Towards the development of Surveillance and Reconnaissance Capacity in Ecuador: Geolocation system for ground targets based on an electro-optical sensor

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Abstract. This paper presents the progress of a research work that seeks to determine the geographic coordinates of an object on land of interest by applying the Denavit-Hartemberg methodology to the surveillance and recognition system developed in the CID-FAE SEO-D1, this together with mathematical cartography will provide information in support of military operations. The results shown in the simulation present a good approximation of the geographic coordinates of interest. In the light of the above, it is suggested that this kind of study provides a low-cost surveillance and reconnaissance alternative to existing advanced systems such as satellites for countries that do not have this type of technology, as is the case of Ecuador.

Keywords: Robot´s articulation, Kinematic chain, Denavit-Hartemberg Algorithm; Mathematical Cartography; Space Projection, Gimbal.

1 Introduction

The Armed Forces of Ecuador, as part of their doctrine, must guarantee Ecuadorian society the defense of sovereignty and territorial integrity and, in addition, support the integral security of the State [1]. This doctrine also establishes a relationship with the socioeconomic development of the population, a relationship that within its process and conception has had changes due to the appearance of organizations that have caused problems within the country. Therefore, the Ecuadorian State has seen the need to prioritize the border sector, specifically the northern border where illegal activities have been developing, which constitute serious threats to the security of the State [2].

On the other hand, the strategic planning of the defense, is intended to guarantee the security and defense of the State, conceiving from a comprehensive approach a correct decision making in everything related to sovereignty and territorial integrity; generating policies aimed at contributing to the safety and welfare of its citizens, through surveillance and control activities such as land, river and air patrol operations.

Therefore, the Research and Development Center of the Ecuadorian Air Force CIDFAE is an entity dedicated to the development of projects oriented to security and

defense. Among the emblematic projects developed in this research center, there is the surveillance and reconnaissance system. This system arises from the need to capture images in real time for surveillance and reconnaissance applications [3].
The surveillance and reconnaissance system developed at the CID FAE consists of a ground station, the gimbal system, and a camera. These sub-systems allow the operation of the gimbal in flight along with the camera and obtaining real time information of images and parameters such as height, gimbal geographic location, Pitch, Yaw and Roll degrees.
The known geographical location (latitude and longitude) corresponds to the gimbal mounted on an aircraft in flight but we cannot say that these coordinates are those corresponding to the surrounding objects on land. That is to say that we can visualize images on the ground without knowing their geographical location.
To solve this problem it is necessary to know the orientation and position of the lens of the Gimbal´s camera in the space, this way we would determine the direction where the camera points and consequently know the location of surrounding objects on land.
In robotics it is a common need to know the orientation and location of the final effector of a robot (a tool normally) from the knowledge of the values taken by the articulations of the robot. This is called the direct kinematic problem [4].

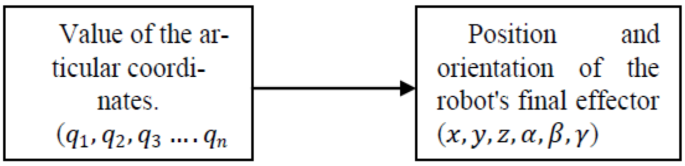


Fig.1 Direct kinematic problem
Source: Robotics fundamentals [4]

There are different approaches to solve the direct kinematic problem, but for the geolocation system developed the Denavit-Hartemberg methodology was used.
Denavit and Hartenberg proposed in 1955 a matrix method to systematically establish a coordinate system which we will call S_i linked to each link i of an articulated chain, and the kinematic equations of the whole chain can then be determined [5] which are the result of the multiplication of the homogeneous transformation matrices.
The homogeneous transformation matrix is symbolized by ${}^{i-1}A_i$, and represents the relative position and orientation of the system S_i with respect to the system S_{i-1}. That is to say that ${}^{0}A_1$ describes the position and orientation of the solidary reference system to the first link with respect to the solidary reference system to the base.

$$ {}^{i-1}A_i = \mathbf{T}(\boldsymbol{z}, \theta_i)\mathbf{T}(0,0,d_i)\mathbf{T}(a_i,0,0)\mathbf{T}(\boldsymbol{x}, \alpha_i) \tag{1} $$

$$ {}^{i-1}A_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & 0 \\ \sin(\theta_i) & \cos(\theta_i) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha_i) & -\sin(\alpha_i) & 0 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

To represent the position and orientation of the solidary reference system to the final effector S_6 with respect to the solidary reference system to the baseS_0. It will only be necessary to multiply the homogeneous transformation matrices of all successive links of the robot.

