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PHD THESIS SUMMARY

CONTRIBUTIONS REGARDING THE USE OF ROBOTS IN THE INSPECTION OF AIRCRAFT FUEL TANKS

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CHAPTER 1

GENERAL CONSIDERATIONS ON AERONAUTICAL SAFETY

1.1. GENERAL INFORMATION ON FLIGHT SAFETY AND VERIFICATION PROTOCOLS

The field of aerospace engineering is represented by a complex set of scientific researches, which have as finality applications through which, gradually, are designed, produced and capitalized mechanisms called aircraft, approved to fly in space.

If we go back to antiquity, we can consider that the first aerospace “engineer” was Icarus, who, together with his father Daedalus, built their feathered wings, over which they applied a layer of wax and tried to flies, thus freeing himself from the Labyrinth of King Minos, which was on the island of Crete. Perhaps the attempt would have been successful if, because of the sun, the wax had not melted. Following this trial, the feathers fell off, and Icarus and his father ended tragically. This unfortunate event could be considered the first "plane crash" [12].

Numerous aviation incidents / accidents have taken place over time and it was necessary for certain specialized institutions to take measures to avoid such unwanted episodes. In this regard, rules and procedures have been developed by the International Air Transport Association (IATA), together with the European Aviation Safety Agency (EASA), which must be followed. respects all participants in air traffic [2].

IATA (International Air Transport Association) is, as it derives from its title, a non-governmental association, whose essential activity is the regulation and development of the air transport industry [2].

The objectives of this organization are:

→ To study, to solve all the difficulties / difficulties that refer: to the safety of the air transport, to the economic part that derives from this activity, but also to ensure a regular transport, in order to satisfy the needs of a large number of potential passengers.

→ To represent an authority that moderates debates and consultations between the members of the airlines, but also of the other participants in the aeronautical field, regarding the aeronautical industry.

→ To collaborate with ICAO (International Civil Aviation Organization) and at the same time with international organizations, but also regional associations of air carriers.

→ To be reflected as an association of carriers, which complies with the principles of competition and free movement of goods in air transport.

►AERONAUTICAL ACTIVITY IN ROMANIA

The Air Code, the internal normative acts in the aeronautical field that are elaborated in accordance with the provisions of the Convention on International Civil Aviation, concluded on December 7, 1944, in Chicago, to which were added amendments and international agreements, to which Romania is a party, represent the regulations which coordinates the civil aeronautical activity and the national airspace in Romania [8, 2], [103].

The aeronautical regulations in Romania are drafted, transmitted and adopted, subject to the provisions of the national laws in force and at the same time, the provisions of the Convention on International Civil Aviation, concluded in Chicago, respecting the standards and practices recommended in the annexes of this convention. and the international agreements to which Romania is a part, thus ensuring a unitary, coherent and modern character for the drafting and development of the national framework regarding the Romanian aeronautical regulations.

In accordance with the provisions of the Air Code and to regulate the field of civil aviation, the Ministry of Transport and Infrastructure (MTI), as a state authority, issues or authorizes competent bodies to develop and / or issue civil aeronautical regulations, which are binding for all participants in civil and related aeronautical activities, as well as for institutions / persons proposing to you, or carrying out activities in the perimeters / areas subject to civil aeronautical easements [8, 103].

The state authority, represented by the Ministry of Transport and Infrastructure (MTI) delegates responsibilities to the Romanian Civil Aviation Authority to ensure that national civil aviation regulations are complied with by all individuals and legal entities, both by Romanian citizens and by those foreigners; by institutions / persons providing products or services for civil aviation in Romania, thus fulfilling the function of security control in the field of civil aviation [8, 103].

►AIRCRAFT MAINTENANCE CHECKS

In order to have a high level of operation of the aircraft and to keep them safe, to perform efficient and punctual work, but also to maintain the value of the most important assets, the capital of an airline is essential to draw up a program. strictly maintenance [1].

The aeronautical industry is an area of activity that is very well regulated, in the sense that both the airlines that carry passengers and the cargo companies must comply with continuous inspection programs, which are established by the air authorities. In the United States, aircraft maintenance and repair programs are monitored by the Federal Aviation Administration (FAA). The FAA requires each airline or operator to establish a Continuous Airworthiness Maintenance Program (CAMP). The CAMP program presents routine and detailed inspections of the aircraft they own. Checks are essential because they keep aircraft safe and operational. The maintenance and repair schedule must be rigorous to ensure that passengers arrive safely at various destinations in an aircraft that has been checked before leaving an airport premises [1,3,4].

While the FAA monitors compliance with regulations and programs, airlines or air operators must ensure that maintenance is performed in accordance with CAMP guidelines. Aircraft controls are established for various time intervals, known as flight line maintenance checks and four other high-level maintenance types, type A, B, C and most elaborate, type D [1].

The purpose of these checks is to perform routine and non-routine maintenance of an aircraft. Maintenance includes: scheduling repair of known issues; replacement of components / parts after a certain time of use, after a number of flight cycles / calendar time; repairing previously discovered defects and performing scheduled repairs.

It should be noted that all aircraft are different and therefore may require maintenance checks at different times.

In addition to the Federal Aviation Administration (FAA), there are other airworthiness authorities, such as Transport Canada, or the European Aviation Safety Agency (EASA) [4].

►LINE MAINTENANCE CHECKS

This type of maintenance is the most common, known as post-flight or pre-flight maintenance, and is performed at night, being one of the most typical types of aircraft maintenance. Line checks require a minimum number of tools used in this process and take place inside the airport [1,3,4].

Line checks are the most common because they cover basic inspections. During line checks, the technical personnel who normally maintain the aircraft will usually consider the following components: wheels, brakes and fluid level - oil, hydraulics.

The line check ensures an aircraft in terms of flight safety, but also the fulfillment of flight plans scheduled by the airline it serves. Airline maintenance is performed every 24 to 60 hours of accumulated flight time, but depends on the aircraft operator [1,3,4].

►MAINTENANCE REVIEW BOARD

Modern aircraft in the transport category have maintenance programs derived from MSG-3 (Maintenance Steering Group - 3rd Task Force - Maintenance Steering Group) which apply parameters necessary for each maintenance requirement, such as flight hours or cycles, in -a determined time interval. The intervals between checks based on the parameters of use, allow a greater flexibility in the design of the maintenance and repair program, thus optimizing the long-term operation of the aircraft, but also reducing the time it is idle on the ground [3].

► VISUAL INSPECTIONS

Aircraft visual inspections are maintenance maintenance overhaul (MRO) procedures to ensure the airworthiness of aircraft. Over 75% of inspections performed on large transport aircraft are visual. It is a process that is done with the naked eye, to inspect and detect damage or anomalies that could pose a risk to the safe operation of the aircraft. Therefore, the basic method of assessing the general condition of an aircraft and its components is visual inspection, which must be accurate and competent and thus report defects, manufacturing errors or component fatigue. [1,3,4].

Depending on their degree of difficulty and effectiveness, visual inspections of aircraft can be divided into the following categories:
→ The walk-around inspection is a check that assesses the general condition of the aircraft and its compliance with safety standards. This inspection is carried out by an inspector, who is moving on the runway, under the plane and around the plane, as the name of this type of aircraft check shows [1].
→ General visual inspection is routinely performed to detect, locate and assess any damage, malfunction or anomaly. For most surfaces, the inspector uses additional equipment, such as special stairs that rise to the level of the plane [1].

The visual examination may be in areas inside, or outside the aircraft, may target an element, or an assembly, to detect obvious damage, malfunction or other irregularities. This type of inspection is carried out remotely, unless otherwise stated. A mirror is used to increase visual access to the areas to be inspected. The general visual inspection is carried out under the following lighting conditions: daylight, if the inspection is carried out during the day; the light received from the hangar, which under certain conditions requires the removal of access panels, or doors; light from a flashlight or lighting lamp. Stands, ladders or platforms are also required in an inspection so that the inspector can approach the area he needs to check.
→ Detailed visual inspection consists of a thorough examination of a particular area, components or systems to detect possible damage. Certain instruments are needed: flashlights, mirrors, magnifying glasses, specific measuring instruments, etc. It is also necessary to clean the surfaces that are subject to inspection and developed procedures for access [1].

► MAINTENANCE PRINCIPLES

Maintenance activities generally include the tasks required to restore or maintain the systems, components and structures of an aircraft in a state of airworthiness. Aircraft maintenance is essential for three main reasons [1,3,4, 71]:
A.Operational - The aircraft must be maintained in a serviceable and reliable condition so as to generate revenue.

B.Maintaining value - The aircraft must retain its value at the time of purchase by reducing physical damage throughout its use.
C.Regulation Commands - The condition and maintenance of commercial aircraft are regulated by the aeronautical authorities in the jurisdiction in which the aircraft was registered. The controls shall establish standards for repairs, periodic overhauls and modifications, requiring the owner or operator to establish an airworthiness maintenance and inspection program to be carried out by authorized persons and to issue a certificate of airworthiness.

► MAINTENANCE TASKS

Aircraft maintenance tasks can be classified as follows [1,3,4]:
→ Hard-time - is a major maintenance process, in which an item must be removed from service, before or at a specific scheduled time. Checking the staff and reviewing the landing gear are considered difficult events.
→ On-Condition (OC) - a limited maintenance process, on components that can be determined to maintain airworthiness, by visual checks, measurements, tests or means, to be performed without an inspection or review. These checks must be carried out within the time limits set out in the maintenance program approved by an operator.

The performance tolerances as well as the damage limitations of each component are described in the Aircraft Maintenance Manuals. The additional criteria applied to determine the condition of a component are the ability to inspect a fully structural area to detect corrosion without disassembling the part.

1.2. MAINTENANCE AND ROBOTIZATION IN AERONAUTICS

1.2.1. General information on aeronautical maintenance

Aircraft maintenance requires programs to ensure that their airworthiness is maintained by inspecting, reviewing, replacing, repairing and making changes in accordance with the airworthiness guidelines (Fig. 1.21) [3].

Fig. 1.21 – Maintenance of an aircraft inside a hangar [3]

Several definitions of what we call aircraft maintenance have been formulated [3,4]:
→ "Actions required to determine the condition of an item, which involves restoring and maintaining it in a working condition, including repair, overhaul, modification and inspection" (World Airlines Technical Operation Glossary).
→ "Maintenance is a necessary action to sustain, or restore, the integrity and performance of an aircraft" (Hessburg, 2001).
→ "Maintenance is the process of ensuring that a system continuously fulfills the function for which it was designed, in terms of its reliability and security" (Kinnison and Siddiqui, 2013).

To ensure safe and proper operation, aircraft maintenance is regulated in accordance with international standards, which are set by the International Civil Aviation Organization (ICAO). ICAO standards are implemented by local airworthiness authorities, which in turn regulate repair, maintenance and inspection tasks. These tasks are performed by authorized technical personnel.

In general, in civil aviation, the maintenance of aircraft is done according to a schedule, which requires repair and maintenance work after a certain time of use.

Upon completion of a maintenance task, the person authorized by the national airworthiness authority shall sign a document certifying that the maintenance has been carried out in accordance with the airworthiness rules in force. For certified aircraft, maintenance is performed by an engineer or maintenance technician, and for amateur aircraft, maintenance is performed by the owner, or by the aircraft manufacturer. After certain types of maintenance are performed, a Certificate of Release to Service (CRS) certificate is issued.

1.2.3. Use of robots in aeronautics

Automation is a major part of the aerospace industry. With a large production of products, but also many orders to be honored, industrial robots can substantially reduce production costs, but also their manufacturing time. Although the aeronautical industry has used classical methods in the production process, lately, it uses robotic applications and large-scale automation [22, 115].

Although the role of robotics in the technological process of production of aerospace products is very important, it does not have as great a representation as in the automotive field. Robots are used in the manufacture of aircraft engines, but at the same time, for other more elaborate activities, such as drilling, painting, etc. . Robots have the ability to repeatedly position very large aerospace components with a high degree of accuracy.

Technical Director of the Motoman Robotics Group at Yaskawa America Inc. (Miamisburg, Ohio), Erik Nieves says: “Traditional robots that have worked so well in Detroit for the last 30 years are not working well in Everett. Today's robots are more rigorous and capable, because they have reached a level of performance, indispensable in aerospace applications ”[22, 115].

Industrial robotics technology has developed in the aerospace industry, and some of them are widespread and profitable [22, 115].

1) Non-destructive testing and inspection (NDT)

No mistakes are allowed in the aviation industry, and inspections play a critical role in the production of a reliable product. Robotic ultrasonic inspection is one of the most widely used applications in robotic inspections in the aerospace industry, especially for detecting malfunctions of irregularly shaped composite components.

The non-destructive inspection shall include:

→ Ultrasonic Inspection - Ultrasonic Inspection (TTU / PAUT);
→ X-ray;
→ Shearagraphy;
→ NDT (non-destructive testing) Eddy Current (fig. 1.22).

Fig. 1.22 – Industrial arm-articulated robot used in NDT [22]

2) Robotic drilling and fixing

A multitude of activities in the aeronautical industry involve the use of robots for drilling and fixing applications (Fig. 1.23), due to the speed and accuracy with which they perform these operations. Industrial robots contribute to the development of productivity, pilot holes, drilling and reaming [22].

Fig. 1.23 – Industrial arm-joint robot used for drilling and fixing [22]

3) Robotic welding

For welding noble metals, such as titanium or nickel alloy used in engines, industrial robots guarantee the safety and quality of products through repeatability and accuracy (Fig. 1.24). Composite parts are widely used in the aerospace industry, but precision welding is required for engines, turbines and other metal parts [22].

Fig. 1.24 – Industrial arm-joint robot used for welding [22]

4) Robotic sealing and distribution

Typically, in the aerospace industry, sealing and distribution applications were slow and difficult processes, especially for very large parts. Therefore, it was considered that robots can be designed to travel distances of 40 feet (12,192 meters), or more and faster than a human operator. Due to the precision with which they carry out their activity, robots can reduce the amount of scrap resulting from sealing [22].

5) Automated fiber placement (AFP)

Automatic fiber placement is a process in which industrial robots create a combination of several layers of carbon fiber strips, which they place in a mold. Due to the fact that they are light and durable, composite parts are widely used in the aeronautical industry, but also industrial robots for AFP.

The robotic applications presented are the most common, but also the most used in the aeronautical industry [22].

CHAPTER 2

GENERAL CONSIDERATIONS ON MOBILE ROBOTS

2.1 BRIEF HISTORY OF ROBOTS

The term robot comes from the Slavic language, namely, from "rabotnik" which means work (from "rabotnik" - worker). The Czech writer Karl Čapek first used the word robot in 1923 in his play "Rosum's Universal Robots", naming artificial characters in this opera, which became famous. Renowned American scientist Isaac Asimov, a professor at Columbia University who was primarily concerned with astrology and futurology, introduced the three laws of robotics in the early 1940s, which are still relevant today. In this way, Isaac Asimov defined a new science, robotics, referring to those industrial activities that aimed to produce robots. Like many other human trials, robotics has enjoyed widespread development. The industrial robot did not appear at a stage in history in which we can speak of a multitude of technical achievements, but the ground was prepared, at the end of the Second World War. Therefore, the first industrial robot was made in 1961 [66, 74].

In 1961, in the United States, the first industrial robot, UNIMATE 001, began operations at General Motors in Ternsted, New Jersey. His role was to unload a pressure casting plant. The activity was considered to be difficult and dangerous for a worker, primarily because it took place under a high temperature. The robot had managed to cover the work of two workers during the eight hours of work a day. Once installed, the first robot posed a series of problems not only of a technical nature. For many who could decide in the American industry, the robot was a science fiction object. It was not until 1975 that the company producing the world's first industrial robot, Unimation Inc., made a profit from the production and sale of industrial robots. At the moment, the first robot is a museum piece and can be found at Smithonsian's Institute, also in the USA. In 1966 Unimation Inc. was assimilated by a group of competitors. But the interest in robots was much greater in Japan than in his home in the United States. In 1968, Kawasaki bought the first industrial robot in Japan, and in 1971 the Japan Industrial Robot Association (JIRA), an official association for the promotion of robots in industry, was established in Japan (Fig. 2.2). The founding members included the large Japanese companies Kawasaki, Mitsubishi, Fujitsu.

