapped between the granules and the membrane. Applications of this technology are geared towards the food industry, underwater environments, medical applications such as rehabilitation, and collaborative robotics for assembly [37].

Götz *et al.* [35] proposed incorporating soft granules with expanded polystyrene spheres, thereby increasing the gripping force and adapting to the geometry of the granular grippers. On the other hand, Santarossa *et al.* [36] designed a hybrid granular gripper combined with suction cups; this configuration would allow for grasping objects in unstable environments such as sand or water.

Soft, granular-type grippers show optimal characteristics for gripping FOD on irregular surfaces such as the variable geometry of air intakes; however, due to their toroid-like shape, their reach could be limited at reduced angles such as the depth of the peripheral air intake gate.

4) Electro-adhesion

Soft electro-adhesive grippers are an emerging technology that works with electrified sheets arranged symmetrically in the end effector of the gripper as seen in Fig. 5(a). When they come into contact with the surface of the objects to be manipulated, static electricity is generated and consequently electro-adhesion. This technology was developed to manipulate objects of different materials and mainly flat and smooth surfaces [40].

The main disadvantage of electro-adhesive grippers is their relatively low load-bearing capacity. To address this, Chen *et al.* [38] experimented with a gripper using electro-adhesive plates made of sheets with varying rigidity, increasing its load-bearing capacity by up to four times. To achieve a better grip, Kim *et al.* [39] developed an electro-adhesive gripper with scale-like patterns inspired by geckos, manufactured using additive printing. This increased grip and load-bearing capacity without damaging the objects.

Electro-adhesive clamps are shown to be a great alternative for securing FOD in air intakes; however, as seen in the studies, they are limited in their load capacity and may fail when handling heavy FOD. In addition, they

require a certain amount of space around them to operate, which could not be available in the critical area of the air intake.

5) Active materials

Soft forceps with active material end effectors are usually small in size, similar to rigid microforceps, and usually have more fingers for manipulation as shown in Fig. 5(b). These are usually made of plastic or metallic alloy materials and are sensitive to electrical stimuli such as DEA, IPMC and LMPA forceps or to thermal stimuli such as SMA and SMP forceps [41].

This type of tweezers has been studied recently with the aim of being applied in the future for manipulation in very confined environments and for holding objects even much smaller than FODs. Also, due to their size, they would have the ability to enter even the deepest cavity of the air intake, possibly with better results than rigid micro-tweezers. However, being so small, their load capacity is quite limited to holding larger and heavier FODs such as metal tools.

6) Suction cups without membrane

Membrane-less suction cup grippers consist of a flexible, cone-shaped end effector with channels at their midpoint that, via a pneumatic system, draw in air and create a vacuum between the object to be held and the suction cup, as shown in Fig. 5(c). Their development is geared towards applications in various industries such as storage logistics, food handling, automotive assembly, and electronics [43].

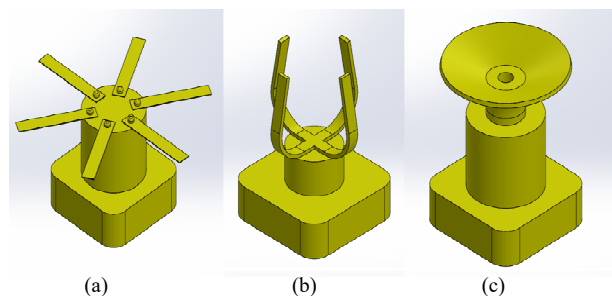


Fig. 5. Soft gripper: (a) electro-adhesion; (b) active materials; (c) membrane-less suction cups.

Soft robotics technologies such as membrane-less suction cups have been combined in recent years with rigid robotics, resulting in more complex manipulation systems with greater gripping and strength capabilities, such as the study carried out by Maggi *et al.* [42], where a rigid robotic gripper was developed with membrane-less suction cups on the inside of its fingers, giving it greater gripping capabilities against objects of varied shapes, unlike simple rigid grippers.

Suction cup grippers without a membrane are a good option because their suction cup allows them to grip flat objects like washers or steel clipboards. However, we also noted a potential complication when operating in confined spaces or areas with sharp angles, due to the shape of the suction cup. Furthermore, being open and without a membrane, they could suck in debris, which could damage the manipulator and cause it to become a

potential source of FOD by getting stuck inside the air intake. Additionally, the use of pneumatic systems would increase the overall weight and dimensions of the robot-manipulator, which could also lead to air intake blockages.