$$ T = {}^{0}A_6 = {}^{0}A_1\, {}^{1}A_2\, {}^{2}A_3\, {}^{3}A_4\, {}^{4}A_5\, {}^{5}A_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

Since the Denavit-Hartemberg algorithm gives us the position and orientation of the final effector in values relatives of the plane X,Y,Z it is necessary the application of mathematical cartography for the representation of values of latitude (ϕ) and longi-tude(λ) of the globe to their respective values passed to a plane and vice versa.
Cartography is the science that deals with the drawing of geographical charts. Geo-graphical charts, also called maps, are representations on a plane of all or part of the earth's surface. In order to make this representation, a certain projection of the afore-mentioned reference land surface on a plane will be used.[6]
Toobtainthecartographicrepresentationsof a terrestrialzoneitisnecessarytoknowthe formulas that relate thevalues in theplanewiththevaluesoflatitude and longi-tude.

$$ x = f_1(\phi, \lambda) \quad (4) $$

$$ y = f_2(\phi, \lambda) \quad (5) $$

To these formulas must exist a biunivocal correspondence for its inverse case.

$$ \phi = F_1(x, y) \quad (6) $$

$$ \lambda = F_2(x, y) \quad (7) $$

For the calculation of these values we used the UTM (Universal Transversal Merca-tor) representation, because it is the most widely used and has less deformations in its representation to the plane. Whose formulas and calculations are detailed in “Bolleti-no de Geodesia e Science Affini” number 1 presented by Alberto Cotticia and Lucia-no Surace.

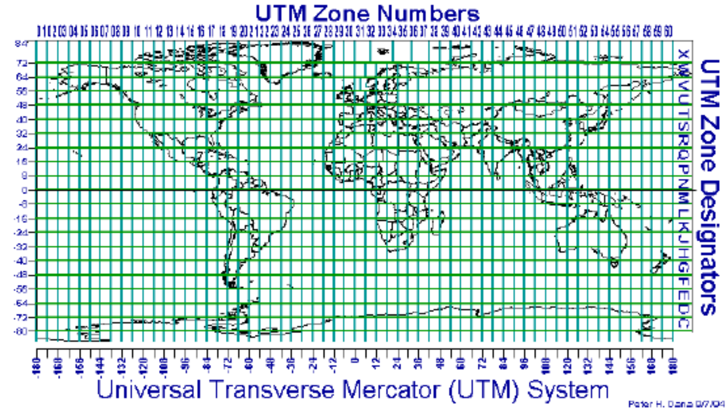


Fig.1 UTM Zones in a Plane
Source: Antonio R. Franco [10]

Ecuador is inside 4 zones (15, 16, 17 and 18) so the formulas applied will have this condition.

Fig.2 UTM Zones for Ecuador
Source: Geo-ingeniería [11]

2 Design of The Geolocation System

The geolocation system is composed of elements that have the electro-optical sensor such as the altimeter and inertial measurement unit (IMU), the gimbal, the ground station with its HMI screen, and algorithms implemented by software. In this paper we will focus on the algorithms to be implemented by software.

First it is necessary to establish the characteristics of the gimbal on which the Denavit-Hartenberg algorithm will be applied.

Since the Gimbal is mounted on an aircraft this will have variations in Height, Pitch, Yaw and Roll product of the maneuvers executed in flight, these four variables will be considered as values equivalent to those taken by the joints of a robot (4 degrees of freedom).These 4 degrees of freedom are added to 2 degrees of freedom corresponding to two servomotors that integrate the Gimbal.