Fig.2.2 – The first Japanese robot [64]

In 1973, a book entitled "Robot Industry" was published at the University of Stuttgart, Germany, listing all the types of robots that appeared, without criticizing their performance. The authors reviewed 71 companies that produced industrial robots at the time. By 1978, there were already over 200 manufacturing companies. Today there are many more, even if a number of companies have had to give up the production of robots, due to strong competition and fluctuations in certain years, in the demand for industrial robots.
Writer Isaac Asimov defines the three laws of robotics in science fiction.

The three fundamental laws of robotics are [64]:

1. A robot must not, by its action, harm or allow a human being to be harmed.
2. A robot must obey orders given to it by human beings, unless those orders conflict with the first law.
3. A robot must protect itself, except when the protection measures do not conflict with the first two laws.

Much of Asimov's creation is built around the three laws of robotics, which the author created, to establish clear parameters for the operation of robots, to prevent them from getting out of control.

The action in his novels led to the appearance of an additional law, entitled Law 0 (zero) and it is worded as follows:

A robot is not allowed to cause harm to humanity, or to allow humanity to be endangered by non-intervention.

As a result of Law 0, all other laws are amended accordingly, Law 0 being the supreme law.

CHAPTER 3
THEORETICAL CONTRIBUTIONS

3.1. MOBILE ROBOT LOCOMOTION SYSTEMS

A robotic vehicle is a device that has the ability to be programmed to move under the supervision of an operator and to perform a certain indicated task. In practice, there is a fairly wide variety of robotic vehicles. A minimum classification is described in Figure 3.1:

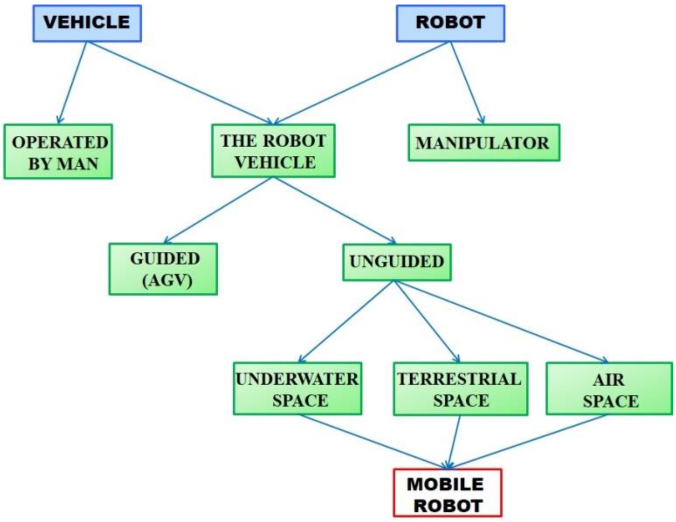

Fig. 3.1 - Classification of vehicles - robot [80]

From the first classification that can be noticed in figure 3.1, it derives the fact that a distinction is made between guided vehicles, such as Automated Guided Vehicles (AVGs) and non-guided ones. A guided vehicle is usually delimited by a set of predefined paths in its operating area. These paths can be drawn on rails, optical lines, magnetic lines, or programmed. Guided vehicles cannot abandon the already determined position. The second classification can be distinguished by the area in which the robot vehicle operates. The guided robot vehicles are terrestrial, the unguided ones can operate both in the aquatic environment and in space. The most common robot vehicles are the unmanned ones, and they operate on the ground [5, 6].

In the field of specialization, non-ground-guided robotic vehicles with a locomotive system equipped with wheels are also called - mobile robots or wheeled mobile robotic vehicles (Wheeled Mobile Robots) [80].

A mobile robot has in its composition a series of elements, some of a physical nature (hardware) and others of a logical nature (software). From a hardware point of view, a mobile robot can be considered as a collection of systems for:

→ LOCOMOTION - the mode by which the robot moves in the work area;

→ SENSORY SYSTEM - the regime by which the robot evaluates its properties and the environment;

→ PROCESSING - the regime by which the robot appreciates and makes decisions about the information received from the sensory system;

→ COMMUNICATION - the mode by which the robot communicates with other robots or with an operator in the environment.

Locomotion is the process by which the mobile robot is allowed to move through the environment, by exerting certain forces on it. The study of the action of these forces is called dynamics, and the study of mathematical formulas associated with motion, without considering physical forces, is called kinematics.

A technique for assessing the position of a mobile robot in its work area is called odometry. Odometry calculates the distance traveled by a mobile robot based on the number of turns while running. In the case of an ideal wheel, at each rotation it can be seen that the robot has achieved a distance of 2πr, where r is the radius of that wheel. In practice, however, due to frictional forces and slippage, the estimates are less accurate.

The existing mobile robot has three degrees of freedom: a position (x, y) and an orientation θ with respect to the horizontal axis. The triplet (x, y, θ) is also called the relative or absolute position and creates the effective control variable of the locomotion system.
The mobile robot does not have complete control over the three variables. A series of complex actions must be performed for the mobile robot to move from one position to another. In the literature, the starting position is denoted by $((x_s, y_s, \theta_s))$, and the position where the robot must reach with (x_g, y_g, θ_g).

In addition to the driving wheels, in addition to the driving wheels, either additional wheels or other contact elements are rediscovered, which ensure the support of the robot. Model-beaver wheels are the most common and are also wheels that are not considered in the kinematic equations of the mobile robot. The locomotion system can have different features and elements.

In the following I will present some of the most common locomotive structures of mobile robots, to determine which system is suitable for the use and implementation of the mobile robot, in the inspections inside the fuel tank of the aircraft, as follows:

3.1.1. Differential locomotion systems

Differential systems are simple systems, without complex connotations, of locomotion encountered in a mobile robot. A differential system consists of two wheels mounted on a common shaft, controlled by two separate motors (see Fig. 3.2).

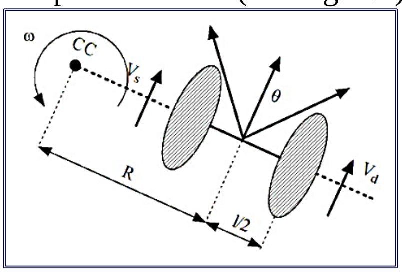

Fig. 3.2 – Differential locomotion system [63]

Kinematics is concerned with the relationships between control characteristics and the conduct of the whole in the space in which it is located. In a differential locomotion system, the robot is required to rotate around a point on the common axis of the two drive wheels. By changing the speeds of the two wheels, the direction of rotation can be changed. The speeds of the two wheels must comply with the following relationship [63]:

$$\begin{cases} \omega\left(R+\frac{l}{2}\right) = v_d \\ \omega\left(R-\frac{l}{2}\right) = v_s \end{cases} \tag{3.1}$$

Where v_s - represents the speed of the wheel on the left, v_d- represents the speed of the wheel on the right, R - is the distance between the middle of the axis of the two wheels and the center of curvature CC, ω - the angular velocity, and l - the distance between the two wheels. The rotation angle is θ. Solving the system of equations of the two wheels, leads to the solutions:

$$R = \frac{l}{2}\frac{(v_d+v_s)}{(v_d-v_s)}, \quad \omega = \frac{(v_d-v_s)}{l} \tag{3.2}$$

A special case is $v_s = v_d$. The distance R in this case becomes infinite, so the robot will move in a straight direction. If $v_s = -v_d$, the distance R becomes 0, and the robot will move to the place around the middle of the axis l. For any values of v_s and v_d, the robot will rotate making a circle of radius R with respect to the center of curvature.

A lot of points other than the starting point can be achieved by selecting the speeds v_s and v_d. The direct kinematic equations of the robot represent the establishment of a point that can be mastered by the robot by maneuvering the control parameters.

$$\begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} \cos(\omega\delta t) & -sin(\omega\delta t) & 0 \\ sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x - x_{CC} \\ y - y_{CC} \\ \theta \end{bmatrix} + \begin{bmatrix} x_{CC} \\ y_{CC} \\ \omega\delta t \end{bmatrix} \tag{3.3}$$

The equation presented above shows the rotational motion of the robot at the distance R between the middle of the axis of the two wheels and the center of curvature CC having the angular velocity ω.

By integrating the above equation, starting from a set of initial conditions (x_0, y_0, θ_0), the position of the robot with a time t can be determined, based on the control parameters $v_1\,(t)\ and\ v_2(t)$.

$$x(t) = \frac{1}{2}\int_0^t [v_d(t) + v_s(t)]\, cos[\theta(t)]dt$$

$$y(t) = \frac{1}{2}\int_0^t [v_d(t) + v_s(t)]\, sin[\theta(t)]dt \tag{3.4}$$

$$\theta(t) = \frac{1}{2}\int_0^t [v_d(t) - v_s(t)]\, dt$$

The inverse kinematic equations of the mobile robot, establish the control parameters (velocities $v_s\ and\ v_d$) to reach a certain point already established. Due to the fact that solving the above system of equations is difficult, it is recommended to create two situations of movement of the robot with differential locomotion system.

In the first case, if v_s is equal to v_d = v, the above equation becomes:

$$\begin{pmatrix} x' \\ y' \\ \theta' \end{pmatrix} = \begin{pmatrix} x + vcos(\theta)\delta t \\ y + vsin(\theta)\delta t \\ \theta \end{pmatrix} \tag{3.5}$$

In the second case, if $v_s = -\,v_d = v$ is equal, the equation becomes:

$$\begin{pmatrix} x' \\ y' \\ \theta' \end{pmatrix} = \begin{pmatrix} x \\ y \\ \theta + 2\frac{v\delta t}{l} \end{pmatrix} \quad (3.6)$$

Thus, to move a robot from x_s, y_s, θ_s)to x_g, y_g, θ_g)with $\theta_g \neq \theta_s$, the second control situation can be used: $v_s = -v_d$until $\theta_g = \theta_s$, then continuing by moving the robot, using the first control situation $v_s = v_d$.

3.1.2. Synchronous locomotion systems

The synchronous locomotion system is characterized by the fact that each wheel can be controlled separately. The representative configurations of the synchronous locomotion system admit the presence of three drive wheels positioned on the ends of an equilateral triangle (see fig. 3.3).

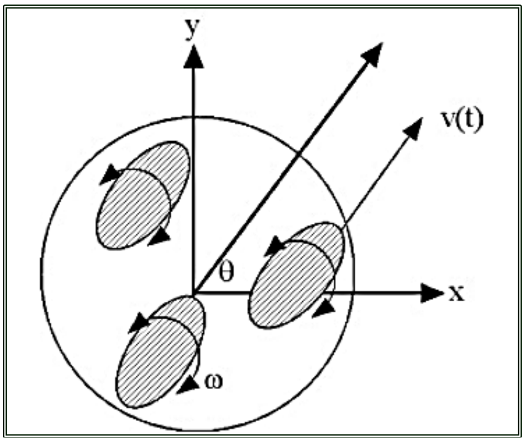

Fig. 3.3 – Synchronous locomotion system [63]

For a robot model to have a synchronous locomotion system, it must use two motors, one to run all the wheels in one direction, and the second motor is to be able to move forward or backward. Due to the fact that all the wheels remain parallel, the robots with synchronous locomotion run around their own center of gravity.

The direct kinematic equations of a robot with a synchronous locomotion system, which run at angular velocity ω and move at velocity v, are:

$$x(t) = \int_0^t v(t)\, cos[\theta(t)]dt$$

$$y(t) = \int_0^t v(t)\, sin[\theta(t)]dt \quad (3.7)$$

$$\theta(t) = \int_0^t \omega(t)\, d$$

3.1.3. Tricycle locomotion system

A tricycle locomotive system consists of three wheels: two in the rear, passive and one wheel in the front; engines with which the travel speed and the direction of the vehicle can be specified. The tricycle-type robot is controlled by the angle α and the travel speed v, respectively (see fig. 3.4).

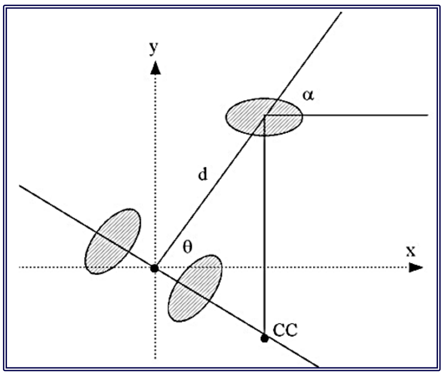

Fig. 3.4 – Tricycle locomotive system [63]

The robot will run at an angular velocity ω, with a distance R in the direction of a perpendicular line passing through the rear wheels, only if the front wheel is positioned at an angle α. R and ω are given by the equation:

$$R = d \cdot tan\left(\frac{\pi}{2-\alpha}\right),\ \ \omega = \frac{v}{(d^2+R^2)^{\frac{1}{2}}} \tag{3.8}$$

As with the differential locomotion system, inverse kinematic equations are quite complicated. With these arguments, two separate cases are considered.

In the first case: α = 0, the robot moves forward, its position being given by:

$$\begin{pmatrix} x' \\ y' \\ \theta' \end{pmatrix} = \begin{pmatrix} x + vcos(\theta)\delta t \\ y + vsin(\theta)\delta t \\ \theta \end{pmatrix} \tag{3.9}$$

In the second case, if the robot has the ability to maneuver the drive wheel, the angle of +/- 90 °, then the robot can turn around and the position will be given by:

$$\begin{pmatrix} x' \\ y' \\ \theta' \end{pmatrix} = \begin{pmatrix} x \\ y \\ \theta \pm \frac{v\delta t}{d} \end{pmatrix} \tag{3.10}$$

The emphasis is on the fact that if the front wheel does not meet the condition of rotating at angles of +/- 90 °, it is practically unfeasible to change the orientation of the robot without changing its position.

3.1.4. Ackerman locomotion system

Ackerman locomotion systems are present in the structure of cars. In the Ackerman model, the front wheels can be rotated individually to change the distance from the center of curvature, which is in a direction perpendicular to the center of the rear wheels (see Fig. 3.5).

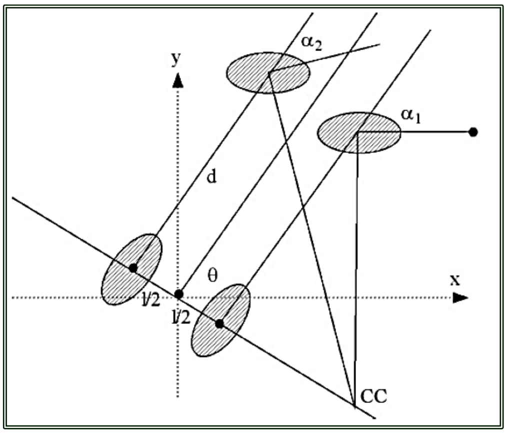

Fig. 3.5 – Ackerman locomotion system [63]

In the locomotive system based on the Ackerman model, the robot runs near a point on the right perpendicular that passes through the center of the rear wheels at a distance R, expressed by the equation:

$$R + \frac{1}{2} = d \cdot tan\left(\frac{\pi}{2} + \alpha_1\right) \qquad (3.11)$$

Since the robot has to make a twisting motion, it is necessary for the second drive wheel to rotate at an angle of α_2, where:

$$R - \frac{1}{2} = d \cdot tan\left(\frac{\pi}{2} + \alpha_2\right) \qquad (3.12)$$

3.1.5. The locomotion system with legs - hexapod robot

The main problem of an autonomous mobile robot is to complete the control of locomotion on an accidental terrain. Some of the structures used to build mobile robots were obtained through inspiration from the animal kingdom, such as the hexapod. Many researchers have been inspired by their research, modeled on quadrupeds or insects. In the case of standing robots, it can be said that the most used is "BigDog". It has four legs and operates in military applications. Also worth mentioning are the "RHex" (Moore, 2002) and "MELMANTIS" (Melmantis, 1997) robots, which have six legs, referred to in modern literature as hexapod robots. The first, also called "Robot Parkour", has a single engine at the limbs, with the ability to jump on solid ground and from one end to the other. The "MELMANTIS" robot has the ability to use wide bars at its extremities and therefore can perform a movement between the legs and the handling arm. Also in 2006, researcher Jianhua refers to robots that have a large number of servomotors on each of their legs, with 42 degrees of freedom.

