Dangerous entry into the aircraft fuel tank – Introduction of mobil robot

Maria-Giorgiana GAINA*

*Corresponding author
"POLITEHNICA" University of Bucharest,
Doctoral School of Aerospace Engineering,
Polizu Street 1-7, sector 1, Bucharest 011061, Romania,
mariagiorgiana_gaina@yahoo.com

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Abstract: *This paper focuses on the dangers assoicated with entry into aircraft fuel tank. The analysis will help to demonstrate that in the future a mobil robot will make this work easier for the human factor. There are number of advantages from this automation to make the job of the human factor easier and to work in a safe environment. The risk of contamination with harmful substances is reduced because we can put the robot to work. After detailed analysis of the working environment to which a mechanic is exposed in the aviation world, it has come to light that the introduction of a robot makes it minimal. I tried to analyze several types of mobile robots, and after this analysis I decided that the most suitable mobile robot is the hexapod.*

Key Words: *Identification, Control, Human factor, Aircraft, Fuel tank, Robots*

1. INTRODUCTION

A large number of inspections and changes to an aircraft's fuel tanks and their adjacent systems must be made inside them. Fulfillment of the required maintenance and repair tasks must be performed by a technical person who must physically enter the fuel tank and this exposes them to many environmental hazards [13]. 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 must develop specific identification and control procedures to eliminate hazards.

Maintenance and repair technicians entering the aircraft's fuel tank for inspections or modifications are in close contact with many potential hazards [13, 14]. They are: exposure to toxic and flammable chemical substances, atmospheric conditions with potentially harmful health and limited container configuration. Operators and repair stations can protect technical staff against these hazards by developing safety procedures. To successfully prevent associated accidents, both operators and technical staff need to be aware of the following:

- Possibility of accidents / hazards in the fuel tank;
- Necessity to prepare for entry into the fuel tank;
- Knowledge of conditions for entering the fuel tank;
- Use of emergency plan.

2. POSSIBLE ACCIDENTS/HAZARDS IN THE FUEL TANK

The potential danger that technical staff can experience materialized in two forms: chemical and physical.

a) Chemical

The most commonly encountered and recognized danger in 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 vapors of a flammable liquid can "ignite" is known as the ignition point. A dangerous 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 [13, 14]. Fuel under LFL/ LEL is considered too low for combustion. If the fuel vapor concentration exceeds the upper flammability limit or the upper explosion limit, the fuel is considered too rich to burn. A fuel vapor concentration between these two limits is considered to be within its range of flammability. It will ignite and burn in contact with a source of ignition. One of the best ways to control unwanted fires and explosions is to keep fuel vapor concentrations below LFL/ LEL, preventing it from reaching its range of flammability [13].

Other flammable chemicals may also be present during maintenance and repair in the fuel tank (fig. 1). Low-ignition chemicals (less than 70°F (21°C)), such as methylethyl kenone (MEK), are more dangerous than fuel in the tank, and their use must be strictly controlled [13, 14]. Chemicals, including fuel, may also present a toxic or irritating hazard. In high concentrations, fuel together with other hydrocarbons can affect the nervous system, causing headaches, dizziness and lack of coordination. Chemicals can cause chronic health problems that can affect the liver and kidneys, irritations to the skin if not controlled.

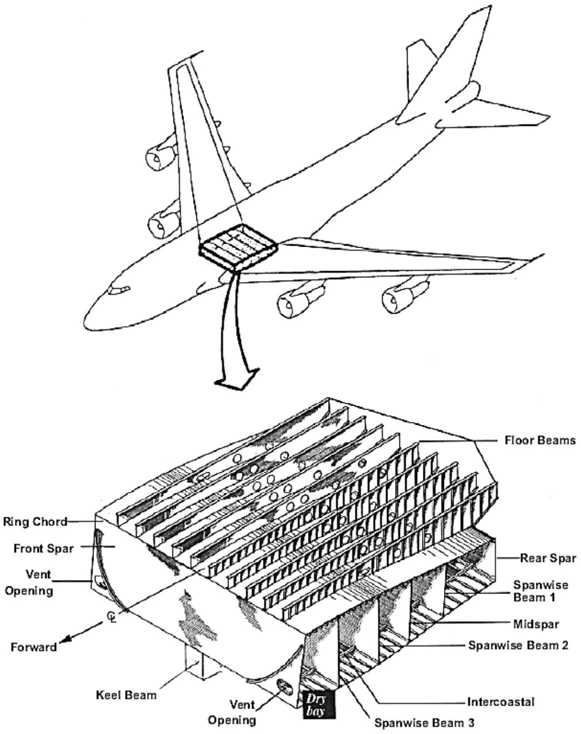

Figure 1. Center fuel tank of the aircraft [13]