7) Membrane suction cups

Recent research has focused on membrane-combined suction cup clamps, as shown in Fig. 6(a). These clamps, in addition to possessing the characteristics of clamps without a membrane, offer improved gripping capabilities, making them ideal for handling delicate objects. Their development is geared towards applications in the food industry, digital manufacturing, and medical manipulation [45].

As seen previously, rigid gripper technologies are those already incorporated in the industry. An effective way to introduce membrane suction cup technology to the industry is by combining the technology as done in the research of Mehta *et al.* [44], where a hybrid system of rigid gripper and membrane suction cups on the outside of its grippers was developed. This was validated on the RISO robot where the ability to hold large objects was extended to small and delicate objects.

The soft gripper technology with a suction cup and integrated membrane has the ability to manipulate small objects on smooth surfaces, such as FOD in the air intake. Being a closed system, there is no risk of aspirating debris that could damage the manipulator. However, it also uses a pneumatic system, which makes the overall system robust and heavy, not ideal for a device that will be inserted into air intakes. While it allows for the manipulation of small objects, if these are located in the sharp cavities of the peripheral gate, difficulties could arise during extraction.

8) Origami

Origami tweezers have foldable fingers and folds inspired by origami as shown in Fig. 6(b), their application is aimed at the agricultural sector, food, handling of fragile objects and even the transport of organisms.

Li *et al.* [46] designed a bistable gripper that maintains its position under pressure during both opening and closing due to a non-Euclidean origami configuration. This system allows for energy savings in manipulators of this type. Pronoy *et al.* [47] developed a hybrid soft gripper that combines origami with fluidic elastomer technology, achieving greater flexibility and reach in confined spaces. In a study by Xue *et al.* [48], 3D printing technology was applied to the fabrication of origami grippers. Nate *et al.* [49] designed an origami gripper focused on transporting fry within their aquatic environment. The combination of folds and cuts inspired by kirigami was also explored in the study by Hu *et al.* [50], which increases deformation and precision of the manipulator while using less actuation energy.

Origami clamp technology allows for gripping various objects, although it would have difficulty with flat objects due to the robustness of its clamps. However, its foldable nature and even, in some cases, the application of

kirigami make it a good option for maneuvering in hard-to-reach spaces such as the critical area of air intakes.

9) Flexible strips

The grippers with flexible strip technology, as shown in Fig. 6(c), have a design that is composed of flexible strips configured in various patterns to hold various objects with precision and delicacy.

Lee *et al.* [51] developed a flexible strip gripper with an actuation mechanism inspired by the iris of the human eye, which combines lightness, precision, and high load capacity for object manipulation. Liu *et al.* [52] experimented with various flexible strip patterns and various objects (weight, size, and shape), finding configurations for both light and heavy loads.

The flexible strap gripper technology allows for the manipulation of a wide variety of objects, whether metallic or non-metallic. It is characterized by its ability to lift heavy loads with considerable precision without damaging surrounding surfaces. However, it requires space to maneuver and grip objects, which could lead to air intake issues.

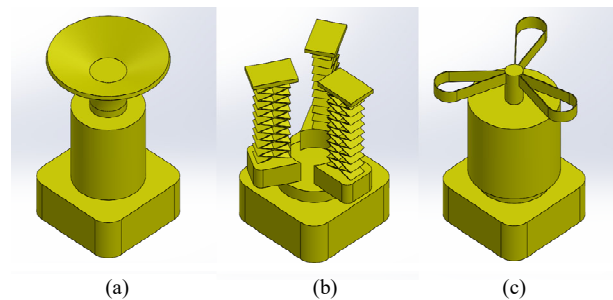


Fig. 6. Soft gripper: (a) membrane suction cups; (b) origami; (c) flexible strips.

IV. ANALYSIS OF TECHNOLOGIES WITH A FOCUS ON CLEANING/EXTRACTION OF FOD FROM AIR INTAKES

This chapter presents a technical and economic analysis of the robotic handling technologies classified in the previous chapter, with an applied focus on cleaning and FOD extraction in air intakes.

A. Scoring Procedure

The evaluation of robotic handling technologies was carried out using a structured scoring process based on the expert judgment of FAP technical staff.

