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The Kinematics of a Puma Robot

Highlights

Interfaces Board for Family

Therapeutics Tools to Surgical Robots

Discovering Thoughts, Inventing Future

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The Kinematics of a Puma Robot using Dual Quaternions

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Kinematics analysis studies the relative motions, such as, first of all, the displacement in space of the end effector of a given robot, and thus its velocity and acceleration, associated with the links of the given robot that is usually designed so that it can position its end-effector with a three degree-of-freedom of translation and three degree-of-freedom of orientation within its workspace.

First of all, examples of basic solid movements such as rotations, translations, their combinations and general screw motions are studied using both (4x4) rigid body transformations and dual quaternions so that the reader could compare and note the similarity of the results obtained using one or the other method.

Keywords: *dual quaternions, forward kinematics, screw motion, denavit and hartenberg parameters.*

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Strictly as per the compliance and regulations of:

The Kinematics of a Puma Robot using Dual Quaternions

Mahmoud Gouasmi [α], Belkacem Gouasmi [σ] & Mohamed Ouali [ρ]

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First of all, examples of basic solid movements such as rotations, translations, their combinations and general screw motions are studied using both (4x4) rigid body transformations and dual quaternions so that the reader could compare and note the similarity of the results obtained using one or the other method. Both dual quaternions technique as well as its counterpart the classical 'Denavit and Hartenberg parameters method' are finally applied to the first three degree of freedom of a Puma 560 robot. Finally, we and the reader, can observe that the two methods confirm exactly one another by giving us the same results for the considered application, while noting that the fastest, simplest more straightforward and easiest to apply method, is undoubtedly the one using dual quaternions. As a result this chapter may as well act as a beginners guide to the practicality of using dual-quaternions to represent the rotations and translations in character-based hierarchies.

We must emphasize the fact that the use of both Matlab software and quaternions and / or dual quaternions in the processing of 3D rotations and/or screw movements is and will always be the most efficient, fast and accurate first choice. Dual quaternion direct kinematics method could be generalised, in the future, to all kind of spatial and/ or industrial robots as well as to articulated and multibody systems.

Keywords: dual quaternions, forward kinematics, screw motion, denavit and hartenberg parameters.

I. Introduction

Many research students have a great deal of trouble understanding essentially what quaternions are [1], [2], [3] and how they can represent rotation. So when the subject of dual-quaternions is presented, it is usually not welcomed with open arms. Dual-quaternions are a break from the norm (i.e., matrices) which we hope to entice the reader into supporting willingly to represent their rigid transforms. The reader should walk away from this analysis with a clear understanding of what dual-quaternions are and how they can be used [4]. First we begin with a short recent and related work that emphasises the power of dual-quaternions:

The dual-quaternion has been around since 1882 [5],[6],[7] but has gained less attention compared to quaternions alone; while the most recent work which has taken hold and has demonstrated the practicality of dual-quaternions, both in robotics and computer graphics can be resumed in: - Kavan [8] demonstrated the advantages of dual-quaternions in character skinning and blending. - Ivo [9] extended Kavan's work with dual-quaternions and q-tangents as an alternative method for representing rigid transforms instead of matrices, and gives evidence that the results can be faster with accumulated transformations of joints if the inferences per vertex are large enough. - Selig [10] address the key problem in computer games. - Vasilakis [11] discussed skeleton-based rigid-skinning for character animation. - Kuang [12] presented a strategy for creating real-time animation of clothed body movement.-Pham [13] solved linked chain inverse kinematic (IK) problems using Jacobian matrix in the dual-quaternion space. -Malte [14] used a mean of multiple computational (MMC) model with dual-quaternions to model bodies. - Ge [15] demonstrated dual-quaternions to be an efficient and practical method for interpolating three-dimensional motions. -Yang - Hsing [16] calculated the relative orientation using dual-quaternions. - Perez [17] formulated dynamic constraints for articulated robotic systems using dual-quaternions.- Further reading on the subject of dual numbers and derivatives is presented by Gino [18].

In the last three decades, the field of robotics has widened its range of applications, due to recent developments in the major domains of robotics like kinematics, dynamics and control, which leads to the sudden growth of robotic applications in areas such as manufacturing, medical surgeries, defense, space vehicles, under-water explorations etc.

To use robotic manipulators in real-life applications, the first step is to obtain the accurate kinematic model [19]. In this context, a lot of research has been carried out in the literature, which leads to the evolution of new modeling schemes along with the refinement of existing methodologies describing the kinematics of robotic manipulators.