A robot with legs has the ability to move on terrain with a high degree of difficulty, which is why mobile robots with wheels do not have this advantage. Robots with their feet can move over landslides, gravel, uneven roads, obstacles or over terrain where there are no flat roads. However, the ability to control a hexapod mobile robot is a complex issue. The locomotion system employed on the robot, costs in the simultaneous coordinated movement of six feet, each with three degrees of freedom (G.D.L.), the hexapot robot having a total of 18 degrees of freedom. Due to the fact that the robot interacts with an unstructured environment while moving the robot, it is necessary to use an electronic sensory system to detect obstacles. However, it should be noted that the main problem is the coordination of the angular movement of the 18 joints of the robot while moving, emphasizing the sequence of steps. This problem is achieved by implementing an electronic system dedicated to distributive architecture [78, 23].

a) The kinematic model of a leg

It is important to select a mechanical configuration for the robot's leg, which maximizes movement and imposes a small number of restrictions on its movement. A three-rotation kinematic chain or RRR joints was used to size each leg of the hexapod robot. The direct geometric model for the mechanism of each leg was formulated, using a mobile reference system $O_i(x_i, y_i, z_i)$for each joint, with i = 1..2 and a fixed reference system $O_W(X_W, Y_W, Z_W)$. The different connections of the robot's legs were named as follows: thigh, femur and tibia (see fig. 3.6).

The reference system of the hexapod robot's foot starts with the zero connection, which is the starting point of the robot's structure, where the foot is anchored or mounted on the ground; connection one is the thigh, connection two is the femur and connection three is the tibia with the final extremity as a base [20, 21].

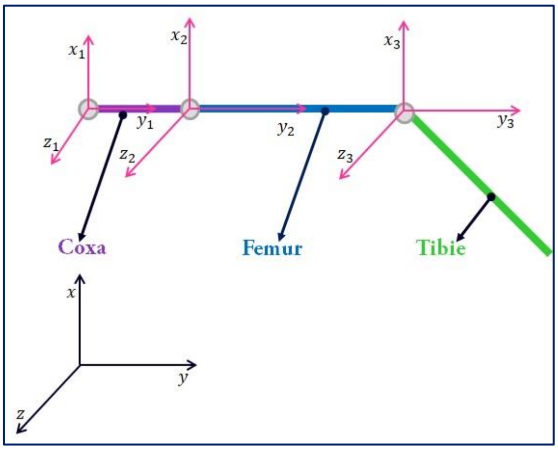

Fig. 3.6 – The connection between the thigh, femur and tibia of the hexapod robot's foot [34]

To calculate the direct kinematic equation, the Denavit-Hartenberg parameters are used (see Fig. 3.7), with modifications by Craig (Ollero, 2007), which result in the following transformation matrices [33]:

$$T_1^0 = \begin{bmatrix} cos(q_1) & -sin(q_1) & 0 & 0 \\ sin(q_1) & cos(q_1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} cos(q_2) & -sin(q_2) & 0 & l_1 \\ sin(q_1) & cos(q_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.13)$$

$$T_{OT}^2 = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: T_1^0 ,T_2^1,T_{OT}^2 are transformation matrices, $q_1$is the angle of the femur [degrees], $q_2$is the angle of the tibia [degrees], $l_1$is the measure of the femur [cm], l_2 is the measure of the tibia [cm].

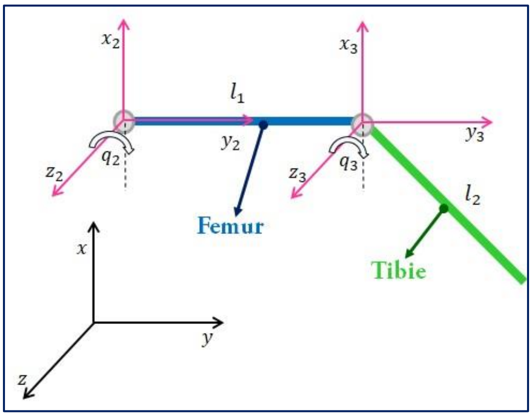

Fig. 3.7 - Denavit-Hartenberg parameters for one foot [34]

To find the transformation matrix $T_{OT}^0$the product $T_1^0 \cdot T_2^1 \cdot T_{[OT]}^2$is made. The result obtained corresponds to the following equations for direct kinematics, for each leg of the hexapod robot. Thus, the coordinates of the final extremity of a robot leg are:

$$x = l_1 cos(q_1) + l_2 cos(q_1 + q_2)$$
$$y = l_1 sin(q_1) + l_2 cos(q_1 + q_2) \tag{3.14}$$

While direct differential kinematics relates joint velocities to workspace velocities through the robot's Jacobian matrix, the formula is obtained using velocities, whose equation is [33,34]:

$$v = \begin{bmatrix} 0 \\ 0 \\ \dot{q_1} \end{bmatrix} . \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} + R_2^0 \left(\begin{bmatrix} 0 \\ 0 \\ \dot{q_2} \end{bmatrix} . \begin{bmatrix} l_2 \\ 0 \\ 0 \end{bmatrix} \right)$$
$$R_2^0 = \begin{bmatrix} cos(q_1 + q_2) & -sin(q_1 + q_2) & 0 \\ sin(q_1 + q_2) & cos(q_1 + q_2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.15}$$

Where $\vec{v}$ is the vector of the translation velocities of the tibia extremity [cm / s], $\dot{q_1}$and $\dot{q_2}$the speeds of the servomotors [degrees / s]. By developing equation (3.15), a reduced Jacobian can be obtained, which is [33, 34]:

$$J(q) = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix}$$

$$j_{11} = -l_2 sin(2q_1 + 2q_2) + l_1 sin(q_1) + l_1 sin(2q_1 + q_2)$$

$$j_{12} = -l_2 sin(q_1 + q_2) \tag{3.16}$$

$$j_{21} = l_2 cos(2q_1 + 2q_2) + l_1 cos(q_1) + l_1 cos(2q_1 + q_2)$$

$$j_{22} = l_2 cos(q_1 + q_2)$$

Therefore, direct differential kinematics is defined as:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = J(q) \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{3.17}$$

Where $\dot{x}$ and $\dot{y}$ are the translation velocities [cm / s] of the tibia extremity with the plane.

b) The inverse kinematic model of a leg

The inverse kinematic model consists in determining the variables of the joints, starting from a position and orientation of the frame located at the final extremity. In obtaining the solution to this problem, it is important to specify the trajectories of the movement of the joint variables for each leg of the hexapod robot. These trajectories are obtained due to the transformation of the movement from the assigned trajectory into the working coordinates (x, y, z), corresponding to the desired movement of the reference system, of the final extremity of the foot. Therefore, the aim is to obtain the two variables of the joint θ_2 and $\theta_3$and which correspond to the desired position of the end frame (see Fig. 3.8) [33. 34].

In this case, the orientation of the end extremity reference system is not analyzed, because we are interested in its position. We apply the direct kinematics from equation (3.13) and consider the following limitations: all joints allow rotation only around one axis, the connections of the femur and tibia always have a rotation on parallel axes; physical limitations that can be determined for each angle in the joint.

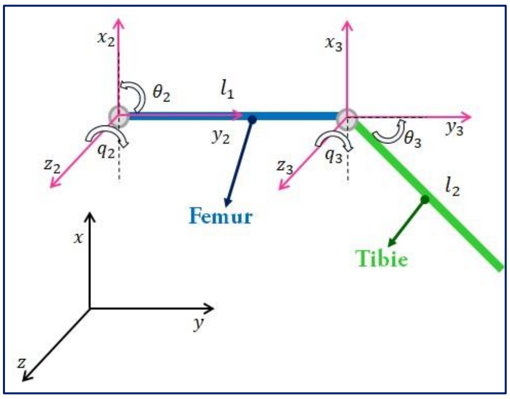

Fig. 3.8 – Diagram diagram of hexapod robot foot for reverse kinematics [34]

According to the above considerations, the inverse kinematic model of a leg of the hexapod robot has the following shape for the joints of the femur and tibia [33]:

$$q_1 = arctan2(x, y) - arctan2\big(l_2 - sin(q_2), l_1 + l_2 cos(q_2)\big) + \frac{\pi}{2}$$
$$q_2 = -arccos\left(\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right) \quad (3.18)$$

While inverse differential kinematics links velocities in the workspace with joint velocities through the Jacobian matrix of the hexapod robot, it can be expressed as:

$$J^{-1}(q) = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$h_{11} = \frac{cos(\theta_1+\theta_2)}{l_2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{12} = -\frac{sin(\theta_1+\theta_2)}{l_2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{21} = -\frac{l_2 cos(2\theta_1+2\theta_2)+l_1 cos(\theta_1)+l_1 cos(2\theta_1+\theta_2)}{l_2^2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{22} = \frac{l_2 sin(2\theta_1+2\theta_2)+l_1 sin(\theta_1)+l_1 sin(2\theta_1+\theta_2)}{l_2^2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)} \quad (3.19)$$

Precum și:

$$J^{-1}(q) = \begin{bmatrix} h_{34} & h_{45} \\ h_{56} & h_{66} \end{bmatrix}$$

$$h_{34} = \frac{cos(\theta_1+\theta_2)}{l_2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{45} = -\frac{sin(\theta_1+\theta_2)}{l_2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{56} = -\frac{l_2 cos(2\theta_1+2\theta_2)+l_1 cos(\theta_1)+l_1 cos(2\theta_1+\theta_2)}{l_2^2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

$$h_{66} = \frac{l_2 sin(2\theta_1+2\theta_2)+l_1 sin(\theta_1)+l_1 sin(2\theta_1+\theta_2)}{l_2^2 sin(\theta_1+\theta_2)+l_1 sin(\theta_1)-l_1 sin(\theta_2)}$$

3.2 PROPOSED ROBOTIZED AERONAUTICAL APPLICATION

3.2.1 Aircraft fuel tank

A large number of inspections and modifications of an aircraft's fuel tanks (Fig. 3.9), as well as their adjacent systems, must be made inside them. The necessary maintenance and repair tasks must be performed by technical personnel, who must physically enter the fuel tank, where it is exposed to many environmental risks. These potential risks include: fire and explosion, toxic and irritating chemicals, oxygen deficiency, and the limited nature of the fuel tank. In order to prevent associated injuries, maintenance organizations as well as operators need to develop specific identification and control procedures to eliminate hazards [10, 43, 45].

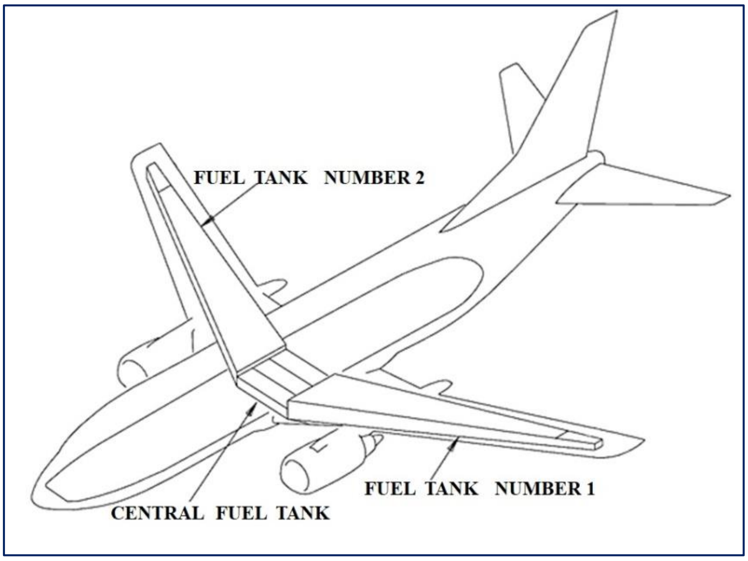

Fig. 3.9 – Aircraft fuel tanks [10]

Maintenance and repair personnel entering the aircraft's fuel tank for inspection or modification are closely related to various and many potential hazards. These are: exposure to toxic and flammable chemicals, potentially harmful weather conditions and limited tank configuration. Operators and repair stations can protect technical personnel from these hazards by developing safety procedures [10, 43, 45].

In order to successfully prevent associated accidents, both operators and technical staff must take into account:

→ possible accidents / dangers in the fuel tank;
→ preparation to enter the fuel tank;
→ the conditions necessary to enter the fuel tank;
→ emergency response plan.

3.2.2. Possible accidents / hazards in the fuel tank

The potential danger that technical personnel may experience is present in two forms: chemical and physical.

a) Chemical

The most common and recognized danger of the tank is the fuel itself. Fuel is a flammable liquid that can ignite under certain environmental conditions, temperature and vapor concentration. The temperature at which the flames of a flammable liquid can "ignite" is known as the flash point. A critical vapor concentration is present when a fuel vapor reaches a level, known as the Lower Flammability Limit (LFL), or Lower Explosive Limit (LEL). These limits are usually expressed as a percentage of the volume. Fuels below LFL / LEL (Lower Flammability Limit / Lower Explosive Limit) are considered too weak to burn. If the fuel vapor concentration exceeds the upper flammability limit or the upper explosion limit, the fuel is considered too rich to burn. A concentration of fuel vapor between these two limits is considered to be within its flammability range, it will ignite and burn in contact with an ignition source. One of the best ways to control unwanted fires and explosions is to keep the fuel vapor concentration below the LFL / LEL (Lower Flammability Limit / Lower Explosive Limit), thus preventing it from reaching its flammability range [10, 43 , 45].

Other flammable chemicals may also be present during maintenance and repair work on the fuel tank. Chemicals with a low flash point (less than 70 ° F (21 ° C)), such as methylethyl kenone (MEK), are more hazardous than fuel in the tank, so their use must also be be strictly controlled [10, 45].

Chemicals, including fuel, can also be toxic or irritating. In high concentrations, the fuel together with other hydrocarbons can damage the nervous system, causing headaches, dizziness and lack of coordination. Chemicals can cause chronic health problems, which can affect the liver and kidneys, skin irritations if left unchecked [10,45].

b) Physically

The physical characteristics of the fuel tank can create fire, explosion and toxicity hazards. The entrance is through an elongated hole less than 2 ft (0.6 m) long and 1 ft (0.3 m) wide. Although the internal dimensions of the fuel tanks vary considerably compared to the central wing tank, which is the largest, all fuel tanks have a limited volume. A relatively small amount of a chemical inside one of these enclosures can create significant levels of flammability or toxic fumes [10].

The wing tanks usually have a single access hole between each frame of the section. The inner part of the fuel tank, the wing, provides sufficient clarity for the technical staff, who have access from the waist up, leaving their feet outside the access hole. The tank becomes smaller as it moves out of the wing, significantly reducing access, and the technical staff can only enter with their head and arms. The central tank may be large enough to allow full access to the technical staff [10].

3.2.3. Steps prior to internal inspection

Before the technical staff enters the aircraft's fuel tank, several steps must be taken. These include: grounding and emptying the tank in accordance with standard practices. In order to ensure safe conditions for technical staff, three final steps must be completed and these are [10]:

a) ensuring adequate ventilation;

b) following the recommended ventilation techniques;

c) adequate monitoring and control of the air in the fuel tank.

a) Ensuring adequate ventilation

Ventilation is the only way to control fire, explosion and toxic accidents in the open fuel tank. The environment in which the technical staff operates becomes safer when clean air enters. Continuous cooling of the air in the fuel tank prevents the increase in the level of fuel vapor concentration, which can reach the LFL (Lower Flammability Limit), preventing a fire or explosion. Also, clean air reduces the concentration of chemical vapors, hence the risk of toxic exposure. A large volume of clean air will prevent the occurrence of an unwanted condition, that of oxygen deficiency [10].

The normal concentration of atmospheric oxygen in the air is 21%. The level of oxygen deficiency (19.5% and below) in a person is manifested by signs of "oxygen hunger", having headaches, nausea, drowsiness and speech disorders. At a lower oxygen concentration, more severe reactions occur that can cause death by suffocation [10, 43, 45].

Oxygen deficiency is often caused by the movement of oxygen in space. For example, pumping nitrogen into the tank to prevent the fire from igniting will cause the oxygen concentration to drop. Oxygen deficiency can cause a material to oxidize because it uses up available oxygen from space. Oxidation is a chemical reaction that combines atmospheric oxygen with another element to form an oxide. An example is iron oxide, known as rust [10].

b) Supervision of recommended ventilation techniques

The physical characteristics of aircraft fuel tanks present challenges, which are inevitable in ensuring adequate ventilation. These are those spaces where no fresh air enters, which are called - "dead spaces" and the small openings between the sections of the tank, which have the ability to inhibit the flow of air that must enter inside. That is why it is necessary to plan as accurately as possible in order to achieve adequate ventilation.