The selection criteria for the 15 experts included direct experience in aircraft inspection, FOD removal, and maintenance supervision. The scoring process was developed based on the definition of relevant technical and economic indicators, whose priority was determined using the Mudge method in collaboration with expert personnel. Subsequently, a technical-economic evaluation of the technologies was carried out using a specific four-level scoring scale, and the scores obtained were adjusted with weightings according to the established relevance factors. Disagreements in the assignment of scores were managed through collective technical

discussions until consensus was reached among the participating experts. To ensure the reliability of the scoring process, virtual verification was used as a tool to complement the experts' criteria, and a qualitative sensitivity analysis was performed to assess the stability of the results in the face of variations in the assigned scores. The details of the analysis and the corresponding results are presented in the following subsections of this chapter.

B. Technical and Economic Indicators for the Robotic Manipulator

To evaluate robotic manipulator technologies with an application focus on cleaning and removing FOD from the air intakes of a fighter jet, technical discussions were held with aircraft maintenance personnel from the Peruvian Air Force. Nine indicators were identified: seven reviewing technical aspects (adaptability, reach, gripping system efficiency, stability, maneuverability, structural characteristics, and payload capacity), and two focusing on economic aspects (cost and availability). Each indicator is described below:

- (1) Adaptability refers to the ability of the robotic manipulator to adjust its dimensions and not interfere with or collide with the surface of the air intakes while the robot is moving.
- (2) Reach measures the manipulator's ability to reach the deepest areas of the air intake.
- (3) Gripping System Efficiency refers to the manipulator's ability to grasp and extract FOD.
- (4) Stability measures the ability of the robot-manipulator assembly to maintain its balance during operation inside the air intake.
- (5) Maneuverability measures the manipulator's ability to perform the operations required by the user.
- (6) Structural characteristic evaluates the complexity of the design and its characteristics such as lightness, modularity and simple assembly, the latter to reduce risks of generating new FOD by detachment of parts.
- (7) Payload capacity measures the ability of the robotic manipulator to hold heavy and large FOD stably and without compromising its structural integrity.
- (8) Cost refers to the reference price of the clamp and its spare parts in the international or national market.
- (9) Availability refers to the ease of acquiring spare parts quickly and at an affordable price in the local market.

Next, the indicators were evaluated using the Mudge diagram, as shown in Fig. 7. This method involves assigning a letter to each indicator; in this case, since there were 9 indicators, they were assigned from "A" to "I". The letters are placed at the top of the diagram and along its diagonal. Then, the level of importance is evaluated by comparing two indicators. For example, the gripping system efficiency indicator, assigned "C", is moderately more important than the payload capacity indicator, assigned "G", and is therefore assigned a score

of C3. This means that indicator C has 3 points. Indicator C is then compared to all other indicators, completing the table. The sum of the scores for each indicator is placed in the "Sum" column, and the percentage score is assigned in the next column.

PREFERENCE MATRIX WITH MUDGE METHOD												
	A	B	C	D	E	F	G	H	I	Addition	Percentage	Manipulation indicator
A	A3	C3	A1	E3	F3	A3	A1	I1		8	9%	Adaptability
B		B1	F3	F3	B3	B3	B3	B3		10	11%	Scope
C			C5	C1	C1	C3	C5	C1		22	24%	Efficiency of the gripping system
D				D1	F5	D1	H1	I1		2	2%	Stability
E					F5	E3	E3	E1		13	14%	Maneuverability
F						F5	F3	F3		27	30%	Structural characteristic
G							G1	I1		1	1%	Payload capacity
H								H3		1	1%	Cost
I									I1	6	7%	Availability
Total										90	100%	

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

Fig. 7. Results of the Mudge diagram on the preference level for each robotic manipulation indicator.

These results are then assigned an equivalent factor ranging from 0.5 to 2.0, where 0.5 is for the lowest score, in this case it would be cost with 1% and 2.0 for the highest score, in this case it would be structural characteristic with 30%, then a linear interpolation is performed to assign the rest of the relevance factors to each indicator as shown in Table I.