b) Physical

The physical characteristics of the fuel tank may create fire hazards, explosions and toxicity. The entrance to the fuel tank is made through an elongated hole having less than 2ft (0.6m) long and 1ft (0.3m) wide. Although the internal dimensions of fuel tanks vary considerably with the central wing tank, which is the largest, all fuel tanks have a limited volume. A relatively small amount of a chemical within one of these enclosed spaces may create significant levels of flammability or toxic fumes [13, 14].

The wing tanks usually have a single orifice between each frame of the section. The inner portion of the wing fuel tank provides sufficient clarity for the technical staff, with access from the waist up, leaving the legs outside the access hole. The tank becomes smaller as it advances to the outside of the wing, the access decreases significantly and the technical staff can only enter the head and arms. The central reservoir may be large enough to allow access to full technical staff.

3. PREPARED FOR ENTERING THE FUEL TANK

Several steps must be completed before technical personnel enter the aircraft fuel tank, figure 2 [13]. These include: grounding and emptying the tank according to standard practice. Following three final steps need to be taken to ensure safe conditions for technical staff [13]:

1-Ensuring adequate ventilation;
2-Follow-up of recommended ventilation techniques;
3-Monitor and adequately control the air in the fuel tank.

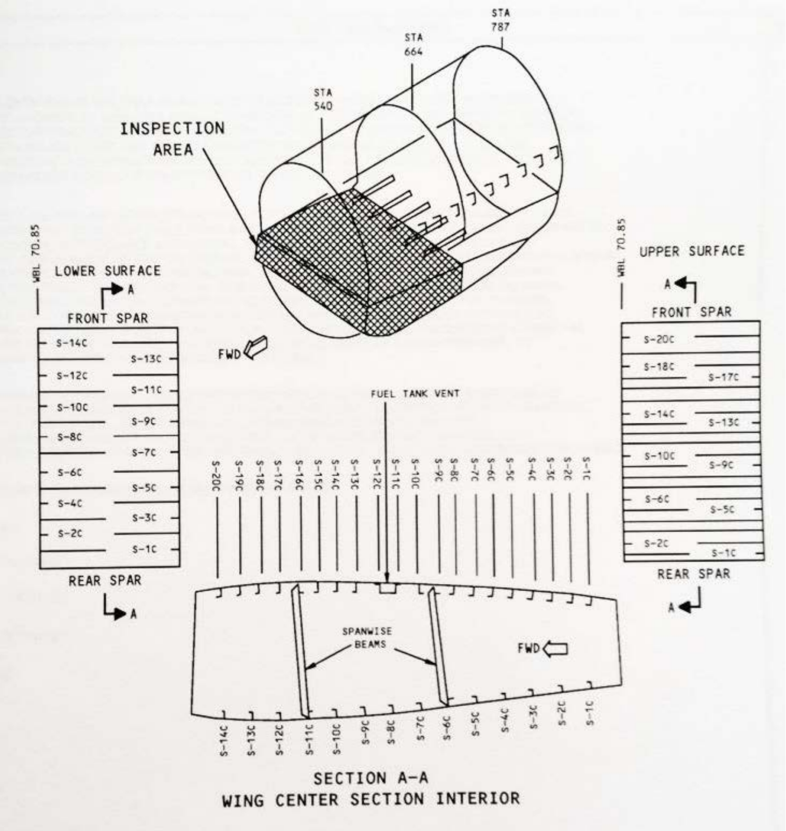

Figure 2. Center fuel tank of the aircraft – Inspection area [13]

1. Ensure adequate ventilation

One of the important ways to control fire, explosion and toxic accidents associated with working in the open fuel tank is ventilation [13]. The more fresh air is present, the more secure the environment will be in which the technical staff is working. The continous pushing fresh air into the fuel tank helps prevent fuel vapor concentration from reaching the LFL, thus preventing fire or possible exposure. Also, fresh air dilutes the vapor concentration of chemicals reducing the risk of toxic exposure. The large volume of fresh air will prevent a condition known as oxygen deficiency [13, 14].