The recommended practice for fuel tank ventilation is the push-pull technique. First of all, the upstream access hole must be open for a proper push; then, a downstream hole must be opened for a "pull". Finally, a blower must be placed in the push hole and fresh air must be forced into the tank [10].

c) Monitoring the air in the fuel tank

If the fuel tank is not properly ventilated, no member of the technical team may enter it. In order to decide whether the tank environment is compliant with the possibility of starting its inspection, the atmospheric conditions, as well as the oxygen concentration, the concentration of flammable vapors and toxic fumes must be continuously checked and monitored. Entry into the tank should not be permitted unless the oxygen concentration is between 19.5 and 23.5%. Concentrations below 19.5% are considered to be - oxygen deficiency, and concentrations above 23.5% are considered to be - enriched oxygen and means increased risk of fire and explosion. If one of these conditions exists, access to the technical staff should not be allowed in the tank [10].

3.2.4. Necessary conditions to enter the fuel tank

In order to prevent possible accidents, which may occur during inspections inside the fuel tank, the technical staff must be properly trained and equipped. The team performing inspections in the fuel tank consists of at least three people: the tank inspection monitor (observer), a waiting attendant and the operator who will actually enter the tank. The monitor (supervisor) authorizes, supervises and coordinates all activity inside the tank, ensuring that all STANDARD procedures are performed. The waiting attendant stays outside the fuel tank and follows all the activity, inside, but also around the area where the inspection takes place.

He is also authorized to decide to evacuate the technician from inside the tank when he finds that the safety conditions are no longer met and endanger his life. The technician entering the fuel tank must be very well trained professionally in order to successfully solve the problems that arise in these situations. They must anticipate and recognize potential hazards and leave the tank if working conditions deteriorate [10, 43].

Each member of the team designated to conduct inspections inside the fuel tank of the airplane must strictly comply with the following requirements:
a) to communicate permanently;
b) to provide respiratory protection to the technician inside the tank;
c) to monitor air quality and ventilation;
d) to provide electrical equipment;
e) take into account and acknowledge any damage resulting from inspections in the fuel tank.

a) Communication

Continuous voice communication between the technician inside the fuel tank and the waiting attendant must be maintained throughout the inspection process. An interruption of communication would alert the waiting attendant and take the necessary action, even leaving the tank [10].

b) Respiratory protection

Depending on the current weather conditions, the technical personnel entering the tank must wear a protective mask. If the oxygen concentration is at least 19.5%, then you must wear an oxygen mask [10].

c) Monitoring of air and ventilation

Prior to an inspection, the technical staff must introduce fresh air into the tank. If ventilation is interrupted, then all activity is suspended until ventilation is restored. The atmospheric conditions in the tank must also be monitored throughout the inspection. If the oxygen concentration drops below 19.5% or increases to 23.5%, then the technical personnel, in particular those inside the tank, must be evacuated immediately. If the flammable vapor level exceeds 10% of the LFL (Lower Flammability Limit), or the toxic vapor concentrations exceed the permissible exposure level (PEL), then the tank inspection should be postponed [10].

d) Electrical equipment

Technical personnel performing work inside the fuel tank use a variety of live equipment, test equipment, including lighting. All electrically operated equipment must be safe and suitable for use in a potentially flammable environment. Pneumatic tools should only be started with compressed air, not nitrogen or other inert gases, which could ignite the oxygen inside the tank [10].

e) Considerations for possible damage caused by technical personnel

If the technical staff performing inspections inside the fuel tank has not been properly trained, or one of the members does not have the necessary experience, serious problems may arise. These consist of damaging the tank. The contact surfaces of the access hole and the covers must be protected during transport in the tank so that they do not scratch or otherwise damage. Also, the components inside the tank, such as: fuel pumps, sensors, cables, pipes, frames, etc. they are vulnerable to damage if abused or misplaced [10].

3.2.5. Emergency response plan

Work procedures inside the fuel tank must also relate to a potential emergency. If emergency procedures are not taken into account, an emergency may result in serious injury or even death to technical personnel. Operators and repairers should prepare procedures for technical staff so that they follow the following four situations [10]:
a) self-evacuation;
b) evacuation ordered by the attendant;
c) alarms on air monitoring;
d) rescue operator in case there is no response from the technical staff inside the tank.

a) Self-evacuation

Technical personnel must be able to recognize the dangers they face when working in a fuel tank and should leave the tank when conditions change, including their psychological state.

Working indoors can lead to claustrophobia which involves a panic attack and an inability to act normally. The technical staff working in the fuel tank must be thoroughly trained, not only professionally but also psychologically [10].

b) Evacuation ordered by the attendant

The waiting attendant has the obligation to constantly monitor the activity carried out by the technical operator inside the tank, but also in its immediate vicinity. If he notices that the technician inside the tank is no longer communicating with those outside, the attendant shall order his emergency evacuation. The attendant is instructed to recognize the time of oxygen deficiency, or exposure to toxic chemicals, and must also anticipate the behavior of the fuel tank operator. Therefore, the waiting attendant can decide on the evolution of events, ie, depending on the situation, to interrupt the inspection activity and resume it, when the environmental conditions will be restored [10].

c) Alarms on air monitoring

If the instruments used to monitor the atmospheric conditions in the tank work in an alarming manner, the technician must immediately evacuate the tank. The specific condition that caused the alarm must be identified and corrected before resuming work inside the fuel tank [10].

d) Rescue operator in case there is no response from the technical staff inside the tank

If, for any reason, the technician in the tank no longer responds, the waiting attendant should immediately initiate rescue procedures, including immediate notification of emergency assistance. The waiting attendant must ensure that the fuel tank is continuously supplied with fresh air. To this end, he must check all ventilation equipment, including additional cavities, which remain open throughout the inspection period in the tank.

The technical personnel entering the tank are specially trained because they need to know rescue techniques. Also, the operator entering the tank is equipped with appropriate equipment, respectively, with a self-contained breathing apparatus.

This analysis, which deals with the inspection of the aircraft's fuel tank, shows that the environment in which the work is being carried out is very harmful to humans. Therefore, the main purpose of this scientific research is to solve this problem by introducing a mobile robot. This robot should not be seen as an obstacle to the development of the capabilities of the human factor, nor as a substitute for it, but as an aid. Through this scientific research I want to emphasize that by introducing a mobile robot in maintenance activities, the human factor is protected from the detrimental influence of environmental factors. This will be demonstrated and developed in the following chapters [10].

3.2.6. Choosing the type of mobile robot for the internal inspection of the aircraft's fuel tank

Carrying out an inspection inside the fuel tank requires considerable effort on the part of the technical staff, who must enter the tank. So, for many researchers, the use of a mobile robot has been a solution to simplify, even partially, this dangerous operation for humans.

Operating a robot in a fuel tank is not always successful. As we have shown, it is extremely dangerous to put a robot in a tank full of kerosene. Therefore, even if it takes a longer time, the kerosene tank must be completely emptied and then vented.

Choosing the right type of robot for this type of inspection is not an easy task. Personally, I bought an octopod mobile robot, which I put in the tank. The robot responded to my commands, but when it had to go over the frames in the tank, it lost its balance.

From the beginning, I thought of this experiment, using the octopod robot - ROBUGTIX. I scheduled it to inspect the inside of the tank, but it seems that the height of the frames was a problem. At one point, in a moment of inattention on my part, it even turned upside down.

From that moment on, I started doing mathematical calculations and came to the conclusion that a hexapod robot is the perfect choice.

The hexapod mobile robot has a higher safety in operation, because the positioning of its legs makes it stable.

The experiment was a success because the robot moved all over the tank, transmitted video images from all its compartments, did not present balance problems, did not overheat and did not lose energy.

We followed the evolution of the hexapod mobile robot, both inside the tank, next to it, and outside it, because, in the end, its role is to perform inspections, without human intervention. I programmed, controlled and controlled the robot outside the tank.

Maybe other mobile robots can be just as efficient in fuel tank inspections, but because I'm a practitioner of the profession, not just a theorist, I say that the hexapod mobile robot is effective in this type of inspection.

3.3. HEXAPOD-AFTRH ROBOT (AIRCRAFT FUEL TANK HEXAPOD ROBOT) USED IN RESEARCH

3.3.1. Description of the robot and main technical characteristics

The hexapod robot - A.F.T.R.H. (Aircraft Fuel Tank Robot Hexapod) (fig. 3.16) that I designed, is a mobile unit remotely controlled by a single operator, from a computer or a smartphone, in order to perform the inspection, inside the fuel tank, of the plane. Because the inside of an aircraft's fuel tank is a highly toxic human environment, the designed AFTRH hexapod robot successfully performs these operations.

The hexapod robot - AFTRH that I designed, has a structure consisting of:

→ mechanical system;
→ location system;
→ environmental perception system;
→ information processing and task management system.

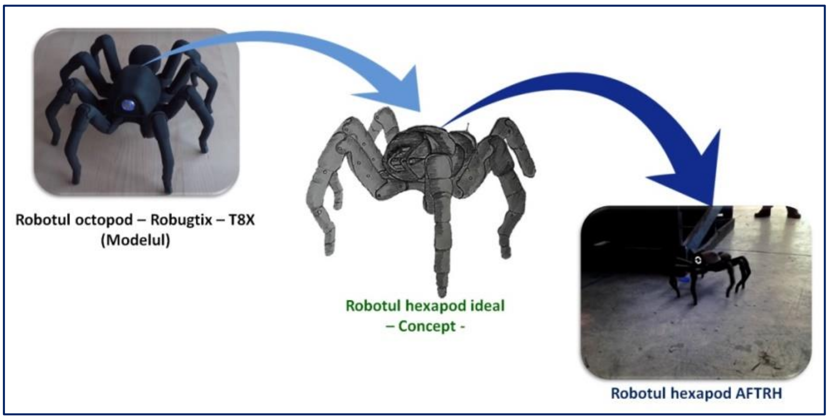

Fig. 3.16 – Transforming the A.F.T.R.H. Hexapod Robot (Aircraft Fuel Tank Hexapod Robot) from the Robugtix-T8X octopod robot model

The only task of the hexapod robot is to search and follow the trajectory in order to inspect some surfaces inside the aircraft's fuel tank. The operation of the AFTRH robot in the fuel tank is defined by agility and maneuverability. Agility is the ability of the hexapod robot to overcome obstacles, and maneuverability is defined by the minimum area required to maneuver it.

The AFTRH hexapod robot we designed for inspections has the following features:
→ degree of mobility: allows to follow a varied trajectory in terms of shape, length and number of stopping points;
→ travel speed: it is between 1 - 10 m / s, as it works in the fuel tank, or outside it, in this case, the hangar;
→ autonomy: it is dependent on its own energy sources (accumulator batteries);
→ command: via a computer or smartphone via the wi-fi connection.

The design hexapod AFTRH robot will be characterized as a mobile platform-type mechanical system, equipped with a leg-type locomotion system and multiple sensors, equipped with video cameras. The whole system is designed in such a way as to move with a certain degree of independence in an environment unfavorable to man, by checking a hierarchical computing system, multiprocessor type.

The sensory subsystem will allow the real-time updating of the references regarding the current configuration of the environment (inside the fuel tank) and the recognition of the internal operating conditions, thus allowing the online generation and modification of movement trajectories and work actions [78, 80]. The tasks of the robot control system are:
→ acquisition of information from external sensors;
→ providing data from sensors with different characteristics in their interpretation and processing;
→ the decision, based on previous training, recognition of previous behaviors and the combination of action reactions to build agreed behaviors;
→ generating travel commands within the navigation mode, according to the "look / sense-and-move" principle, by avoiding collisions with unknown obstacles in motion.

In addition, the control system must perform, in particular cases, additional functions:
→ modeling the environment, based on the fusion of sensory information different in nature;
→ trajectory corrections to the target point / area;
→ immediate response to orders received at higher levels;
→ error balancing and recovery after an error mode;
→ maintaining an online communication with status information with the human operator, through a human-robot interface.

3.3.4. Simulation of the locomotion system

The implemented locomotion algorithm that completes the robot's navigation is programmed in the C ++ programming language for the ARM CORTEX M3 microcontroller. The forward movements of the hexapod robot are calculated in the workspace (x, y, z), by means of parabolic trajectories, so that the sequence of the robot's step is performed by controlling the tripod movement, with the task of following the parabolic trajectory.

The robot can advance frontally and sideways, but also to make the rotational movement around its geometric center. To perform simultaneous movements with three legs, the concept known as walking with a tripod or balance triangle is applied, where the hexapod robot maintains its own balance, if it is supported statically, or performs a forward or rotating movement. The concept is to keep the center of gravity of the robot inside the surface formed for the tripod, or the equilibrium triangle.

Using the LabView 14.0 program we analyzed the parameters of speed, angular displacement and the final position of the robot's legs, which are represented in figures 3.34 - 3.42.

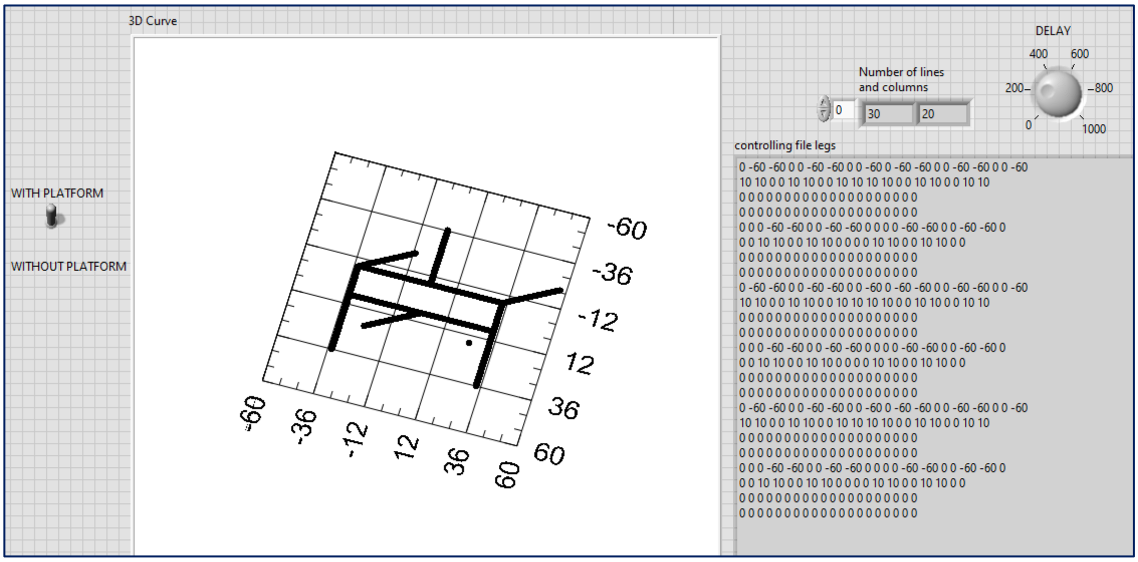

Fig. 3.34 - Front panel showing the simulation of the movement of the hexapod robot in 3D diagram and the command file of the legs S2, D1 and D3