TABLE I. RELEVANCE FACTORS

Indicator	Percentage (%)	Score
Structural feature	30	2.0
Efficiency of the gripping system	24	1.7
Maneuverability	14	1.2
Scope	11	1.0
Adaptability	9	0.9
Availability	7	0.8
Stability	2	0.6
Payload capacity	1	0.5
Cost	1	0.5

Regarding the problem of FOD removal raised in this study, the FAP technical team, responsible for assigning scores through a collective discussion process, indicated that small FOD such as bolts, washers, and rivets are the most frequent cases during inspections, while large FOD such as wrenches, screwdrivers, and aluminum or steel paper clips are rare. Therefore, high load capacity was not considered a priority, since a manipulator with moderate or low load capacity and an efficient gripping system is sufficient to cover the vast majority of FOD removal cases. The structural characteristic indicator was assigned the highest score, as experts consider that the introduction of a robot with a manipulator inside an aircraft requires a high level of structural integrity to ensure safe removal operations and prevent the detachment of components that could become FOD. Given this, the cost indicator was considered to be of lower priority, as a moderately or highly priced prototype that guarantees reliability and

structural safety is preferable to a low-cost prototype that could exacerbate the existing problem.

C. Virtual Verification of Manipulation Technologies in a Replica of the Air Intake of a Mirage 2000 Aircraft

To assess the feasibility of each of the robotic handling technologies presented above, a representative 3D model of the 12 grippers and a 3DoF robotic arm was designed and assembled in the virtual presentation of the ALLQU robot, as shown in Fig. 8. In each case, possible collisions in their FOD extraction operation were verified in a virtual replica of the critical section of the air intake of a Mirage 2000 fighter jet, as shown in Fig. 9. This virtual verification provides experts with a complementary technical basis to support decision-making and evaluation in the subsequent techno-economic analysis.

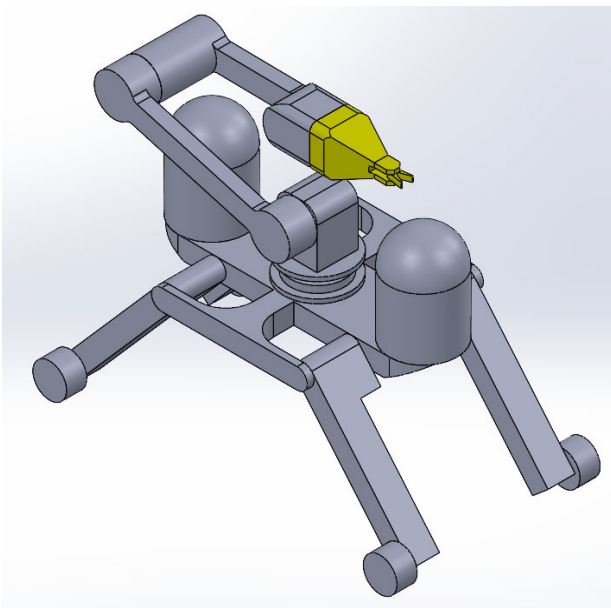


Fig. 8. Virtual implementation of robotic manipulator concept in ALLQU robot.

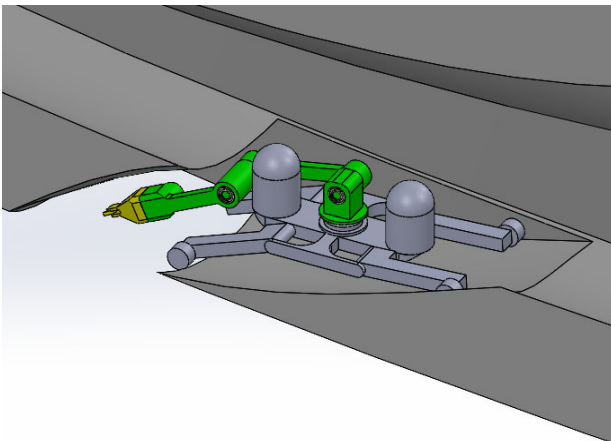


Fig. 9. Virtual operation of a robotic manipulator in the critical air intake zone of a fighter jet.

D. Technical Analysis

This section presents the results of the technical analysis of robotic handling technologies, evaluating them using indicators such as adaptability, reach, gripping efficiency, stability, maneuverability, structural characteristics, and payload capacity. Each indicator is first rated on a scale of 1 to 4, where 1 is very poor, 2 is fair, 3 is good, and 4 is very good. These scores are then adjusted using the relevance factor calculated for each indicator, as shown in Table I, resulting in the final scores presented in Tables II and III. Fig. 10 then illustrates the robotic handling technologies that perform best: micro-gripper (25.7), membrane-less suction cup (22.5), flexible strips (22.3), passive structure (21.8), and active materials (21.0). As seen in the results, the rigid micro-gripper type gripper has the best result, however on average the soft gripper technology also has good results (20.4), a higher value than the rigid grippers (19.9), this suggests a better technical performance with a hybrid gripper.