The normal atmospheric oxygen concentration in the air is 21%. The level of oxygen deficiency (19.5% and below) in one person is manifested by signs of "hunger of oxygen," with headaches, nausea, drowsiness and speech disorders. At a lower oxygen concentration, more severe reactions may cause death by asphyxiation [13]. The main reason of oxygen deficiency is due to displacement of oxygen in space. For example, pumping nitrogen into the tank to prevent ignition will cause the oxygen concentration to drop. Oxygen deficiency can also be caused by the oxidation of a material by using oxygen available from space. Oxidation is a chemical reaction that combines atmospheric oxygen with another material to form an oxide. Iron oxide, known as rust, is an example.

2. Recommended ventilation techniques

The physical characteristics of airplane fuel tanks present some inevitable challenges in ensuring adequate ventilation. Some of the challenges are those spaces where fresh air does enter. These are called “dead spaces” and also small openings between the reservoir sections, which have the ability to inhibit the air flow. Therefore, it is important to plan as accurately as possible to achieve adequate ventilation[13, 14]. The recommended practice for fuel tank ventilation is the push-pull technique. First, a upstream access hole must be open for an appropriate “push”. Then for a “pull”, a hole must be opened down stream. Eventually, a blower must be located at the pushing hole, forcing the fresh air to enter the tank.

3. Properly monitor and control the air in the fuel tank

No technical personnel should enter the fuel tank until it has been properly ventilated. To determine if the atmosphere in the tank is suitable for entry, atmospheric conditions should be continuously checked and monitored, along with oxygen concentration, flammable vapor concentration and toxic vapors. Entry should not be allowed, unless the oxygen concentration is between 19.5 and 23.5% [13]. Concentrations below 19.5% are considered to be - oxygen deficient, and concentrations higher than 23.5% are considered to be - oxygen enriched. This signifies an increased risk of fire and explosion. Based on this reason technical staff should not be allowed in the aircraft fuel tank.

4. THE NECESSARY CONDITIONS FOR ENTERING THE FUEL TANK

The most important factor in preventing injury during work in the fuel tank is appropriate installation and equipment. The tank crew is composed of the Entry Supervisor, a waiting companion, and a person entering the tank. The Entry Supervisor authorizes the activity and ensures that it is conducted in accordance with the procedures [13]. The waiting party remains outside the fuel tank to monitor the conditions in and around the work area and is also authorized to order the evacuation of the person in the tank if the safety is compromised. The technical entry staff enter the fuel tank and carry out the work. They must be able to recognize possible hazards and exit the tank if working conditions deteriorate. Individually or collectively, members of the fuel tank team must be aware of the following requirements for safe working conditions[13, 14]:

a – Communication.
b - Respiratory protection.
c - Air and ventilation monitoring.
d - Electrical equipment.
e - Possible damage caused by technical personnel.

a - Communication

Continuous voice communications should be maintained between technical entry staff and waiting personnel throughout the process of entering the tank. Voice communications can be assisted by radio and electronic equipment. These devices must be evaluated and should be suitable for the work enviornmemnt.

b - Respiratory protection

Depending on the atmospheric risks, the technical personnel entering the tank must wear a protective mask. Oxygen mask must be worn, if the oxygen concentration is at least 19.5% [13].

c - Air and ventilation monitoring

Fresh air must be supplied at the entrance of the tank. If the ventilation is interrupted, the entry to the tank must be suspended until ventilation is restored. The atmospheric conditions of the tank must also be monitored during entry into the tank. If the oxygen concentration drops below 19.5% or increases by 23.5% then the technical personnel should be evacuated immediately. If the level of flammable vapors exceeds 10% of the LFL or the toxic vapor concentrations exceed the permissible exposure level (PEL), entry into the tank should be postponed [13].

d - Electrical equipment

The technicians working in the fuel tank have to deal with a variety of live equipment, including lighting or test equipment. All electrically driven equipment must be very safe and suitable for use in a potentially flammable environment. Pneumatic tools should only be started with compressed air, not with nitrogen or other inert gases, which could displace the oxygen inside the tank [13].

e - Considerations of possible damage caused by technical personnel

In-service technical staff who carry out work in the fuel tank may damage the airplane reservoir if it has not been properly fitted. Contact surfaces of the access hole and covers should be protected during insertion so that they do not scratch or otherwise damage. Also, components inside the tank, such as: fuel pumps, sensors, cables, pipes, frames, etc. are vulnerable to damage if they are hit or dislocated in an abusive way.