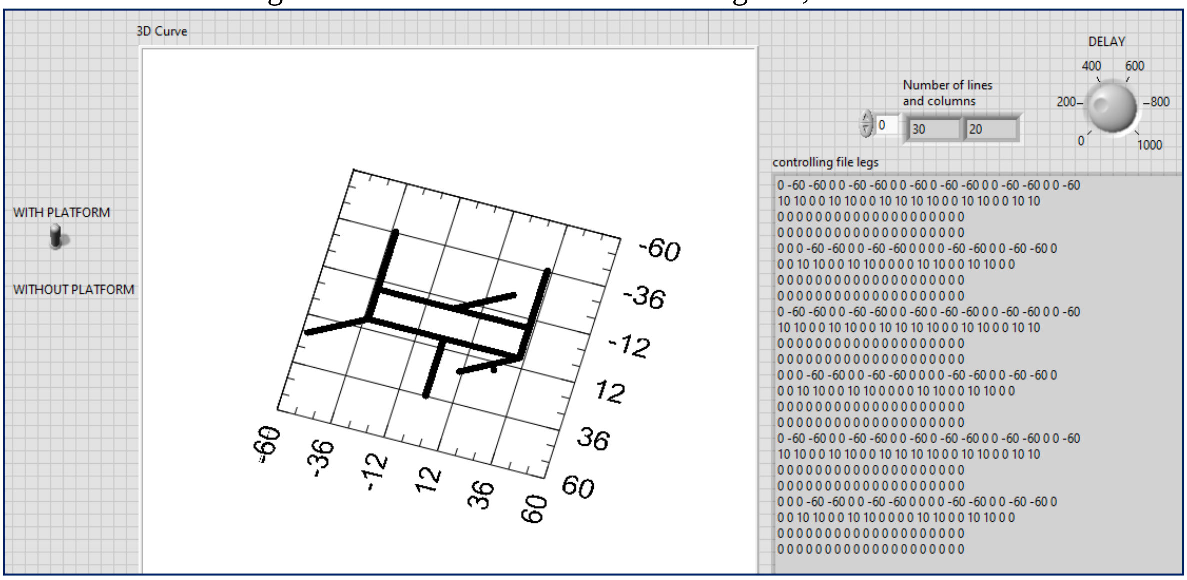

Fig. 3.35 - The movement of the hexapod mobile robot S1, S3 and D2 legs

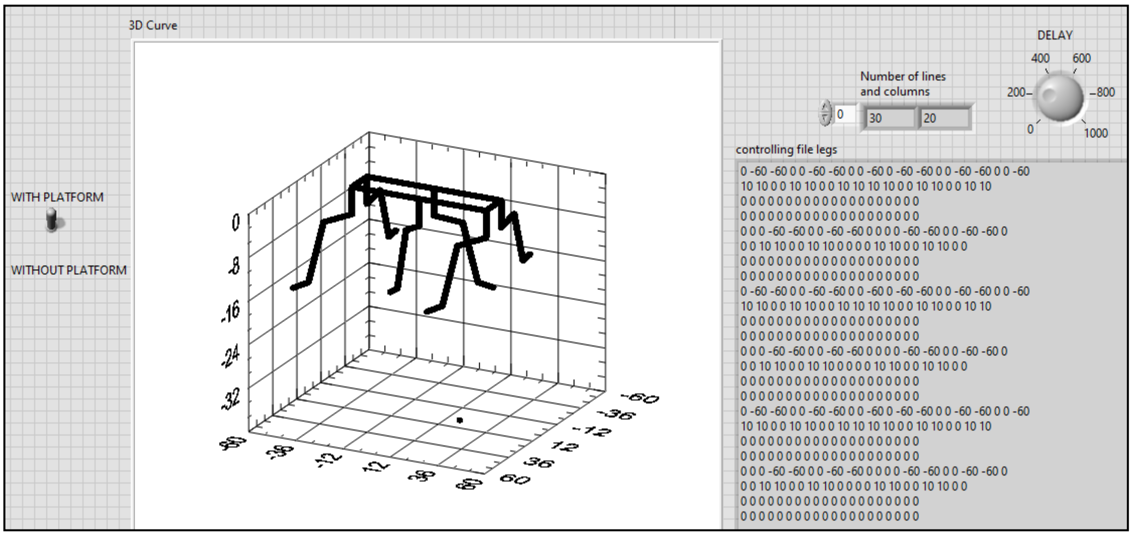

Fig.3.36 - The movement of the hexapod mobile robot's legs in 3D

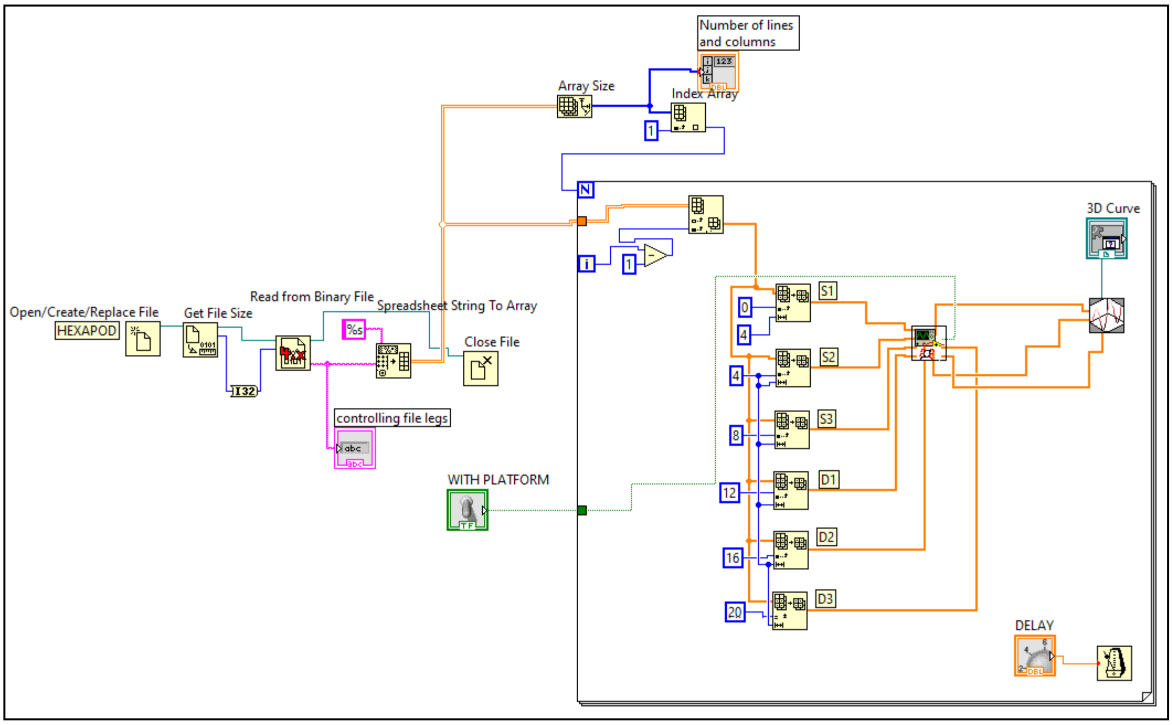

Fig.3.37 – Block diagram of the hexapod mobile robot in the LabView program

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Fig. 3.38 – File with control of the numerical parameters of the hexapod mobile robot

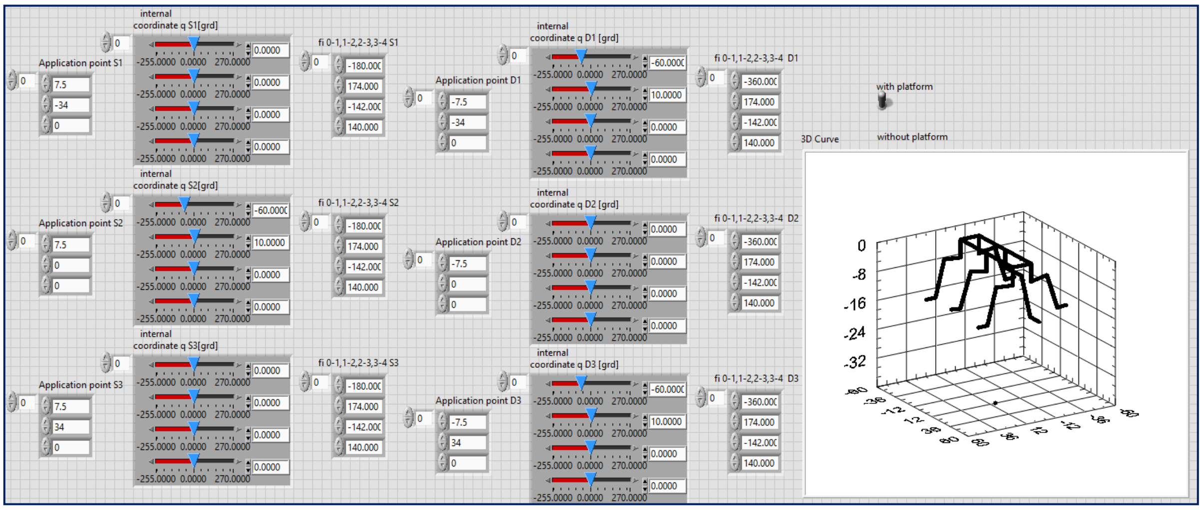

Fig. 3.39 - SubVI -LabView front panel for hexapod mobile robot, with control blocks for each robot leg

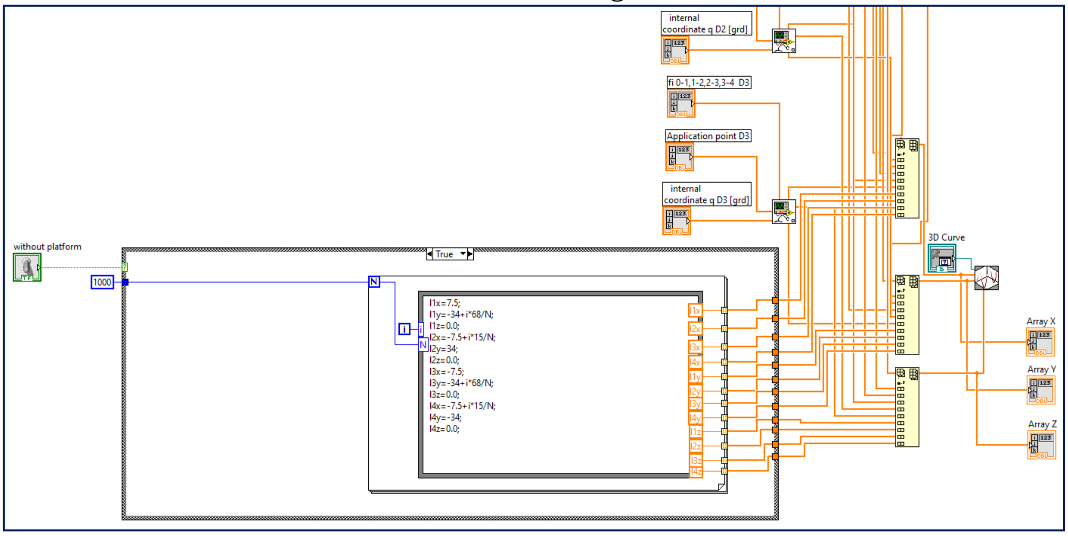

Fig. 3.40 - Part of the block diagram of the hexapod mobile robot control in the LabView program

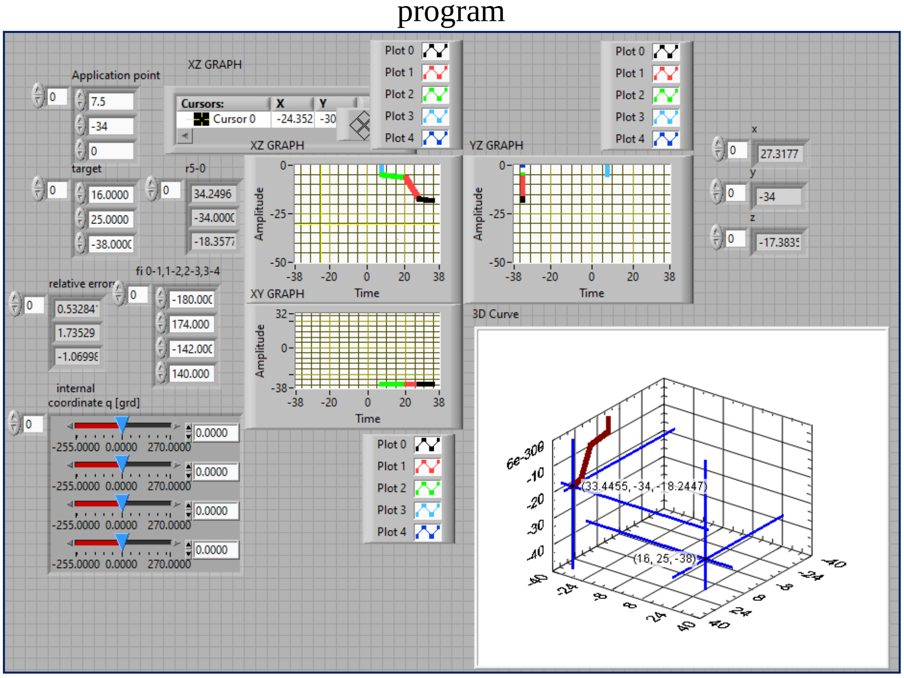

Fig. 3.41 - Front panel to simulate a robot's leg

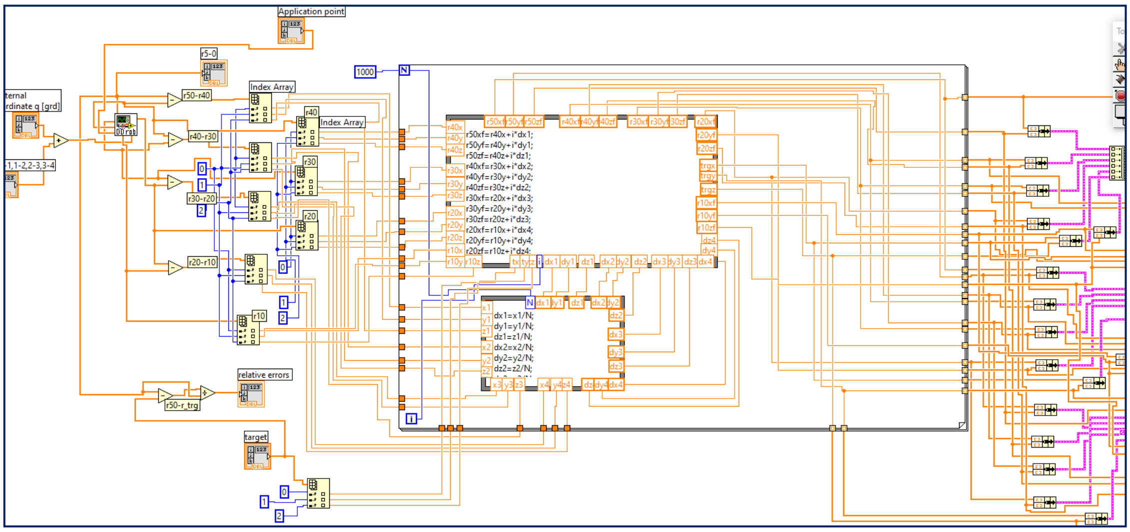

Fig. 3.42 – Block diagram in the LabView program of the hexapod mobile robot

The hexapod robot movement simulation contains some SubVI-s designed for legs and mobile platform fig. 3.34-3.36. Figure 3.37 contains the block diagram in the LabView program to simulate the movement of the hexapod robot: simultaneous movement of three legs - legs S1 and S3 on the left side of the robot and foot D2 on the right side and three legs remaining on the ground, to ensures its stability. Figure 3.34 shows the animation file for this type of movement. The application for the hexapod robot consists of a platform that represents a six-legged robot, and they have different application points, basic, as shown in Figure 3.35. The robot's legs can move separately, as can the starting position of each, which can also be set separately. The block diagram of the hexapod robot control in the LabView program is shown in Figure 3.36. The subVI corresponding to one leg of the robot, shown in Figures 3.37-3.42, have control modules for each internal coordinate, but also variable coordinates, which have the ability to control each joint, remotely. These SubVIs ensure the solution of the direct kinematics (FK), but also the inverse kinematics (IK) of the hexapod mobile robot. In the block diagram structure, for each command, there is a model for FK, which indicates the new position of each joint, as well as its animation.

CHAPTER 4
EXPERIMENTAL RESEARCH

4.1. OVERVIEW OF ROBOTIZED APPLICATION AND FUEL TANK INSPECTION TECHNOLOGY

4.1.1. General safety rules in the inspection of fuel tanks

The rules of occupational safety inside the fuel tank of an airplane apply: before the start of the inspections, during the conduct of the inspections and at the end of the activities.

Before entering the fuel tank, the inspection team must check the working conditions: tank ventilation, electrical cables, electrical voltage, the presence of objects that may hinder the activity, the presence of unauthorized persons and most importantly, the protective equipment of the work.

During the inspections, the robot operator, inspector B1.1 must ensure a constant connection with it, without making any changes to the software and without leaving the control panel.

The hexapod mobile robot must be monitored continuously.

At the end of the inspection activity, the robot will be extracted from the inside of the fuel tank by qualified personnel. The robot will not be abrupt, hit and will be placed on a flat surface, in suitable environmental conditions (constant temperature, minimum humidity level).