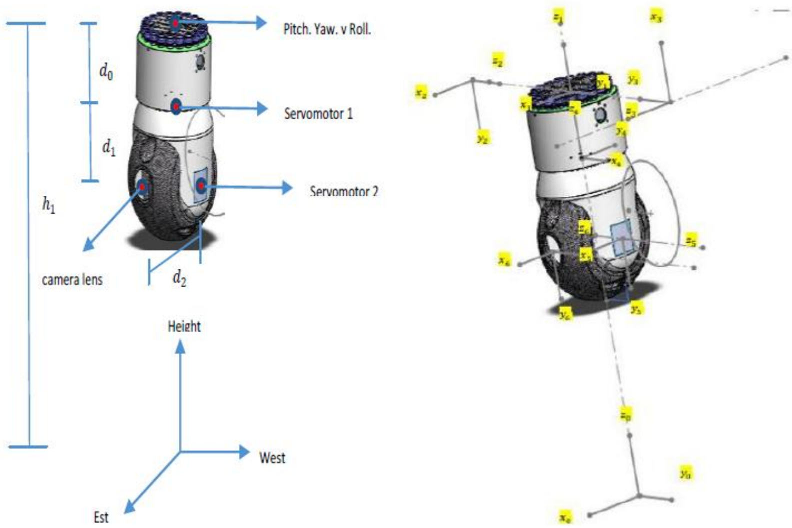
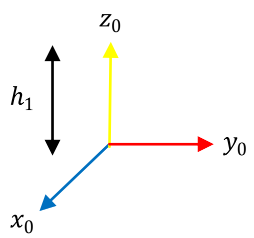
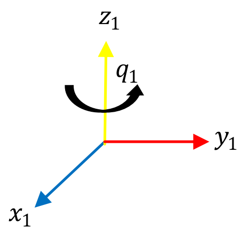
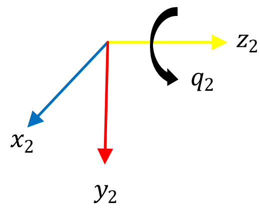
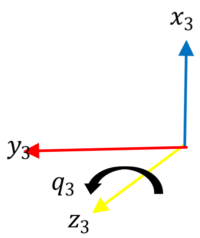
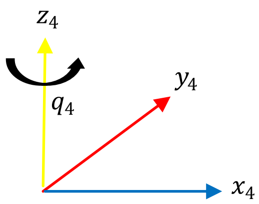
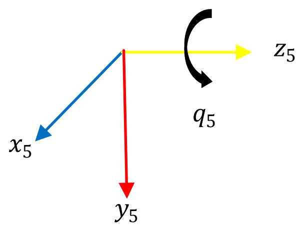


Fig.3 Gimbal Characteristics.

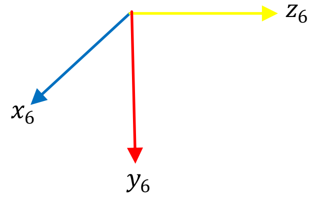
Source: Author

With these conditions we proceed to put all systems associated with each joint in accordance with Denavit-Hartemberg.

Table 1. Systems associated with each articulation.

S_0 (Altimeter)	S_1 (Yaw)	S_2 (Pitch)
		
S_3 (Roll)	**S_4 (Servomotor 1)**	**S_5 (Servomotor 2)**
		

S_6(Camera Lens)



Once the systems associated with the joints have been established, we can obtain the values for the homogeneous transformation matrices.

Table 2. Denavit-Hartemberg parameter table.

Joins		θ_{zi-1}	d_{zi-1}	a_{xi}	α_{xi}
$^0A_1$	1	0	h_1	0	0
$^1A_2$	2	q_1	0	0	-90
$^2A_3$	3	$q_2 - 90$	0	0	-90
$^3A_4$	4	$q_3 - 90$	0	$-d_0$	-90
$^4A_5$	5	$q_4 - 90$	$-d_1$	0	-90
$^5A_6$	6	q_5	0	$+d_2$	0

$$T = {}^0A_6$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & h_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(q_1) & 0 & -\sin(q_1) & 0 \\ \sin(q_1) & 0 & \cos(q_1) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(q_2-90) & 0 & -\sin(q_2-90) & 0 \\ \sin(q_2-90) & 0 & \cos(q_2-90) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{(¡ Error! Marcador no definid}$$

$$\begin{bmatrix} cos(q_3-90) & 0 & -sin(q_3-90) & -d_0\, cos(q_3-90) \\ sin(q_3-90) & 0 & cos(q_3-90) & -d_0\, sin(q_3-90) \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(q_4-90) & 0 & -\sin(q_4-90) & 0 \\ \sin(q_4-90) & 0 & \cos(q_4-90) & 0 \\ 0 & -1 & 0 & -d1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \cos(q_5) & -\sin(q_5) & 0 & d_2\cos(q_5) \\ \sin(q_5) & \cos(q_5) & 0 & d_2\sin(q_5) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The T matrix will allow obtaining the orientation and position of the camera lensS_6 with respect to the S_0 system.
In this way a straight line in the x axis (camera lens) of the system S_6can be projected into space using two points that are part of the x-axis(camera lens).The equation of the line in space with the continuous form is given by[8]:

$$\frac{x - x_0}{v_1} = \frac{y - y_0}{v_2} = \frac{z - z_0}{v_3} \quad \text{(¡ Error! Marcador no definido.)}$$

$$v_1 = x_1 - x_0 \quad (8)$$

$$v_2 = y_1 - y_0 \quad (9)$$

$$v_3 = z_1 - z_0 \quad (10)$$

From this projected line, the x and y values of the plane z=0 are determined. Which we will call x_{0utm} and y_{0utm} , theseare the differential values in X and Y with reference to the origin system S_0.