5. EMERGENCY RESPONSE PLAN

The working procedures inside the fuel tank must also address a potential emergency situation. If intervention procedures are not developed, an emergency may result in serious injury or even the death of technical personnel. Operators and repository stations should prepare procedures for technical staff so that they follow them in the following situations:

1. Auto-discharge.
2. Development ordered by the attendant.
3. Alarms on air monitoring.
4. Rescue Operator, if there is no response from the technical staff in the tank [13].

1. Auto-evacuation

Technical staff must be able to recognize the hazards they are exposed to by working in a fuel tank. They should evacuate the tank when conditions change, including psychological state.

Entry into enclosed spaces can lead to uncontrolled claustrophobia, resulting in panic and an inability to function normally. Tank entries should be preceded by training, thus enabling the technical staff to recognize the initial stages of claustrophobia and reaction measures when they occur [13].

2. Equipment ordered by the attendant

The waiting party must keep an eye on the conditions in and around the work area. If conditions change that put the operator at risk, they should be forced to evacuate from the tank. The attendant should be trained to recognize symptoms of oxygen deficiency and overexposure to toxic chemicals and should closely monitor the physical state of the technician within the tank. In case of unpleasant situations and if the technician has negative symptoms, the attendant must order the immediate evacuation from the reservoir [13].

3. Alerts on air monitoring

If the instruments used to monitor the atmospheric conditions in the tank raise the alarm, the participants must immediately evacuate the tank. The specific condition that caused the alarm must be identified and corrected before starting work inside the fuel tank [13, 14].

4. Rescue worker if there is no response from the technical staff inside the tank

If for any reason the participant in the tank no longer responds, the waiting party should immediately initiate rescue procedures and this includes immediate notification of emergency assistance. The waiting assistant must ensure that fresh air is fed into the tank where the operator is located. All ventilation equipment should be checked and, if possible, additional holes should be opened. The personnel arriving in emergency containers must be specifically trained in rescue techniques and should be provided with adequate equipment with self-contained breathing [13].

6. INTRODUCTION OF ROBOTS USED IN AIRCRAFT FUEL TANK INSPECTIONS - HEXAPOD ROBOT

A large number of inspections and changes to an aircraft's fuel tanks and their adjacent systems must be made inside them. Maintenance and repair tasks must be performed by trained technical staff that is required to enter inside 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 limited nature of the fuel tank. To prevent associated injuries maintenance organizations and operators should develop specific procedures to detect and eliminate hazards. Entry into airplane fuel tank is needed for inspections and modifications, but these works may pose a risk factor for technical staff. Working in the fuel tank can be done safely if technical staff is trained especially has the necessary equipment. In this area robots can intervene successfully.

Therefore, this paper aims to implement a mobile robot. Due to its characteristics, the robot can easily sneak into the fuel tank of the aircraft and the operator can guide robot from outside to facilitate its aircraft maintenance activities.

The main problem of an autonomous mobile robot is to carry out the control of locomotion on land.

Some of the structures used to build mobile robots have been obtained thanks to the inspiration of the animal kingdom, such as the hexapod. Several researchers were inspired and then relied on, emulating the four-legged animals or insects.

Among the most remarkable legged robots we could mention the “Big-Dog” with four legs which is operating military applications, but also “RHex” (Moore, 2002) and “MELMANTIS” (Melmantis, 1997) [1-10].

A legged robot has the ability to move on land with a high degree of difficulty, which is why mobile wheeled robots do not have this advantage. Robots with legs can move over landslides, gravel, uneven roads, obstacles or land where there are no roads. However, the ability to control a hexapod robot is a complex issue.

The system of robot locomotion employed, coordinated simultaneous movement and consists of six legs, each with three degrees of freedom (G.D.L.). The Hexapod robot (fig. 3) has 18 degrees of freedom [1-11, 12].

Due to the fact that the movement of the robot is achieved by interaction of unstructured environment, it is necessary to understand the specific use of an electronic system for obstacles detection.

However, it should be stressed that the main problem is the coordination of angular movement of the robot's 18 joints during movement, emphasizing the sequence of steps. This problem is achieved by implementing an electronic system dedicated to distributive architecture.