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Screw theory based solution methods have been widely used in many robotic applications. The elements of screw theory can be traced to the work of Chasles and Poinsot [20], [21], in the early 1800's and Whittaker [22]. Using the theorems of Chasles and Poinsot as a starting point, Robert S. Ball developed [23] a complete theory of screws which he published in 1900. Throughout the development of kinematics, numerous mathematic theories [24] and tools have been introduced and applied. The first pioneer effort for kinematic modeling of robotic manipulators was made by Denavit and Hartenberg in introducing a consistent and concise method to assign reference coordinate frames to serial manipulators, allowing the (4×4) homogeneous transformation matrices to be used (in 1955) [25], followed by Lie groups and Lie Algebra by J.M Selig and others, [26], [27], [28]) and quaternions and dual quaternions introduced by Yang and Freudenstein (1964) [29], see also Bottema and Roth (1979) [30] and McCarthy (1990) [31].The original D–H parameter method has many counterparts: Distal variant, proximal variant, …to name but a few. There even exist different options for these counterparts.

In this method, four parameters, popularly known as D–H parameters, are defined to provide the geometric description to serial mechanisms. Out of the four, two are known as link parameters, which describe the relative location of two attached axes in space. These link (See appendix 10,3,1.) parameters are: The link length (a_i) and the link twist (α_i).

The remaining two parameters are described as joint parameters, which describe the connection of any link to its neighboring link. These are the joint offset (d_i) and the joint angle (θ_i).

Modeling the movement of the rigid body by the theory of the helicoidal axis: a combination of an amount of rotation about and an amount of translation along a certain axis, hence the term helicoidal axis is used in various fields such as computer vision and biomechanics. The application of this theory in the field of robotics is taking more and more space. We can consider the motion of a joint segment as a series of finite displacements. In this case the movement is characterized by an angle of rotation about and an amount of translation along an axis defined in space by its position and its orientation. This axis is referred to as the finite helicoidal axis (FHA), because of the discretization of the movement into a series of displacements. On the other hand and by taking the continuity of the movement into account, this movement will be characterized by a rotational speed (angular velocity) about and translation speed along an axis defined by the instantaneous position and orientation in space. One speaks in this case of an instantaneous helicoidal axis (IHA).The application of the helicoidal theory with its two versions (FHA and IHA) is used to describe and understand the joint movement, and to study in biomechanics, for example, the different positioning techniques of prothèses. Thus there are several methods to estimate the helicoidal axis from a set of points representing a rigid body.

Any displacement of a rigid body is a helicoidal motion which may be decomposed into an angular rotational movement about and a linear translational movement along a certain axis in 3D space. The methods differ in the way of mathematically representing these two movements. These movements can be expressed using rotation matrices and translation vectors, homogeneous matrices, unit quaternions, dual quaternions, ...

The two representations; using (3x3) matrices or (4x4) homogeneous matrices and dual quaternions will be simultaneously used for all and each examples or applications studied so that comparisons for each case could be done.

II. Dual Quaternions

a) « Product type » dual quaternions

The dual quaternions have two forms thus two readings which are complementary and simultaneous: The first is the << product type >> description:

$$\hat{T}_G = \left\{T_R + \varepsilon \frac{T_T.T_R}{2}\right\} \text{ With: } T_R = \left\{\cos\frac{\psi}{2}, \text{n}.\sin\frac{\psi}{2}\right\} = \left\{\cos\frac{\psi}{2},\ \sin\frac{\psi}{2}.n_x, \sin\frac{\psi}{2}.n_y, \sin\frac{\psi}{2}.n_z\right\}$$

and $T_T = (0,\{T_x, T_y, T_z\} = (0, \{T\})$

Then, the transformation is:

$$\hat{T}_G = \left\{T_R + \varepsilon \frac{T_T.T_R}{2}\right\} = \left\{\cos\frac{\psi}{2}, \text{n} \sin\frac{\psi}{2}\right\} + \varepsilon\left\{0, \frac{T}{2}\right\}.\left\{\cos\frac{\psi}{2}, \text{n} \sin\frac{\psi}{2}\right\}$$

$$\hat{T}_G = \left\{\cos\frac{\psi}{2}, \text{n} \sin\frac{\psi}{2}\right\} + \varepsilon\left\{-\left(\frac{T.n}{2}\right)\sin\frac{\psi}{2}, \left\{\frac{TXn}{2}\sin\frac{\psi}{2} + \frac{T}{2}\cos\frac{\psi}{2}\right\}\right\} \qquad \text{<< product type >>} \quad (1)$$