E. Analysis with Economic Factor

This section presents the results of the technical analysis, including economic indicators such as cost and availability. The results are visualized in Fig. 11, where the best-suited robotic handling technologies are: micro-gripper (30.1), membrane-less suction cup (27.7), passive structure (27.0), membrane-enhanced suction cup (24.7), and flexible straps (24.6). As seen in the results, the rigid micro-gripper maintains the highest score; however, the average score is reversed in favor of rigid grippers (24.7). This is because the acquisition and maintenance costs of rigid grippers are more accessible than those of soft grippers, as they are currently used in various industrial applications, unlike soft grippers, which are still under development.

F. Sensitivity Analysis

To assess the reliability of the results of the technical and economic analysis of handling technologies, a qualitative sensitivity analysis was performed, considering variations in the assignment of scores for the evaluation indicators of robotic handling technologies.

First, alternative scenarios were considered in which the score assigned to each indicator was increased or reduced, noting that the relevance factor did not change in the hierarchy of the six most relevant factors (Structural feature, Efficiency of the gripping system, Maneuverability, Scope, Adaptability, Availability). However, there were hierarchical variations in the last three factors of relevance (Stability, Payload capacity, Cost). Next, in the technical and economic analysis, the scores of the technologies underwent variations in response to changes in the relevance factors. However, the hierarchical order of the best technologies remained stable. The variations were noticeable in technologies with lower scores, but this did not affect the selection of the most suitable technology for cleaning and removing FOD from fighter jet air intakes.

TABLE II. RESULTS OF TECHNICAL-ECONOMIC ANALYSIS OF HANDLING TECHNOLOGIES (PART I)

No Item	Indicators	Rigid Gripper			Soft Gripper		
		Simple	Micro-gripper	Magnetic Structure	Passive Structure	Fluid Elastomer	Granular
1	Adaptability	2.7	3.6	1.8	2.7	1.8	1.8
2	Scope	3.0	4.0	2.0	4.0	2.0	2.0
3	Grip efficiency	1.7	5.1	5.1	3.4	3.4	6.8
4	Stability	1.2	2.4	0.6	1.8	1.8	1.8
5	Maneuverability	1.2	3.6	4.8	2.4	2.4	4.8
6	Structural characteristic	4.0	6.0	2.0	6.0	6.0	2.0
7	Payload capacity	2.0	1.0	2.0	1.5	1.5	1.5
8	Cost	2.0	2.0	1.5	2.0	1.5	1.0
9	Availability	3.2	2.4	3.2	3.2	2.4	1.6
Technical analysis by technology		15.8	25.7	18.3	21.8	18.9	20.7
Average score			19.9			20.4	
Economic analysis by technology		21.0	30.1	23.0	27.0	22.8	23.3
Average score			24.7			23.9	

TABLE III. RESULTS OF TECHNICAL-ECONOMIC ANALYSIS OF HANDLING TECHNOLOGIES (PART II)

No Item	Indicators	Soft Gripper					
		Electro-adhesion	Active materials	Suction cups without membrane	Suction cups with membrane	Origami	Flexible strips
1	Adaptability	2.7	3.6	0.9	0.9	2.7	2.7
2	Scope	1.0	3.0	3.0	3.0	3.0	3.0
3	Grip efficiency	5.1	5.1	6.8	5.1	3.4	5.1
4	Stability	1.2	2.4	1.2	1.2	1.8	2.4
5	Maneuverability	3.6	2.4	3.6	3.6	2.4	3.6
6	Structural characteristic	2.0	4.0	6.0	6.0	4.0	4.0
7	Payload capacity	1.0	0.5	1.0	1.0	1.5	1.5
8	Cost	1.0	1.5	2.0	1.5	2.0	1.5
9	Availability	0.8	0.8	3.2	2.4	2.4	0.8
Technical analysis by technology		16.6	21.0	22.5	20.8	18.8	22.3
Average score				20.4			
Economic analysis by technology		18.4	23.3	27.7	24.7	23.2	24.6
Average score				23.9			