Figure 3. Hexapod robot

a) Cinematic model of a foot

It is important to select a configuration mechanical robot leg that maximizes movement and requires a minor amount of restriction in its locomotion. For the implementation of each leg of the hexapod robot was used a driveline with three turns or RRR joint. Direct geometric model for each foot mechanism was formulated using a mobile frame $O_i(x_i, y_i, z_i)$ for each joint, with i=1..2 and a fixed frame $O_W(X_W, Y_W, Z_W)$ [11]. The various links of the robot legs have been named as: coxa, femur and tibia. The reference framework leg hexapod robot starts with zero touch, which is the structure of the robot, where the foot is anchored or mounted on the ground; one is coxa link, the link is two femur and tibia connection with three is the final end as the base. To calculate the direct of Kinematic equation is to use Denavit-Hartenberg parameters, change by Craig (Ollero, 2007) and has yielded the following matrix transformation [3-5]:

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

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

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

where: q_1 is the angle of the femur [degrees]; q_2 is the angle of tibia [degrees]; l_1 is far femur [cm]; l_2 is far tibia [cm].

To find the matrix transformation T_{OT}^0 is the product of $T_1^0 \cdot T_2^1 \cdot T_{[OT]}^2$ [3, 4, 7]. The result corresponds to the following equations for direct kinematics for each leg of the hexapod robot, so the coordinates of the final end of a leg of the robot are:

$$\begin{aligned} x &= l_1 cos(q_1) + l_2 cos(q_1 + q_2) \\ y &= l_1 sin(q_1) + l_2 cos(q_1 + q_2) \end{aligned} \tag{2}$$

While joint kinematics differential speeds with speeds relate directly to the desktop via the robot Jacobian matrix, this method is obtained by propagation velocity, whose equation are [1-10]:

$$v = \begin{bmatrix} 0 \\ 0 \\ \dot{q_1} \end{bmatrix} \times \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} + R_2^0 \left(\begin{bmatrix} 0 \\ 0 \\ \dot{q_2} \end{bmatrix} \times \begin{bmatrix} l_2 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$R_2^0 = \begin{bmatrix} cos(q_1 + q_2) & -sin(q_1 + q_2) & 0 \\ sin(q_1 + q_2) & cos(q_1 + q_2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

V is the vector of the translation speed of the end of the tibia [cm/ s], $\dot{q_1}$ and $\dot{q_2}$ speed actuators [degrees/ and]. Expanding equation (3) can get a reduced Jacobian, which is:

$$J(q)=\begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix}$$
$$\begin{gathered} j_{11}=-l_2 sin(2q_1+2q_2)+l_1 sin(q_1)+l_1 sin(2q_1+q_2) \\ j_{12}=-l_2 sin(q_1+q_2) \\ j_{21}=l_2 cos(2q_1+2q_2)+l_1 cos(q_1)+l_1 cos(2q_1+q_2) \\ j_{22}=l_2 cos(q_1+q_2) \end{gathered} \tag{4}$$

Therefore, direct differential kinematics is defined as:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}=J(q)\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{5}$$

where $\dot{x}$ and $\dot{y}$ are translational velocities [cm/ s] of the distal tibia with the plan [11].

b) Inverse cinematic

The geometric variables described above establishes the connection between the joints, the position and orientation of the frame located at the foot. The problem of inverse kinematic model is to determine variables joints, starting from a position and orientation of the frame located at the end. To solve this problem, we need to understand the importance of specific variables and joint motion trajectories for each leg of the hexapod robot [1-11]. These paths are obtained from the time the movement path is processed being attributed to the coordinates (x, y, z) corresponding to the desired movement of the reference points of the foot final end. The objective is to get the two variables of joint θ_2 and θ_3, corresponding to the desired position of the frame final end [5, 6, 7, 11]. In this case, we consider the orientation of the reference frame of the final end, because we are interested in the position. We apply direct kinematic equation (2) and consider the following limitations: all joints are allowed only rotation on an axis, ties have always femur and tibia rotation on parallel axes and limited physical position can be determined for each angle of articulation.

In accordance with the foregoing, the inverse kinematic model of a hexapod robot leg has the following form to joints femur and tibia [1-10]:

$$\begin{gathered} q_1=arctan2(x,y)-arctan2\big(l_2-sin(q_2),l_1+l_2 cos(q_2)\big)+\frac{\pi}{2} \\ q_2=-arccos\left(\frac{x^2+y^2-l_1^2-l_2^2}{2l_1 l_2}\right) \end{gathered} \tag{6}$$