A. Before inspections begin in the aircraft's fuel tank

1. Activities where potentially dangerous electrical voltage is applied shall be performed only by qualified persons.
2. The plan for conducting inspections inside the aircraft's fuel tank shall be established in advance and the working partners shall be trained in advance.
3. All objects which make it difficult to carry out the activity, or which adversely affect its carrying out of the place where the inspection is carried out, shall be removed.
4. The mechanical parts of the appliances that could be accidentally energized will be grounded.
5. The connections between the component parts of the assembly shall be made, obligatorily, by perfectly insulated cords and corresponding to the voltages used in the respective action.
6. Due to the highly toxic environment inside the fuel tank, which is due exclusively to kerosene, it will be tested to detect its quality. Thanks to new technologies, the test for possible contamination takes only 15 minutes and is shown in Figure 4.1.

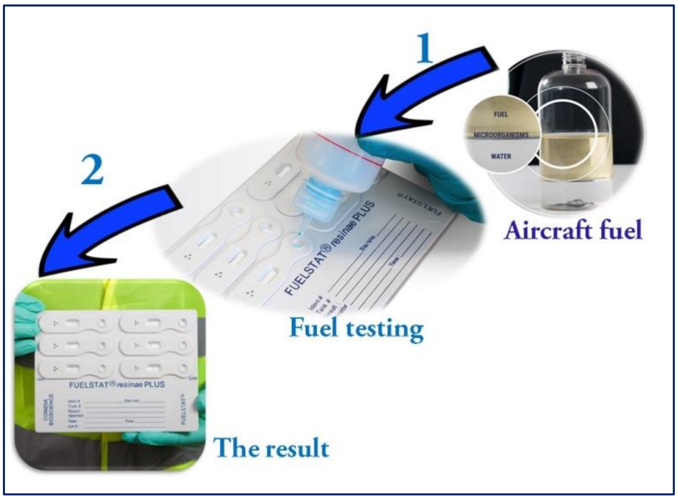

Fig. 4.1 – How to detect possible kerosene contamination

B. During inspections of the aircraft fuel tank

1. The robot operator must remain at the control panel at all times.
2. During the inspection, no objects shall be placed on the control panel other than the components of the apparatus, which could accidentally affect the connection between the robot and the operator.
3. Any change in the software of the device is made only after the control connection with the robot has been interrupted.
4. The connections between the control panel and the robot shall not be connected until all electrical circuits have been checked.
5. It is forbidden to leave the control panel.
6. The robot operator must choose a safe place, its position depending on the connection between the source and the robot.
7. The robot must be coordinated precisely, every move made by chance can unbalance the robot.

8. The specialist, Inspector B1.1, must ensure that the robot is able to monitor the entire desired surface.
9. In special cases where the robot is no longer able to communicate information to the operator, or it is no longer functioning properly, the robot will shut down and another operator will enter the aircraft's fuel tank.
10. In order to make it possible to provide first aid, if the human operator in the aircraft's fuel tank has been harmed, the space where the aircraft is located must be fitted with special equipment (first aid kit). oxygen, garou, asbestos foils etc).
11. During the inspection, the priority of the investigation of the fuel tank belongs to the inspector, then to the robot.
12. It is mandatory for inspector B1.1 to be in constant contact with the robot. After thorough investigation and following the analysis performed by the robot, the inspector can observe all the details regarding the fuel tank and in this way, can make the decision to enter or not, in the tank.
13. It is mandatory that the inspector must be placed at a distance of 1.5 - 2 meters from the plane, in order to be able to maneuver the robot efficiently.
14. The robot must be operated by qualified personnel.
15. It is necessary for the robot to have the navigation function, having the following sub-functions: workspace representation, obstacle avoidance, location function, motion planning, motion control.
16. The robot must be able to lift the frames easily.
17. The robot must operate in a wide range of terrain.
18. The robot must be easy to maintain and repair.
19. Maintenance and repair of the hexapod robot is performed in specialized units by authorized personnel.

C. General security rules

⚠ It is strictly forbidden:

1. Access by unauthorized personnel to the hangar, inside the aircraft's fuel tank, but also by the maneuverability of the robot;
2. Carrying out activities in the airplane's fuel tank when it is connected to a power source;
3. Any unauthorized intervention by the command and control elements of the robot;
4. Additional maneuverability than provided in the technical manual of the robot.

4.1.2. Presentation of the general assembly of the robotic application

The robotic application consists of the use of a hexapod mobile robot inside the aircraft's fuel tank, and it must be able to complete the inspection for which it was scheduled [48].

We designed the AFTRH hexapod robot to detect cracks and other dangerous non-conformities inside the aircraft's fuel tank, with an emphasis on simplicity of operation and maintenance. The AFTRH hexapod mobile robot can be guided / controlled by a single technical operator (see fig. 4.2).

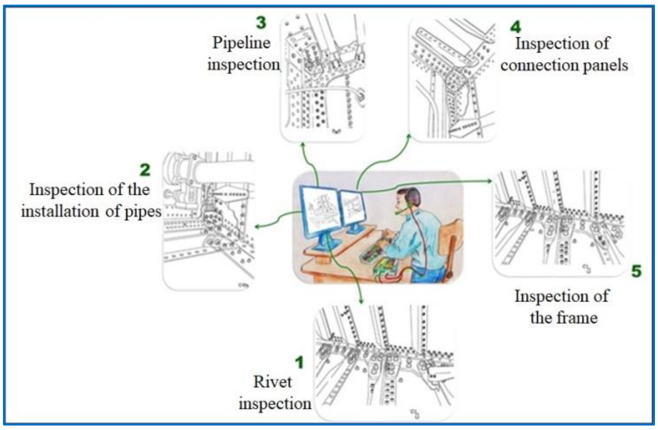

Fig. 4.2 – Inspection by the hexapod mobile robot - AFTRH in the aircraft's fuel tank

4.1.3. Fuel tank inspection technology

The technology of inspecting the aircraft's fuel tank, using a hexapod mobile robot that we created, is simple. Applying the Boeing-Task Card workloads as a model, we performed step by step how to inspect the fuel tank using a hexapod mobile robot, as follows:

→ **Step 1**: Establish the area to be inspected inside the central fuel tank of the Boeing 737-300 aircraft;

→ **Step 2**: Zone 1 - Rivet inspection;
Zone 2 - Inspection of the installation of pipes and their integrity;
Zone 3 - Inspection of the installation of screws on the partition panel.

→ **Step 3**: Establishing the handling of the hexapod mobile robot: computer, laptop or smartphone;

→ **Step 4**: Check the wi-fi connection between the human operator and the robot as well as the robot program;

→ **Step 5**: Check the battery of the hexapod mobile robot;

→ **Step 6**: Positioning the hexapod mobile robot inside the central fuel tank of the Boeing 737-300 aircraft;

→ **Step 7**: Inspection of established areas using the hexapod mobile robot and interpretation of data;

→ **Step 8**: End of inspection - removal of the hexapod mobile robot as well as all foreign objects inside the central fuel tank.

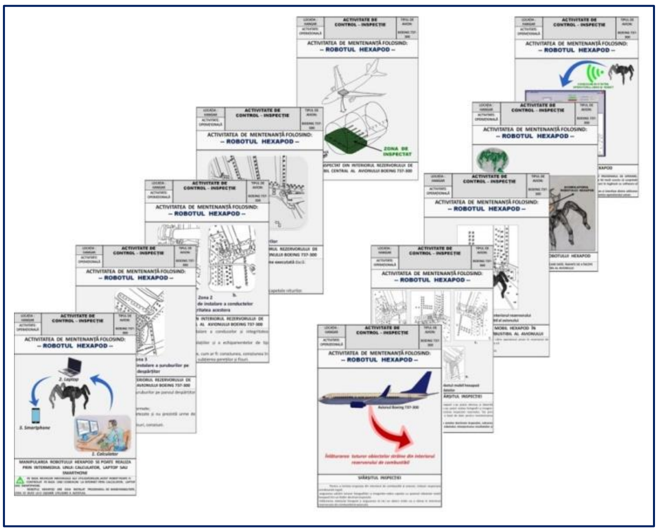

Fig. 4.3 - Worksheets - Aircraft Central Fuel Tank Inspection Tasks Using the Hexapod Mobile Robot

4.3. EXPERIMENTAL USE OF THE HEXAPOD-AFTRH ROBOT

4.3.1. Application of robotic inspection in the tank of the Boeing 737-300 aircraft

The practical application was carried out in a hangar, on a Boeing 737-300 aircraft (fig. 4.9), and the aircraft was in type C control. This type of control is carried out only inside a hangar, and during this verification , most aircraft systems and subsystems are dismantled for detailed inspection and verification and then reassembled and tested for safety and continuing airworthiness certification [47].

I must point out that not all type C checks also include the inspection of the inside of the aircraft's fuel tank. Regarding the Boeing 737-300 aircraft where I performed the experiment, I found that:

→ the tank has been inspected, following a previous work;

→ controls and monitoring of the tank were performed, consisting of removing old rivets and installing new ones.

This work has been done to prevent fuel leaks.

Fig. 4.9 – Boeing 737-300 aircraft on which the practical application was made [47]

In order to implement the practical application of the aircraft fuel tank inspection, we used a mobile hexapod robot and went through the following steps [47]:

<u>Step 1</u>*: *Carefully study the documents and understand the inspection inside the aircraft's fuel tank. These are also called work tasks. Aircraft inspection requires that certain tasks be assigned to each segment of the aircraft. As an aircraft engineer, I was part of the control team in the wing and central fuel tank segments. Having the opportunity to inspect the fuel tank, I came up with the idea of using a hexapod mobile robot. The robot would be the solution to reduce the time that the technical staff spends inside the tank, which, as mentioned above, is an extremely toxic environment.

<u>Step 2</u>: Access to the tank. In order to reach the central fuel tank of the airplane, where the inspection is to be performed, several pipes and the whole of the air conditioning part of the airplane cabin are dismantled, as can be seen in Figure 4.10.

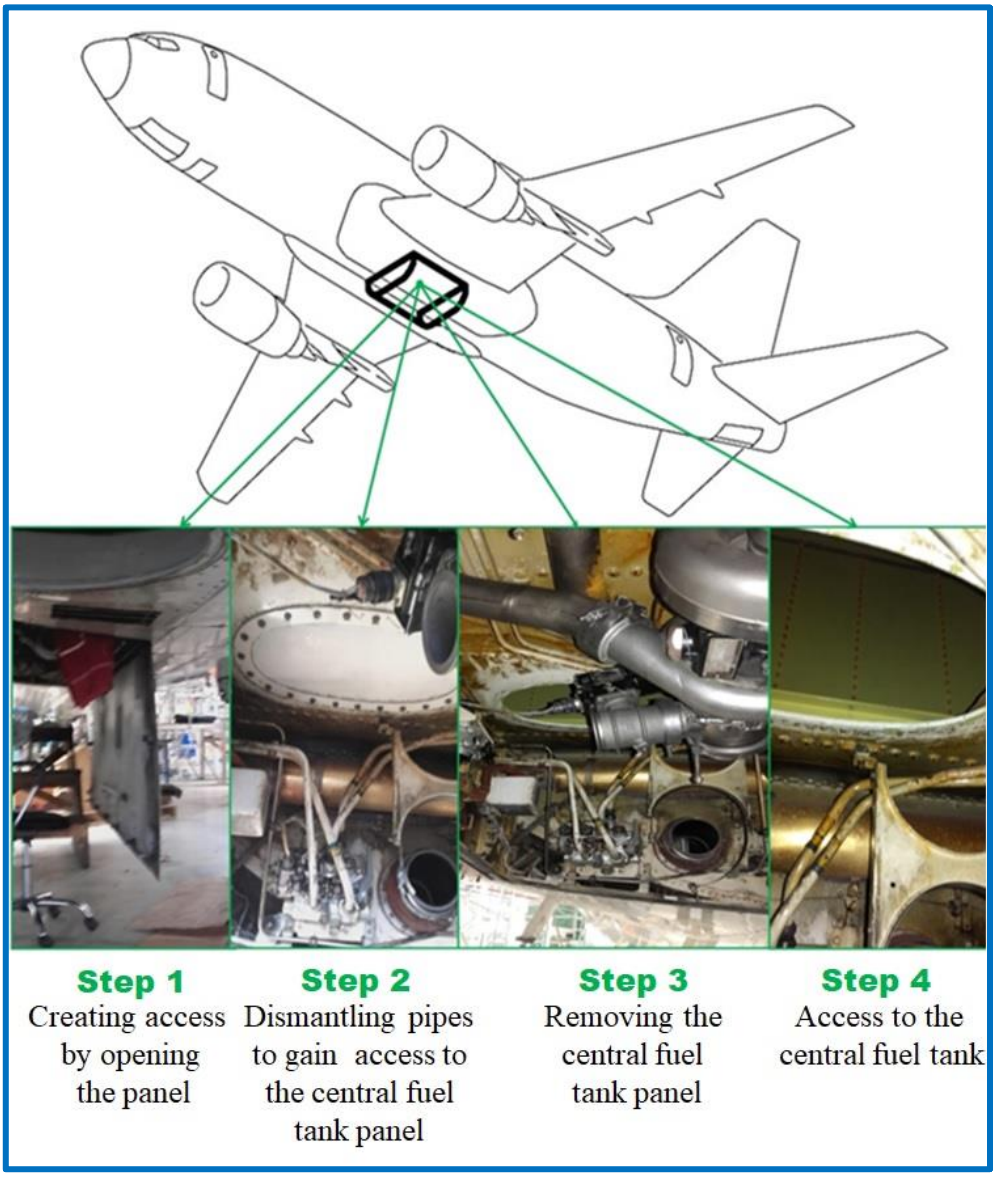

Fig. 4.10 – Access to the fuel tank of the Boeing 737-300 aircraft [47]

In the following, I will describe the steps leading to the access to the central fuel tank, in order to carry out its inspection, with the help of a hexapod mobile robot (fig. 4.10). ***Step 1*** - Access to the tank is made by opening a panel, belonging to the air conditioning sector of the aircraft. This is quite simple, because the panel can be opened by means of clips. ***Step 2*** is a more complex one, as it consists of dismantling some pipes and positioning them in a safe and secure place. ***Step 3*** is a simpler step, because once the pipes have been removed, the tank panel has only screws that can be removed, relatively easily. The last step, ***Step 4*** - access is made inside the aircraft's fuel tank.

Step 3*: *Vent the tank. After the successful completion of each individual access step, the aircraft's fuel tank is vented. Ventilation is very important because the environment is very toxic and the kerosene vapors are very strong. Ventilation can take between 7 days and 2 weeks, to reduce as much as possible the amount of kerosene vapor and other gases.

After the ventilation period ended, I started the actual practical application. As can be seen in the figure below (fig. 4.11), access is quite difficult to achieve, as the entrance area to the tank is quite limited.