b) « Dual type » dual quaternions

Indeed a general transformation, screw type, can be also described using dual angles and dual vectors and have therefore the following form << Dual type >>:

$$\hat{T}=\left\{\cos\frac{\hat{\theta}}{2},\ \sin\frac{\hat{\theta}}{2}\hat{w}\right\}=\left\{\cos\frac{\theta}{2},\sin\frac{\theta}{2}n\right\}+\varepsilon\left\{-\frac{d}{2}\sin\frac{\theta}{2},\left\{\mathrm{m}\sin\frac{\theta}{2}+\frac{d}{2}n\cos\frac{\theta}{2}\right\}\right\}\quad <<\mathit{dual\ type}>> \tag{2}$$

It is defined by the dual angle $\hat{\theta}$ and the dual vector $\hat{w}$ the rotation being represented by the angle θ around the axis n = (n_x, n_y, n_z) of norm 1, and a translation *d* along the same vector n.

The vector m = (m_x, m_y, m_z) is the moment of the vector n about the origin of reference (O, x, y, z); it is named the moment of the axis n, with: $\hat{\theta} = \theta + \varepsilon\, d$ *with d* being the amplitude of the translation along the dual vector $\hat{w}$ = n +ε m with m = *p* x n (the green vector see figure 1) that defines the vector according to Plücker coordinates, *p,* (the blue vecor), being the vector that gives the position of n ,(the red vector), using the vector OO_1 (see figure (1)).

The parameters of the transformation, the angle θ, the axis of rotation n, the magnitude of the translation *d* and the moment m are the four characteristics of all, any and every 3D rigid body transformation (4x4) matrix, a screw motion or a helicoidal movement of any kind (or type).

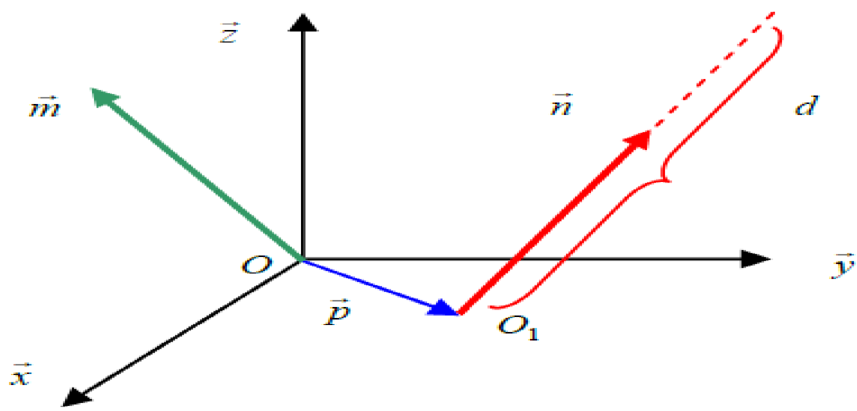

Figure 1: Helicoidal or screw motion

Note that this form resembles that used for classic quaternions; using the dual angle and the dual unitary vector instead of the classical ones.

And as a matter of fact: The screw displacement is the dual angle $\hat{\theta} = \theta + \varepsilon\, d$, along the screw axis defined by the dual vector $\hat{l}$ or $\hat{s}$ or in our case $\hat{w}$ = n +ε m; such that we will obtain (respecting the rules of derivation and multiplication of dual numbers), dual vectors, quaternions and dual quaternions (see appendix 10,2. and eq (A15)):

$$\hat{T}=\left\{\cos\frac{\hat{\theta}}{2},\ \sin\frac{\hat{\theta}}{2}\hat{w}\right\}=\left[\cos\frac{\theta}{2}-\varepsilon\frac{d}{2}\sin\frac{\theta}{2},\left(\sin\frac{\theta}{2}+\varepsilon\frac{d}{2}\cos\frac{\theta}{2}\right)(\mathrm{n}+\varepsilon\,\mathrm{m})\right]=$$

$$\cos\frac{\theta}{2}-\varepsilon\frac{d}{2}\sin\frac{\theta}{2},\ \mathrm{n}\sin\frac{\theta}{2}+\varepsilon\left(\mathrm{n}\frac{d}{2}\cos\frac{\theta}{2}+\sin\frac{\theta}{2}\mathrm{m}\right)=\left(\cos\frac{\theta}{2},\mathrm{n}\sin\frac{\theta}{2}\right)+\varepsilon\left(-\frac{d}{2}\sin\frac{\theta}{2},\ \sin\frac{\theta}{2}\mathrm{m}+\mathrm{n}\frac{d}{2}\cos\frac{\theta}{2}\right) \tag{2}$$