The inverse kinematics differential link to the desktop speed can be achieved through joint hexapod robot Jacobian matrix, it can be expressed by the following equation:

$$J^{-1}(q)=\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$
$$\begin{gathered} h_{11}=\frac{cos(q_1+q_2)}{l_2 sin(q_1+q_2)+l_1 sin(q_1)-l_1 sin(q_2)} \\ h_{12}=-\frac{sin(q_1+q_2)}{l_2 sin(q_1+q_2)+l_1 sin(q_1)-l_1 sin(q_2)} \\ h_{21}=-\frac{l_2 cos(2q_1+2q_2)+l_1 cos(q_1)+l_1 cos(2q_1+q_2)}{l_2^2 sin(q_1+q_2)+l_1 sin(q_1)-l_1 sin(q_2)} \\ h_{22}=\frac{l_2 sin(2q_1+2q_2)+l_1 sin(q_1)+l_1 sin(2q_1+q_2)}{l_2^2 sin(q_1+q_2)+l_1 sin(q_1)-l_1 sin(q_2)} \end{gathered} \tag{7}$$

7. STABILITY AND CONTROL OF HEXAPOD ROBOT

Stability analysis of a robot with multiple legs is necessary to control, especially in dynamic situations on an uneven terrain. The main concept of this type of vehicle stability is that its center of gravity (CG) of the robot must be kept within a stable regions, to prevent its overthrow [7]. Therefore, under both conditions of static and dynamic, when the robot walks, move or handle, it is essential to monitor the stability of the robot at each point using a criterion of stability in the control [11]. In particular while crossing a frame or uneven terrain. There are several criteria for stability of the systems that can be divided into static and dynamic criteria. However, they can be classified on the basis of their stability metric, as follows [1-10]:

Criteria based on distance: distance between each polygon support and projection CG (center of gravity) or the distance between support and force vector polygon net, acting on CG, which is the metric stability. Stability edge (SM), established by McGhee, is the most notable distance based on stability, because stability is the edge shown for the first time. MS is defined as the minimum distance between CG and limited support polygonal projection [4, 7, 11].

Angle-based criteria: use the angle of the polygon support and the net force acting on CG accounting system stability. Based on the number of indications of its shares, the most notable criterion in this category is the angular edge stability force (FASMA). FASMA is defined as the net force and angle between the line connecting the center of mass of the rotation point (the plan) and the axis of rotation (in space) [3, 6, 8].

Criteria based on energy: They start from the energy difference between the robot in two different situations and overthrow the current configuration. The first static based on the stability (ESM) was presented by Messuri and Klein in “Automatic body regulation for Maintaining stability of a legged vehicle during rough-terrain locomotion” and the dynamic (DESM) was presented by Ghasempoor and Sepehr in “a measure of stability for moving base machine manipulators”, which was normalized by S. Hirose (NESM) and Garcia (NDESM) [1-10]. Most of stability criteria fall under the criteria based on time since overthrowing takes place when the time exceeds one of the axes of rolling. However, the criterion based on time can be quite difficult to implement especially on uneven terrain because it requires understanding of axis and the position of each leg. The most notable moment is the stability criterion based on dynamic image (DSM), zero moment point (ZMP) and Roll Stability edge (TSM) [1-10].

Criterion based on force: the focus is on the forces acting on the robot. When inverting the leg strength, the exception is that the rolling axis or planar point of robot becomes zero. Although attempts have been made to use this concept for controlling the robot, there is no certainty concerning the exact way of monitoring it. Researchers Garcia, Roan and many others have concluded that a mobile robot is controlled by several feet on three levels: the torso, legs and joints [1-11]. This criterion is applied to any mobile robot.

Leg strength - edge stability

In dynamic situations, it is essential to monitor the stability of the robot every time by using a stability criterion, especially while crossing a frame, an undulating ground, as shown in figure 5. According to E. Garcia and P.A.G. Santos, a car in motion is dynamically stable if the time limit j's support polygon is caused by ground forces and moments are positive (in clockwise). It emphasizes that with E. Garcia and P.A.G. Santos used the F × R not R× F. Using R × F, the definition of dynamic stability can be rewritten as: a running car is stable dynamic if time j which limits the support polygon caused by the ground forces and moment are negative (reverse clockwise). From Newton's law, the following limits must be met in support of the polygon [1-10], each as follows:

$$M_{in,j} = M_{gr,j} + M_{man,j} + M_{sup,j} \tag{8}$$

where $M_{in,j}$ it is the moment due to the inertial force and moment $M_{gr,j}$ it is the moment due to gravity and $M_{man,j}$ it is the moment is due when handling (external) and force and moment $M_{sup,j}$ is the moment based on contact force and moment. All times are calculated on j, support polygon limit. From Equation (8), the following can be written:

$$M_{sup,j} = -\left(M_{gr,j} + M_{man,j} - M_{in,j}\right) \tag{9}$$

The term in brackets from equation (9) is the net moment when acting upon j, the support polygon limit, due to all forces and moments handled. Therefore, it can be replaced with $M_{Net,j}$ which may be offset by moments and ground forces, $M_{sup,j}$. Therefore, in order to have a stable dynamics of the robot, the following equation must be satisfied:

$$M_{sup,j} = -M_{Net,j} \tag{10}$$

Indicating that a robot to be dynamically stable, the net time support polygons j limit must be positive (in clockwise), but with the same amplitude as support forces and moments due time. Otherwise, the robot will roll. Assuming the point of contact, the legs point, the equation can be written accounting $M_{sup,j}$:

$$M_{sup,j} = \sum_{i=1}^{n} R_i \times F_i = \sum_{i=1}^{n} f_i \cdot R \times \left(\sqrt{1+\mu_i^2} \cdot e_{F,i}\right) \tag{11}$$

where n is the number of the legs, R_i is the position vector perpendicular to the contact of the feet, on the limit j support, F_i foot is in contact force vector, $f_i = \|f_i\|$ amplitude is the normal leg strength, where f_i it is a normal component of F_i shown in figure 4. μ_i is the friction of the foot / ground and $e_{F,i}$ is the unit vector of force foot contact, F_i.

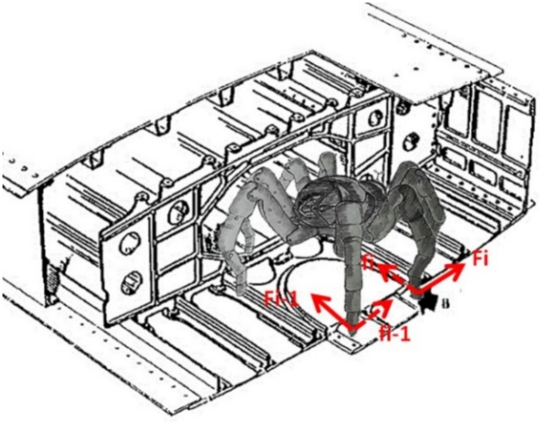

Figure 4. The robot studied in the fuel tank (robot has n foot and is on an uneven terrain)

Therefore, the dynamic stability of normal strength correlates with the robot foot (f_i), as well as the coefficient of friction (μ_i) and foot positions (R_i) in accordance with E. Garcia and P.A.G. Santos in the paper "A new energy dynamic stability margin for walking machines", in International Conference on Advanced Robotics, pp. 1014-1019, 2003 equations (10) and (11). However, to analyze the stability of an ideal robot with multiple legs, the friction coefficient is considered high enough to prevent slippage of the robot. Therefore, the instability is considered overturning / rolling not slipping. It is assumed that the distribution leg is necoliniar, $\sum_{i=1}^{n}\|R_i\| \neq 0$. Also, all contacts between the legs of the contact surfaces are assumed to be contact point [1-10].

Giving the robot with multiple legs (n≥3) with only two forces strictly positive, indicating that only two legs are in contact with the ground, creating j limited support, it is determined that $M_{sup,j}$ is zero and requires $M_{Net,j}$ to be the same, namely zero. Otherwise, if $M_{Net,j} \neq 0$, equation 10 will be satisfied and the robot will roll. Therefore, to be considered dynamic stability, the robot must have at least one foot on the ground with a force strictly positive to negative because of a time limit on support and to offset the positive j, $M_{Net,j}$. If $M_{Net,j}$ is negative, the robot is unstable [2-7].

Taking into account the assumptions in the above discussion, it is assumed the following conclusion:

Definition 1 - ideal mobile robot with n foot (n≥3) at time t is dynamically stable if and only if there are at least three non-collinear legs and a strictly positive force $(f_i > 0)$ at time t [11]. This definition provides a quick method for determining measurable system stability. However it neglects R_i, which greatly influences $M_{sup,j}$ [2, 4, 7].

The current relationship between stability and leg strength requires strictly positive forces $(f_i > 0)$; however, the relationship may change if considering riding on walls, frames, ceilings and surfaces very inclined [3, 5, 8].