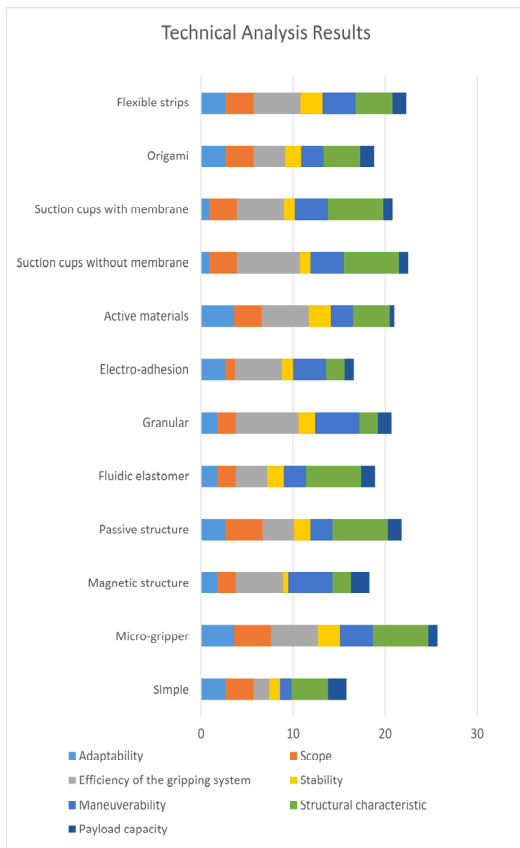


Fig. 10. Stacked bar chart of robotic handling systems according to technical analysis.

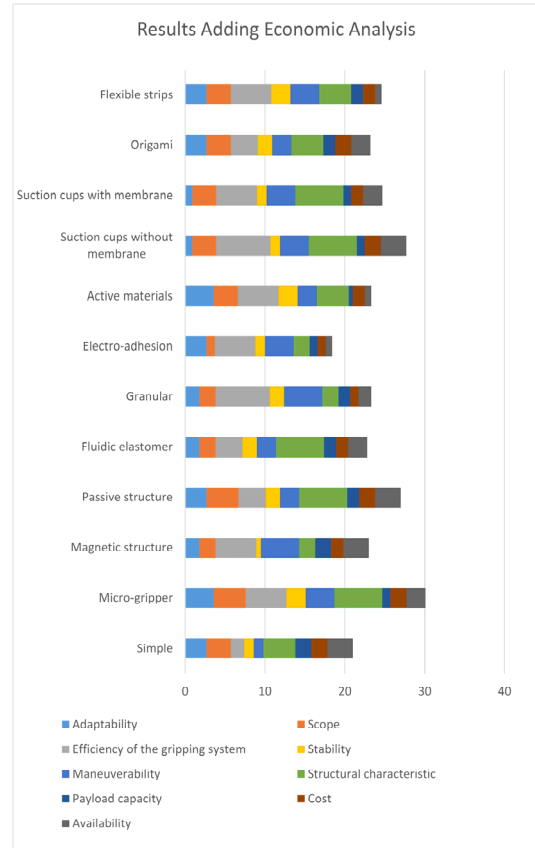


Fig. 11. Stacked bar chart of robotic handling systems according to the technical-economic analysis.

V. DISCUSSION

This study reviewed and evaluated various robotic handling technologies, developing a classification based on the type of end effector and considering its application in the aerospace industry for handling FOD in aircraft air intakes. While some reviews classify rigid and soft grippers in general terms, this study adopts an approach focused on aerospace applications, where the constraints of fighter jet air intakes determine the viability of each technology. In this context, the virtual verification performed complements the experts' opinions, providing them with a technical basis for more robust decision-making in the techno-economic analysis. The classification was divided into two categories: rigid grippers and soft grippers. The rigid gripper category included three subcategories (simple, micro-gripper, magnetic structure), while the soft gripper category included nine subcategories (passive structure, fluidic elastomer, granular, electro-adhesion, active materials, membrane suction cups, membrane suction cups, origami, and flexible strips).

In the virtual verification, a 3DoF manipulator was selected due to the simplicity of its design, with the aim of making an initial approximation to the technologies reviewed in a virtual environment similar to air intakes. This approximation provided experts with greater criteria for decision-making and determining weightings for the technical-economic analysis. Therefore, the kinematic analysis, compliance, and control strategies of the virtual manipulator are not addressed in this preliminary study.

In the classification of rigid grippers, the micro-gripper is recommended if the goal is to develop a manipulator system with a simple design, easy to manufacture, and low cost. While it could perform well in removing FOD from critical air intake areas, its small size might present difficulties when handling heavier objects.