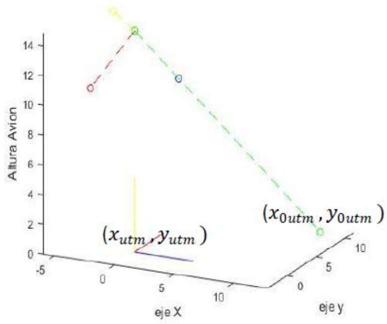


Fig.4 UTM targetpoints
Source: Author

As already mentioned, the surveillance and reconnaissance system already provide the geographic coordinates of the gimbal in real time. Then it will be necessary to pass these coordinates to UTM values through the formulas presented in "Bolletino de Geodesia e Science Affini" to obtainthe x_{utm} and x_{utm} values. [12]

$$x_{target} = x_{utm} + x_{0utm} \quad (11)$$

$$y_{target} = y_{utm} + y_{0utm} \quad (12)$$

If it is required to obtain in geographic coordinates it will be necessary to carry out the conversion of UTM coordinates to geographic coordinates. These values will be ap-propriate if the coordinates of both the gimbal and the ground target are within the same UTM zone.

3 Simulation and test

In order to carry out the simulations, the conditions in a certain period of time in which the Gimbal is in flight are established. For this it is imposed that the Gimbal is up to 1000 meters of height, in the coordinates (1.285309,-78.834736) and whose orientation is the result of the variation of q4 and q5 in 45 degrees.
With these parameters, the orientation given by the transformation matrix T will be as follows.

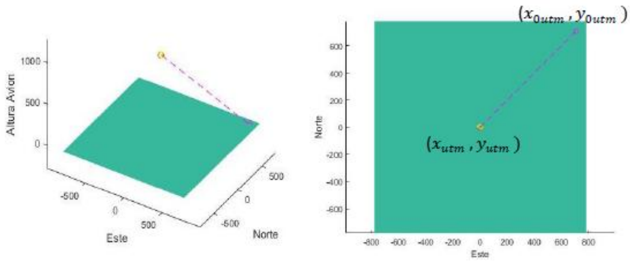


Fig.5 UTM target points simulation
Source: Author

The values of the desire parameters are obtained by programming in MatLab the for-mulas presented or mentioned in this paper.

Table 3. Parameter results table.

Parameter	Value
Xutm	7.409466249039110e+05
Yutm	1.421692420845669e+05
xoutm	7.070360705084230e+02
youtm	7.070360705084230e+02
xtarget	7.416536609744194e+05
ytarget	1.428762781550754e+05
Target Coordinates	(1.291695931165799,-78.828379873412587)

In order to appreciate the results, Google maps [9] are used, where the gimbals and target will be visualized.

Fig.6 UTM targetpoints Google Maps
Source: Google maps [9]

As we can see the geolocation system of targets on land shows a good approximation of the geographical coordinates of the target pointed by the camera.
In order hand to test the system, preliminary experiments were carried out in controlled conditions and in locations with heights of no more than 13 meters.

Fig.7 Geolocation Test
Source: Author

Table 4. Preliminary experiments table.

	Test Height(m)	**Objective** Range(m)	Error x (m)	Error y (m)	Range Variation (m)
1	5	22,5	1,4468	0,88633	1,6967
2	5	37,4	3,5672	4,3113	5,5958
3	13	37,3	4,7877	0,55752	4,8201
4	13	43,2	4,6758	1,2211	4,8326
5	10	46,6	1,7792	2,7675	3,2901
6	10	1,1	0,3338	0,2215	0,4007

4 Discussion

This paper presents the results of the simulation of the designed geolocalization system. This is a tool that can give information in real time of the geographic coordinates of the surroundings, specifically of the objects visualized by the camera of the Gimbal. This information can be very useful as an input for the planning of military ground operations.
The results of the preliminary tests of the table 4 show good results with a tolerable error, this error was product in greater proportionby the sensitivity that presented the servomotors of the gymbal which by their physical characteristics and the time of operation presented a resolution of 1.5 degrees, if this resolution is improved the error will consequently reduce.
It is important to emphasize that the system has the limitation of the UTM zone, since the formulas of transformation of geographic coordinates to UTM and vice versa use as input the central coordinate of the corresponding UTM zone, which is different for each zone.
With the development of the geolocation system, a boost will be given to the development of operational capabilities in the Air Force by means of new technologies. The use of this technology will be attached to the nation's security and defense activities. In addition, this technology can be extrapolated for use in civilian applications.

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