As shown in the above finding, the stability occurs when there are at least three feet forces of the leg strictly positive. Intuitively, stability occurs when the maximum size of the leg forces are all the same, that forces of the legs are all the same and the forces are evenly distributed on all four feet. It is desirable to have an appropriate understanding that provides a normalized current stability of the system based on force amplitude leg. FFSM uses forces of foot and foot stability to describe their status [4, 7, 10].

It allows $f_1, f_2, \ldots, f_n$ amplitude to be normal force to support legs. The product of all forces leg, $\prod_{i=1}^{n} f_i$ is used as a basis to define FFSM since it satisfied the definition of 1 instability. FFSM maximum stability of the robot, the product is normalized between 0 and 1. For this purpose, the ratio of force - the total force measured individual leg, $\frac{f_i}{f_{tot}}$, it is used when $f_{tot} = \sum_{i=1}^{n} f_i$ is observed that $\sum_{i=1}^{n} \frac{f_i}{f_{tot}} = 1$. The maximum amplitude $\prod_{i=1}^{n} \frac{f_i}{f_{tot}}$ is $\frac{1}{n^n}$ which correlates with the condition of maximum stability of the machine. For FFSM to result in a number between 0 to state 1 state unstable and stable maximum term n^n it is multiplied by the product. FFSM at time t for a robot with n foot support is defined as:

$$FFSM = S = \prod_{i=1}^{n} \frac{f_i}{\bar{f}}, \quad 0 \leq S \leq 1 \tag{12}$$

Where n is the number of the legs with strictly positive forces on foot and $\bar{f} = \frac{f_{tot}}{n}$ there is the average of all normal forces on foot. Therefore, FFSM is based on the fractions to the average of all the forces of the foot [4, 8, 10]. Equation (12) provides an amplitude stability margin between zero and one, 0≤S≤1, indicating how close the system is to achieve maximum state of instability or stability condition. As expected, the equation (12) shows that a uniform distribution of forces improves the stability of the whole system legs. Therefore, maximum stability FFSM = 1, occurs only when the forces are evenly distributed on foot, that is to say the standard deviation of the amplitude of the force of the foot is zero[1-10].

Given a system $n \geq 4$ and m standing $m \leq n-3$, due to the loss of contact with the ground, which usually happens on an uneven terrain.

Stability will indicate a zero edge while the system will remain stable with n - m support legs. For example, when a robot walks, configuration changes from quadruped, n = 4 from the tripod, n = 3, a foot loses contact with the ground while the tripod support configuration maintains stability.

In order to take into account the loss of contact with the ground on purpose, in the calculating FFSM should be updated accordingly to $n \leftarrow n - m$ at each iteration in the controller.

To ensure that the robot will be stable after switching from n to n -m feet FFSM both states must be calculated simultaneously while the robot switches. Thus, if n -m is not a stable configuration, the robot will recognize and will not fall [1-10].

Since the FFSM only focuses on the amplitude of the normal component of the forces of the foot, taking into account the cross-section of the leg of the robot, on the assumption that $\alpha > 1$ is a constant, FFSM is the same for all four cases:

$$MFFSM = m\,(t)\,S \tag{13}$$

8. CONCLUSIONS

Entry into the aircraft fuel tank is required for inspections and modifications, but these works may present a risk factor for technical personnel.

The maintenance of the aircraft fuel tank can be done safely if the technical staff is trained and has the necessary equipment for the work. In this area of aircraft safety and maintenance the mobile robots can successfully intervene.

Robotics automation provides the flexibility needed to achieve shorter production cycles, new ways of packaging as a form and design, and the creation of new product variants and batch manufacturing. Compared with traditional dedicated automations, robot lines are shorter and allow for much better space utilization. Robot automation is an excellent alternative to manual operation.

In addition to reduce the working time and enhance safety of maintenance staff mobile robots can play an important role.

The decrease in the number of accidents and the increasing demand for labor protection legislation are good reasons for moving to robots.

Entry into airplane fuel tank is needed for inspections and modifications. And this work may pose a risk factor for the technical staff.

Therefore, this paper aims to implement a mobile hexapod robot. Due to its characteristics, the robot can easily sneak into the fuel tank of the aircraft and the operator can guide him outside to facilitate its aircraft maintenance activities.

Due to the fact that the movement of the robot is achieved by interaction of unstructured environment, it is necessary to understand specific use of an electronic system for detection of obstacles in the fuel tank.

However, it should be stressed that the main problem is the coordination of angular movement of the robot's 18 joints during movement, emphasizing the sequence of steps. This problem is solved by implementing an electronic system dedicated to distributive architecture.

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