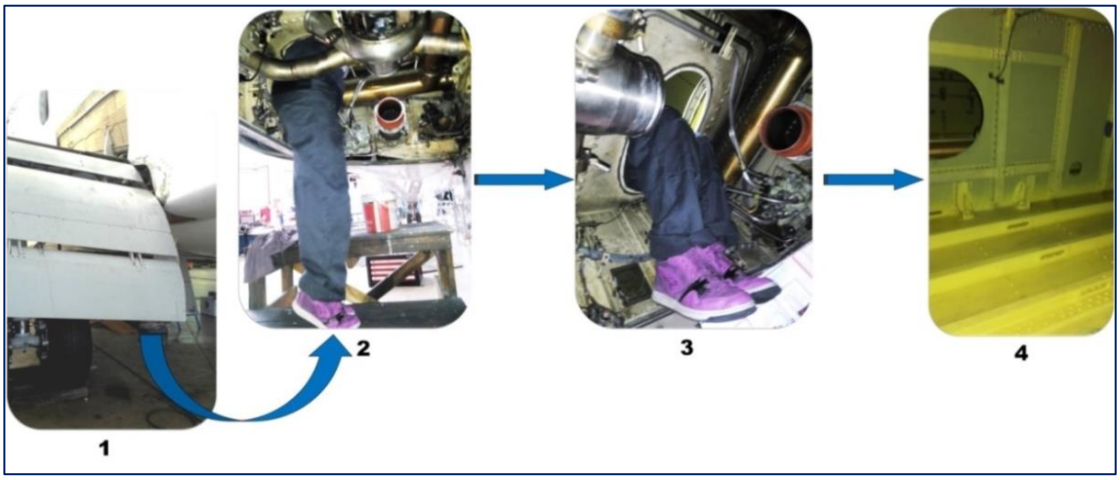

Fig. 4.11 - Entrance to the central fuel tank of the Boeing 737-300 aircraft [47]

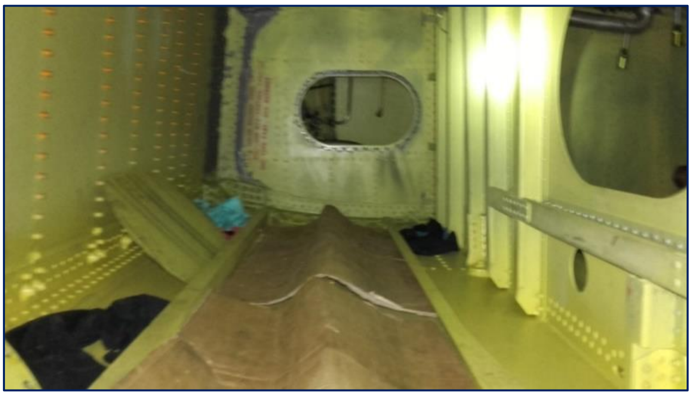

Fig. 4.12 – Removal of traces of kerosene left in the central fuel tank of the Boeing 737-300 aircraft [47]

<u>Step 4</u>: The actual inspection performed by the robot. The shape of the tank is massive, consisting of frames up to 7 mm, as can be seen in Figure 4.12. That's why I used a hexapod robot with elongated legs. Thus, the robot can get over the frames, only with a slight difficulty, depending a lot on the coordination of the operator. But once installed in the tank, the robot was able to perform the inspection, as shown in the figures below.

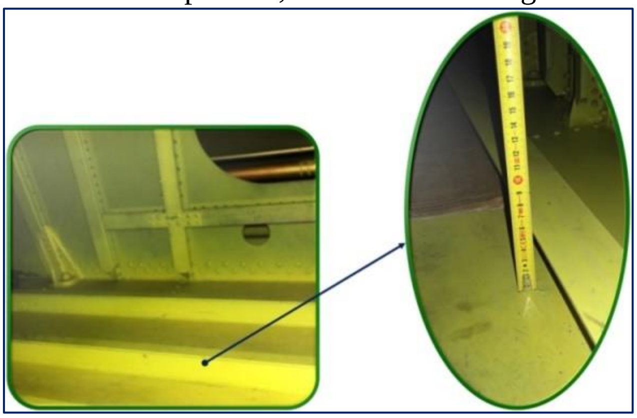

Fig. 4.13 – Identification and measurement of frames in the central fuel tank of the Boeing 737-300 aircraft [47]

It is very important to note that by identifying the frames and measuring them (see Fig. 4.13) we were able to set the limits of the hexapod mobile robot. The measured frames are 7 mm and as a result, we designed the length of the robot's legs to overcome the obstacles in the tank, as seen in Fig. 4.14. The hexapod mobile robot was guided by a smartphone, but I must point out that the operation and guidance of the operator is the main basis in overcoming all obstacles, so that the hexapod mobile robot can complete the task of inspecting the tank aircraft fuel plant [47].

I made the practical application in two ways. In the first method, we operated and guided the hexapod mobile robot inside the central fuel tank of the aircraft, and in the second method, outside it. By the first method I set out to observe the movement of the robot inside the tank. We watched very carefully if the robot could overtake the frames and if it could move, even when there were still traces of kerosene in the tank. The experiment was successfully completed, and the hexapod mobile robot AFTRH overcame all obstacles, as can be seen in the figures below.

Fig. 4.14 a - AFTRH Hexapod Mobile Robot Stationary Standing Inside Boeing 737-300 Central Fuel Tank

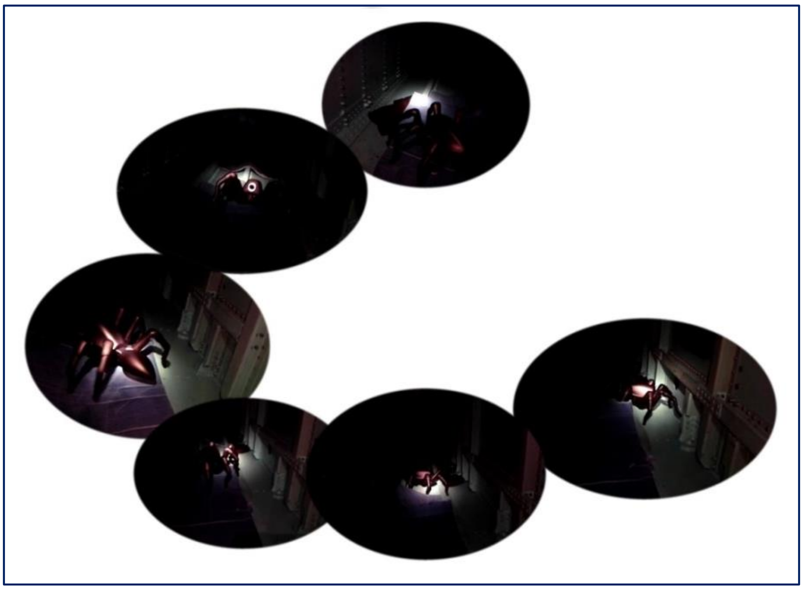

Fig. 4.14b – AFTRH Hexapod Mobile Robot Moving Inside Boeing 737-300 Central Fuel Tank

The second method was to guide the hexapod AFTRH mobile robot outside the tank, which was a challenge. The question was whether the travel controls would reach the robot in real time. It was only equipped with a Sony camcorder, and the commands were transmitted from a smartphone. The images transmitted by the Sony video camera were practically the ones I saw on the phone and in this way, I made commands, through which the robot began to move slowly. I have to point out that I did the experiment very close to the plane, at a relatively short distance from the robot, more precisely, near the entrance to the central fuel tank of the plane [47].

At first, with great caution, through commands, I managed to impress the robot with a slow movement. The average speed of the robot was 3 m / min. The Sony video camera gave me a real advantage, because the image quality was impeccable and this can be seen in the images presented. Every moment of the experiment was captured by the video camera, but I focused on the inspection of the tank. One very important thing to note is that we have made effective communication between the phone we used and the hexapod mobile robot. Another equally important aspect that should be emphasized is that the AFTRH robot has been programmed to perform actions based on the following decisions: to stop automatically, if the guidance mode is chaotic; report by flashing the lamp image on the monitor that the battery is exhausted and the operator must act accordingly, as well as a light on the monitor if the Wi-Fi connection is medium or poor.

When I was about 3 meters away from the plane, I found that the signal remained just as good and in this way, I assumed that the guidance / control of the robot can be done from a greater distance.

The inspection of the central fuel tank of the aircraft, with the help of the hexapod mobile robot, was carried out and completed successfully, because: the robot-human communication was very good; the robot moved in the tank with a speed of 3 m / min, being able to capture the frames that I wanted to highlight in particular and that followed the way of installing the rivets. The time in which the inspection of an area of 5 meters was carried out was 15 minutes, during which time 10 images were taken. The images transmitted by the robot showed that the tank complies with the AMM (Aircraft Maintenance Manual) standards, the rivets are properly mounted and we did not notice any malfunction that would lead to a possible fuel leak on the fuselage of the aircraft.

Following the experiment, we concluded that the hexapod mobile robot was able to meet all the requirements of the inspection procedures. The inspection took place over a period of 2 hours, and the average speed of the robot was 3 m / min, given that the geometry of the robot's configuration allows the correct movement inside the tank.

Following the practical application, we demonstrated that the maintenance activity can be improved by integrating a robot, which would especially benefit the human operator, because the aircraft's fuel tank is an extremely harmful environment, which can affect physical and mental health. of the human, while the robot can successfully intervene and help him.

4.3.4. Image processing obtained from the hexapod mobile robot A.F.T.R.H. located in the central fuel tank of the Boeing 737-300 aircraft

The practical application as well as the images provided by the hexapod mobile robot A.F.T.R.H. were made 5 years ago, as can be seen in Figure 4.22.

At that time, having limited resources, as well as the conditions required to enter the tank, both the video and the images captured by the robot did not have very good qualities. However, by using different image processing methods, they can be improved.

Fig. 4.22 – Image taken on 07/06/2017 by the mobile robot hexapod A.F.T.R.H. located in the central tank of the Boeing 737-300 aircraft

At that time, having limited resources, as well as the conditions required to enter the tank, both the video and the images captured by the robot did not have very good qualities. However, by using different image processing methods, they can be improved.

Image processing obtained from the hexapod mobile robot A.F.T.R.H. located in the central fuel tank of the Boeing 737-300 aircraft, aims to transform them into digital format, performing a process on them, to obtain improved images, or to take some information that has a decisive role in the image. It is a method to convert the image to digital form, to perform some operations, to obtain specific models, or to extract useful information from it. To use this method, using the hexapod mobile robot A.F.T.R.H. (fig. 4.23) located in the central fuel tank of the Boeing 737-300 plane, a video and several photos were taken, which led to the so-called images. Following this process, the A.F.T.R.H hexapod mobile robot provides the desired information through images.

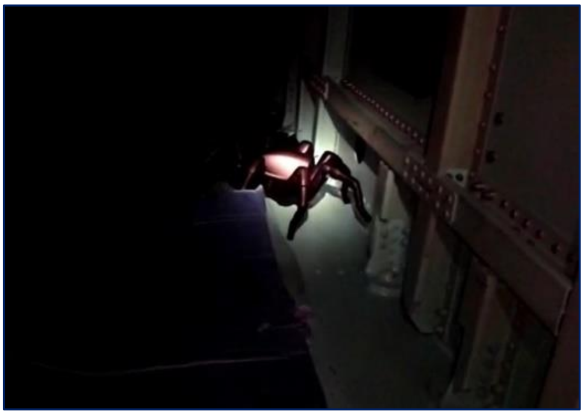

Fig. 4.23 – The hexapod mobile robot A.F.T.R.H. located in the central fuel tank of the Boeing 737-300 aircraft

In principle, the image processing provided by the mobile robot A.F.T.R.H. involves three steps:

1 → Obtaining images through digital photographs;

2 → Analyze and use images that include color patterns, such as: compressing data, fixing images and photos provided via the wi-fi connection;

3 → Removal or modification based on the analysis of the results obtained, and the final product is ready to be applied in a new image.

In addition, it should be borne in mind that the aircraft's central fuel tank is a rather difficult and complex environment, and some images are difficult to produce, thus distinguishing different image processing features:
1. Visualized - identifying elements that are difficult to observe;
2. Improving and restoring images - fixing images that contain discordant sounds;
3. Image recovery - studying the relevant image, giving it a high resolution;
4. Pattern recognition - defining different objects / elements in an image;
5. Image identification - detecting / discovering objects in an image.

Analog and digital methods are used to process images from the central fuel tank of the Boeing 737-300 aircraft. Analog or visual image processing techniques are used to make printed copies, as are photocopies provided by the Boeing task-card, specifically work tasks. The specialists, in this case, the B1 inspector who studies the images, establishes an interpretation for the various media, using visual techniques. Image processing should not be limited to technical knowledge, but should be based on the imagination and inventiveness of engineers. Another essential tool in the field of image processing using visual techniques is raw data, which is expressed by images previously collected by the hexapod mobile robot A.F.T.R.H. and which have not been processed. The analysis studies the operations prior to the processes they want to identify in the data system. As a type of deep learning, image processing works on the basis of historical data.

Digital processing techniques support the manipulation of digital images with the help of computers. It should be noted that the images provided by the hexapod mobile robot A.F.T.R.H. may be incomplete due to camera error. In order to overcome these shortcomings and obtain the most accurate information possible, they have to go through different stages of processing.

As a conclusion, I could say that the importance of image processing provided by the hexapod mobile robot A.F.T.R.H. refers to the method by which some processes are performed on it, in order to obtain an improved image, or to extract certain useful information from it. The goal is to convert the raw image to a properly processed image that is archived and used at some point. Based on these archives, inspections in the central fuel tank of the Boeing 737-300 aircraft could be optimized by the quality of the inspection and the reduction of time.

In order to process the images obtained from the hexapod mobile robot A.F.T.R.H. I used the program MatLab (fig. 4.31), because it facilitates: pre-processing of images, applying the technique of improvement and filtering; separates the elements of interest using segmentation techniques as well as tests the algorithm on large sets of images.

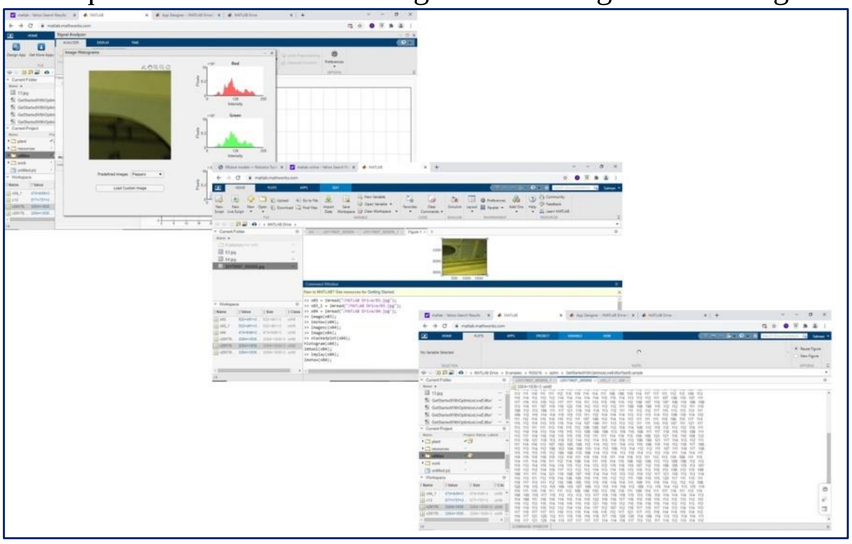

Fig.4.31 - Image processing by the hexapod mobile robot A.F.T.R.H. were made through the MatLab program

CHAPTER 5
CONCLUSIONS AND PERSPECTIVES

5.1. Conclusions

At the time of writing, we are witnessing a significant increase in the number of airlines facing an increase in the number of aircraft that need different types of controls, and these services need to be looked at from several perspectives. such as: compliance, legality, effectiveness, economy, efficiency, accurate and complete picture of the financial position and situation and especially the manner of repairs and the time allotted to them.

The objectives that I set out to accomplish in this work are: to introduce and use a mobile robot in inspections inside the aircraft's fuel tank.

The doctoral thesis demonstrated demonstrates the possibility of integrating and using technology assisted by mobile robots in maintenance activities, so I can emphasize that the objectives I set myself, have been successfully met. A large number of inspections and modifications to the aircraft's fuel tank and its adjacent systems must be carried out inside the aircraft, which poses a high risk to operators. As we have shown in this paper, the human factor that works in maintenance activities, especially inside the fuel tank of the aircraft is exposed every day, both to a physical and a mental danger. In order to eliminate these dangers, we have shown that by introducing a mobile robot to carry out inspections inside the aircraft's fuel tank, the risks mentioned can be considerably reduced, even largely eliminated.

The idea of using the robot is the result of risk assessment, which the human factor always encounters during the inspection of fuel tanks and which is an extremely toxic environment for human beings. The use of the designed hexapod robot could largely eliminate this, by substantially reducing the time required for staff access to the tank, which access will be made only for special situations. In order to materialize this application, we went through the following steps: analysis of the working environment and its risk awareness, theoretical substantiation, conceptualization, implementation, verification and acceptance.

In order to carry out inspections inside the fuel tank of the airplane, as well as to determine its outcome, certain rules must be strictly observed, from the moment of entering the tank until the completion of the inspection. The hexapod robot has a simple level of manipulation and control, its manipulation being possible with a computer or via a smartphone. A possible upgrade of the model could be: the installation of cameras inside each leg of the robot, to see better inside the fuel tank, as well as the installation of certain scan sensors, etc. . In making this application, my intention was to demonstrate that the designed mobile robot can move and capture the images needed for inspection inside the aircraft's fuel tank.

The results of our practical application showed that the use of mobile robots could be an important part of the techniques and tools of inspection, assisted by robots and humans. The use of high-performance software applications, implemented on the robot, can contribute to improving the quality, efficiency and effectiveness of fuel tank inspections, without requiring a long presence of maintenance personnel inside the tank.