In the classification of soft grippers, up to five promising options are recommended. Suction cup grippers, whether with or without a membrane, are economically accessible and relatively simple in terms of design and implementation. However, their requirement for pneumatic systems makes the manipulator and robot heavier and even larger, and they may not be able to move through air intakes. The passive gripper is a good option as it allows for the manipulation of objects of different sizes and shapes; however, it could present complications in the critical area due to the limited space. On the other hand, flexible strip grippers show better results for manipulating all types of objects of different shapes, sizes, and materials; however, in confined spaces, their performance could be reduced, potentially leading to adhesion to the air intake surface. The active material gripper is technically one of the best options, as it can access the deepest parts of air intakes; however, it is also limited with heavy objects and is currently under experimental development.

From the preceding discussion, and in accordance with the technical and economic analysis, it was determined that the micro-gripper robotic manipulator, classified as a rigid gripper, is the most suitable for implementation in a

robotic system to perform cleaning and FOD extraction operations in the air intakes of fighter jets. This result remains stable despite reasonable variations in indicator scores, as seen in the sensitivity analysis. On the other hand, according to the literature reviewed, when a manipulation technology does not fully meet the requirements in a specific application, hybrid technologies are used, combining rigid gripper technologies and soft grippers. In the case of cleaning and removing FOD from a fighter jet, this approach could provide additional advantages to the robotic manipulator with micro-grippers.

According to the results of this study's analysis, load capacity was the indicator with the lowest performance for microgripper technology. Therefore, the technologies with the best scores in the load capacity indicator were reviewed, with magnetic structure technology performing best (2.0), followed by granular technology (1.5). Technologies such as simple rigid grippers, passive structures, fluidic elastomers, origami, and flexible strips were not considered because they would distort the original microgripper design. Consequently, complementary technologies that are non-invasive and complement the load capacity characteristic were selected.

Under this approach, a hybrid system is conceptually proposed that consists of microgripper technology as the main manipulator system and a lateral auxiliary structure based on magnetic or granular technology. From a theoretical point of view, the operation would be as follows: for small FODs, the microgripper acts directly, and when the objects are larger in size or weight, the robotic arm maneuvers in such a way that the auxiliary structure captures the object. The detailed development and analysis of the proposed conceptual hybrid system will be further explored in future work, following experimental validation of each individual technology.

Also in the air intake, the deepest cavity in the peripheral doors was identified as the area of greatest difficulty for extracting FOD in a possible robotic handling operation because this cavity has an acute angle and even the human hand cannot access it. This was corroborated by testimonies from members of the FAP who indicated that these doors are the blind spot during pre-flight inspections of Mirage 2000 fighter jets and that FOD has often been found lodged in that area.

This study uses the Mirage 2000 as a case study because the air intakes on this aircraft represent one of the most complex and difficult-to-access configurations. Therefore, the results of this study suggest that the proposed manipulator system could be applicable to other combat aircraft with similar or less complex air intake geometries.

Furthermore, among the technologies currently used in the aerospace industry, the presence of the first robotic systems that enter to inspect the air intakes was confirmed; however, a device that allows cleaning or extracting FOD after being detected by these robots has not yet been developed.

VI. CONCLUSION

This study conducted a review of robotic manipulators currently used in the industry, classifying and evaluating them from an application approach for cleaning and extraction of FOD in the air intakes of fighter jets, with a technical and economic scoring analysis.

In both the technical and economic analysis, rigid micro-gripper technology performed best compared to the manipulators evaluated for robotic handling of FOD in air intakes. Up to five different types of grippers also showed promising results (membrane-type suction cup, non-membrane-type suction cup, passive structure, flexible strip, and active material grippers).

Micro-gripper technology stands out in the analysis for its affordability, availability and suitability of its technical characteristics for operating inside air intakes. This technology was identified as the alternative with the greatest potential for implementation in a robot for cleaning and removing FOD. This theoretical result is subject to future experimental validation and advanced simulation.

The following recommendations are considered for future work:

- Analyze more closely the combination of micro-gripper with soft grippers for the implementation of hybrid manipulation systems.
- Corroborate the results of this study with advanced simulations or experimental tests of robotic manipulation with FOD in the laboratory and the air intakes of a fighter jet.

These recommendations will be addressed in future research to optimize both the analysis and development of robotic manipulators applied to the cleaning and extraction of FOD in the air intakes of combat aircraft.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

EC and AC developed and wrote the scientific article, while YLS and EVF reviewed and corrected the manuscript for publication; all authors had approved the final version.

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