In order to successfully complete this application, during my doctoral thesis, I studied various bibliographic sources and research methods, among which I mention:

1. Different types of mobile robots, in order to determine the choice of the optimal variant, in carrying out my inspection application inside the fuel tank of the aircraft.
2. The technological impact of mobile robots, both nationally and internationally, in terms of the results of scientific research, but also as a result of their adoption in practice, has proved to be a real support for my research work, and in order to have the desired result I was inspired by these.

3. The novelty of using mobile robots in maintenance activities could favor the human factor. In this regard, I was able to demonstrate that by introducing the hexapod mobile robot into the inspection activity of the aircraft's fuel tank, man will be protected from the influence of environmental factors.
4. We used for the practical application the fuel tank of the aircraft, more precisely the fuel tank of the aircraft type Boeing 737 - 300/400/500, in order to raise awareness and define the workspace in which the mobile robot will work.
5. The mobile robots have not been used so far in the inspection activities in the aircraft's fuel tank, which motivated me to carry out this work.

During the research:
1. We studied the kinematics and dynamics of the mobile robot and we chose a mobile robot to carry out the inspection activities of the aircraft fuel tanks.
2. We identified the possible disadvantages of the mobile robot and of course, we chose the optimal version of the mobile robot as the hexapod type.
3. We designed the hexapod robot and successfully completed the practical inspection application of the aircraft's fuel tank. Thus, I was able to propose a technology for implementing a hexapod mobile robot, used in the maintenance of aircraft fuel tanks.

In my doctoral dissertation I used a methodology that includes theoretical studies and practical applications in five chapters.

After making a brief history of robots from the beginning, where I pointed out the most important discoveries to date, a chapter in which I was able to demonstrate that robotics is developing rapidly, amazingly, from day to day.

After stating the evolution of mobile robots, especially in the aerospace industry, we focused on robots used in operation, explicitly, in maintenance.

By researching the literature, regarding the use of mobile robots in maintenance activities and as an element of originality, I have shown that this has not developed enough, which led me to the main objective of this paper: to introduce robots to be able to prove, through practical application, that a hexapod mobile robot is ideal for performing work tasks in an aircraft’s fuel tank because it has both ideal physical and technical characteristics, and this is the most important element of originality in this work.

Thus, the element of originality is the presentation in its own way of the evolution of robots and the importance of their introduction in the activities of operation, especially in the maintenance activity in the field of aviation.

I made a presentation of the aircraft's fuel tank and demonstrated that the human factor is subject to a hostile environment while inspecting the tank.

In this paper we have demonstrated that both the inspections and the modifications to be performed to the fuel tank and its adjacent systems are performed only inside it. Maintenance and repair work shall only be carried out by qualified technical personnel inside the fuel tank, personnel who may be affected by the environmental conditions with which they come into contact. Therefore, technical personnel must be trained before entering the aircraft's fuel tank to prevent possible incidents / accidents. Precautions must be taken to avoid explosions or fires, technical personnel must wear oxygen masks when oxygen is present or to avoid inhaling toxic and irritating chemicals. It should be noted that only operators of a certain height and weight (not too tall or too tall) can enter the fuel tank, given its limited space. From my own experience, following research and practical application, I had the idea to introduce mobile robots in the inspection activities inside the aircraft's fuel tank.

After a tenacious, repetitive, hard work, which I submitted as an engineer, but also after the analysis I did on the aircraft's fuel tank, I devised a method of inspecting the tank by means of a mobile robot. , a method that is the subject of this thesis. Only through daily practice, I was able to realize the need for a properly designed robot to perform maintenance activities.

Even if the research activity carried out so far has taken into account the role that the human factor has in the maintenance activities, I brought an element of originality, putting the human factor in the foreground, explaining in my paper, the difficult conditions in which it carries out its activity. The technical staff faces daily environmental problems, which directly affect their health. Even if, over time, the same workers perform repair work inside the fuel tank and routine intervention, they are stressed, which can negatively affect the quality of the work performed.

As a maintenance engineer, I was part of the team that had to carry out repairs inside the fuel tank of the Boeing 737-300 aircraft. After completing the work, I came to the conclusion that I need to develop a work that will change the inspection technology.

The technology can be improved, modernized with the help of a robot. The robot is designed to perform the same activities that humans do, except that it is not as physically affected.

Therefore, after analyzing all the negative factors that act on humans when they have to perform work inside the aircraft's fuel tank, I had the idea, but I also put it into practice, that of introducing a mobile robot of the type hexapod.

To use a hexapod robot inside an aircraft's fuel tank, we made a general assembly of it and focused only on the characteristics of the robot we designed. The element of originality is that we made the sizing and modeling of the robot, and through the LabView program we analyzed the speed parameters, angular displacement and final position of the legs, its stability and control and we implemented the calculations in the logic programming schemes.

We designed and presented the general assembly of the robotic application, and the element of originality is that we designed the method by which inspections are performed inside the aircraft's fuel tank. I also described the complete structure of the application, but also the specifics of the programming. Inspired by the Boeing Task worksheets, I developed the tasks needed to perform this inspection using a hexapod mobile robot. For the safety of both the human operator and the robot, we have developed labor protection rules, which we have structured in three stages: before, during and at the end of the activity.

The robotic application consists of placing a hexapod-type mobile robot inside the aircraft's fuel tank, and it must be able to perform the tasks for which it was designed during the inspection.

We designed the AFTRH hexapod robot to detect cracks and other dangerous non-conformities inside the aircraft's fuel tank, and at the same time, we emphasized the simplicity of its operation and maintenance. The hexapod robot can only be operated by one operator. Being a robot that inspects the fuel tank of an airplane, the mechanical design we performed is advantageous due to its modular, compact and robust design. All of its subsystems are built into the robot and can be removed for individual testing, allowing multiple tests to be performed simultaneously. The dimensions of the platform meet the requirements, so that with a small size, the robot can be maneuvered in narrow spaces, respectively, in the fuel tank of the aircraft. Inside the frame, the robot has a compartment with a safe place, where the video camera is attached, as well as the power supply.

Another element of originality is that we have designed a hexapod robot that exceeds frames up to 7 mm. Because it has superior maneuverability compared to other hexapos robots, it is able to climb slopes with an inclination of 15 °.

In the practical application I used the AFTRH robot designed by me. As an element of originality, we developed the technology for the inspection of the central fuel tank of the Boeing 737-300 aircraft.

The inspection of the central fuel tank of the aircraft with the help of the hexapod mobile robot was successful, because: the human-robot communication was very good; the robot moved inside the tank with an average speed of 3 m / min; was able to capture the frames that I focused on, these being related to the way of riveting.

The time in which an area of 5 square meters was inspected was 15 minutes and 10 conclusive images were taken. The inspection inside the fuel tank took two hours and the hexapod mobile robot was able to meet all the requirements of the inspection procedures.

The major importance of using the hexapod mobile robot that I proposed and implemented in such an inspection, in the airline where I worked, is to eliminate the factor of human exposure to a very toxic environment and the economy of time. The duration of the inspection has been reduced by at least two days, because such an inspection is usually carried out in a range of 3 to 5 days, or even longer, depending on the area where the inspection takes place, but more chosen by the time that the technical staff can spend inside the fuel tank (physical / mental resistance).

Considering the risks to which the human factor is exposed when performing inspections inside the fuel tank of the aircraft and taking into account all the characteristics of the space where the maintenance activity is carried out, respectively the hangar and at the same time, as an element of originality, we drafted the rules. labor protection, before, during and at the end of the inspections.

►*Own contributions*

The main personal contributions to the paper are:

We made a brief presentation on flight safety as well as aircraft verification protocols, such as: type A, B, C and D checks, as well as the difference between line and hangar controls. As an element of originality, we made a critical analysis of the verification stage of the aircraft's fuel tanks. Like any field of activity, the aeronautical industry is a challenge for all researchers, who want to contribute, in terms of flight safety, but also the comfort of all participants, both passengers and crew in an aircraft. Given that aircraft fuel tanks are an essential part of aircraft, they must be inspected regularly, as required by the manufacturer's maintenance manual and whenever required. All inspections of fuel tanks shall be carried out by qualified technical personnel, even if the environment inside them is harmful. Various methods of digital inspection have been tried, with continuous robot, Eeloscope, etc., but due to the environmental conditions inside the tank, these experiments have only partially solved the inspection.

I made and established a short presentation of the history of robots from the beginning to the present and I was able to demonstrate, based on the literature, that robotics enjoys a rich history.

In addition to this brief history of the evolution of mobile robots, we also presented their evolution in the aerospace industry, so we made the presentation of robots used in operation, but also of robots used in maintenance activities, of course, focusing on fuel tank maintenance .

As an element of originality, by researching the specialized literature of mobile robots, in the maintenance activities, we demonstrated that this was not developed, which leads to the main objective of this paper: to introduce mobile robots in the activities of maintenance. We have identified some reasons why you can invest in robots, both for operation and maintenance. The main and most important reason, especially in the maintenance activity, would be the very toxic work environment for humans, especially because my thesis focuses on the inspections that are carried out inside the fuel tank of the aircraft. Another very important reason would be the limited space of the fuel tank, the oxygen deficiency and of course the mental state of man. These reasons led me to conduct research and the possibility of introducing the hexapod-type mobile robot into the inspection activity inside the aircraft's fuel tank.

I analyzed the plane's fuel tank as the robot's workspace. We have shown in an original way that the human factor is subject to a very dangerous environment.

A large number of inspections and modifications to an aircraft's fuel tanks, as well as their adjacent systems, must be carried out inside them. Fulfillment of maintenance and repair tasks must be performed by technical personnel, who must physically enter the fuel tank, an environment in which it is exposed to many environmental risks. These potential risks include: fire and explosion, toxic and irritating chemicals, oxygen deficiency, and limited size of the fuel tank. In order to prevent associated injuries, maintenance organizations as well as operators need to develop specific identification and control procedures to eliminate hazards.

In addition, in this chapter we have presented and established that maintenance and repair personnel entering the fuel tank of the aircraft to carry out inspections or modifications are closely related to various and many potential hazards. These are: exposure to toxic and flammable chemicals, potentially harmful weather conditions and limited tank configuration. In order to successfully prevent associated accidents, both operators and technical personnel must consider the following aspects: possible accidents / hazards in the fuel tank; preparation to enter the fuel tank; the conditions necessary to enter the fuel tank, but also the emergency response plan.

Following this analysis, we identified the need to introduce mobile robots in the inspection activity of the aircraft fuel tank, therefore, the element of originality is the implementation of robots in maintenance activities, especially in conducting inspections inside the aircraft fuel tank .

We designed the general assembly of the hexapod robot, chosen for inspections inside the aircraft's fuel tank, taking into account the geometry of the structure, inside the aircraft's fuel tank, for example; the robot must advance over frames of approximately 5 or 7 mm in size. The robot I chose and designed is of the hexapod type, a type of robot that can behave perfectly inside the aircraft's fuel tank due to its shape, but especially due to its physical characteristics which I considered to be : height - 25 cm, width - 27.2 cm and length - 30 cm, as well as the results of kinematic modeling, its stability and control. Thus, as a result of my contribution to determining the physical characteristics of the hexapod mobile robot, it successfully overcomes the obstacles inside the aircraft's fuel tank, making it suitable for the mission for which it was designed.

The calculation methods used to perform the kinematic modeling of the designed hexapod mobile robot - the kinematic model of a leg and the inverse kinematic model, are: Denavit-Hartenberg parameters modified by Craig (Ollero, 2007), Messuri and Klein criteria for stability and control analysis , and for the analysis of the hexapod robot dynamics, we used the Ghasempoor and Sepehri criteria, which was normalized by S. Hirose and Garcia, as well as the PAG criteria. of Saints. My contributions consisted in choosing, interpreting and calculating the data provided by these methods, in order to be able to design the ideal hexapod mobile robot for the fuel tank inspections of the aircraft.

As an element of originality, we designed the general assembly of the robotic application, which consists of inserting a hexapod-type mobile robot inside the aircraft's fuel tank, and it must be able to complete the inspection. The hexapod robot - A.F.T.R.H. (Aircraft Fuel Tank Robot Hexapod) was designed to detect cracks and other dangerous non-conformities inside the aircraft's fuel tank, emphasizing simplicity of operation and maintenance. Only one operator is needed to operate the hexapod robot.

In order for the inspection to proceed normally and be completed successfully, we have designed the inspection technology of the aircraft's fuel tank, which includes ten plugs.

For the safety of both the human operator and the robot, we have developed labor protection rules, which we have structured in three stages: before, during and at the end of the activity.

We designed the working technology to carry out inspections inside the aircraft's fuel tank.

As an element of originality, we made the practical application with the hexapod mobile robot - AFTRH, consisting in the effective realization of an inspection. The practical application validates the whole work and, above all, demonstrates that it is possible for robots to be successfully introduced into aviation, in this case, in maintenance activities, such as conducting inspections inside the fuel tank. The practical application showed that the hexapod robot could completely eliminate the exposure of the human factor to the risks of inspections in the tank. Basically, in the realization of this application the following steps were followed: analyzing the environment and raising awareness of its problems, creating knowledge, conceptualizing, implementing, verifying and accepting.

My own contributions were to: make the robot - AFTRH, to install the video camera - Sony and place it in the fuel tank of the aircraft, as well as to carry out the inspection inside it. This was done successfully, the robot being able to move and capture the images I wanted inside the fuel tank, so that the goal of the work was achieved. Another very important thing to note is that, using a hexapod mobile robot in such an inspection, the factor of human exposure to a very toxic environment for it was eliminated.

Because the human factor that performs the inspections inside the fuel tank of the aircraft is exposed to numerous risks in their performance, but also inside the place of maintenance - the hangar, as an element of originality, we have pointed out the rules of labor protection, both before the start and during the inspections in the fuel tank of the airplane.

Due to the fact that the practical application as well as the images provided by the hexapod mobile robot A.F.T.R.H. were made five years ago, at that time, with limited resources, as well as the conditions imposed on entering the tank, both the video and the images captured by the robot are not of very good quality. However, as an element of originality, we used different methods of image processing to improve them.

Image processing obtained from the hexapod mobile robot A.F.T.R.H. located in the central fuel tank of the Boeing 737-300 aircraft, aims to transform them into digital format, performing a process on them, to obtain improved images, or to take some information that has a decisive role in the image. It is a method to convert the image to digital form, to perform some operations, to obtain specific models, or to extract useful information from it. To use this method, using the hexapod mobile robot A.F.T.R.H. located in the central fuel tank of the Boeing 737-300, I took a video and several photos, which led to the so-called images. Following this process, the A.F.T.R.H hexapod mobile robot provides the desired information through images.

As a conclusion and also as an element of originality, I could say that the importance of image processing offered by the hexapod mobile robot A.F.T.R.H. refers to the method by which some processes are performed on it, in order to obtain an improved image, or to extract certain useful information from it. The goal is to convert the raw image to a properly processed image that is archived and used at some point. Based on these archives, inspections in the central fuel tank of the Boeing 737-300 aircraft could be optimized by the quality of the inspection and the reduction of time. In order to process the images obtained from the hexapod mobile robot A.F.T.R.H. I used the MatLab program because it facilitates: image pre-processing, applying the enhancement and filtering technique; separates the elements of interest using segmentation techniques as well as tests the algorithm on large sets of images.

5.2. Perspectives

As a perspective in the near future, I would propose the use of robotic systems in repair and maintenance activities, focusing on quality assurance, such as: quality of inspections and their supervision, and an example of application could be engine boroscopy or inspections for detecting cracks in the fuselage of aircraft.

With regard to robotic systems, it is clear that they can be an important tool for the development and optimization of maintenance activities. Therefore, future research may consider the design of new expert systems, which can be used in the field of high-precision inspections, such as the detection of cracks in both the fuselage of the aircraft and the frames inside the aircraft. Also, new data analysis functions may be investigated in the future. Regarding the hexapod mobile robot, future research could be done through more complex analyzes and could also consist of improving the structure and performance of the robot. Furthermore, future research could focus on the development of human-robot integration systems, based on new maintenance technologies. Designing new robot models for use in maintenance can be another area of investigation for researchers.

In general, the research may be aimed at analyzing a new approach to aircraft repair and maintenance inspections.

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