The geometric interpretation of these quantities is related to the screw-type motion. The angle θ is the angle of rotation around n, the vector unit n represents the direction of the rotation axis. The element *d* is the translation or the displacement amplitude along the vector n, m being the vector moment of the vector axis n relative to the origin of the axes. The vector m is an unambiguous description of the position of an axis in space, in accordance with the properties of Plückér coordinates defining lines in space.

This form gives another interesting use: Whereas the classics quaternions can only represent rotations whose axes pass through the origin *O* of the coordinate system (*O*, x, y, z), the dual quaternions can represent rotations about arbitrary axes in space, translations as well as any combination of both these two basic spatial motions.

These two forms << *product type* >> eq (1) or $<<\mathit{dual\ type}>>\mathit{eq}$ (2) represent the same motion that describe the same movement 'the screw motion':

III. Example 1: Rotations Represented by Quaternions

Let's apply two successive rotations to a rigid body: the first one of amplitude $\theta_1 = \frac{\pi}{2}$ around the axis Ox followed by a second rotation of the same amplitude $\theta_2 = \frac{\pi}{2}$ around the Oy axis:

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Using quaternions the first rotation will be written; since $\frac{\theta_1}{2} = \frac{\pi}{4}$ then $\cos\frac{\theta_1}{2} = \sin\frac{\theta_1}{2} = \frac{\sqrt{2}}{2}$

$$q_1 = (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0, 0) \ ; \text{ having } \frac{\theta_1}{2} = \frac{\pi}{4} \text{ then } \cos\frac{\theta_1}{2} = \sin\frac{\theta_1}{2} = \frac{\sqrt{2}}{2}$$

The second rotation will have the form: $q_2 = (\frac{\sqrt{2}}{2}, 0, \frac{\sqrt{2}}{2}, 0)$

The final composition of the two movements will be given by the quaternion q such that:

$$q = q_2 . q_1 = (\frac{\sqrt{2}}{2}, 0, \frac{\sqrt{2}}{2}, 0) . (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0, 0) = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, -\frac{1}{2})$$

Using quaternion's definition (A5) and quaternions properties:

$$q = ((\frac{1}{2}, \frac{\sqrt{3}}{2}(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}})) \text{ or } ((\frac{1}{2}, -\frac{\sqrt{3}}{2}(-\frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}))$$

It is then easy to extract both the amplitude and the resulting axis of the rotation from the result q:

$\cos\frac{\boldsymbol{\theta}}{\mathbf{2}} = \frac{\mathbf{1}}{\mathbf{2}}$ and $\sin\frac{\boldsymbol{\theta}}{\mathbf{2}} = \frac{\sqrt{\mathbf{3}}}{\mathbf{2}}$; wich implies the first solution $\boldsymbol{\theta} = +120\,°$, around the unitary axis $(\mathrm{n}) = \frac{\mathbf{1}}{\sqrt{\mathbf{3}}}\begin{Bmatrix}\mathbf{1}\\ \mathbf{1}\\ \mathbf{-1}\end{Bmatrix}$

or

$\cos\frac{\boldsymbol{\theta}}{\mathbf{2}} = \frac{\mathbf{1}}{\mathbf{2}}$ and $\sin\frac{\boldsymbol{\theta}}{\mathbf{2}} = -\frac{\sqrt{\mathbf{3}}}{\mathbf{2}}$; wich implies a second solution $\boldsymbol{\theta} = -120\,°$, around the unit axis $(-\mathrm{n}) = \frac{\mathbf{1}}{\sqrt{\mathbf{3}}}\begin{Bmatrix}\mathbf{-1}\\ \mathbf{-1}\\ \mathbf{1}\end{Bmatrix}$

In fact the two solutions represent the same and similar solution since for any q we have $q(\boldsymbol{\theta}, \mathrm{n}) = q(-\boldsymbol{\theta}, -\mathrm{n})$.

Using our classical (3x3) rigid transformations we get:

$$R_{21} = R_2.R_1 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{pmatrix}$$

Here it is very important to note that unlike the quaternion method we cannot extract the needed results easily and straightforwardly but we must follow a long and sometimes complicated process (determinant, trace, antisimmetry, angle and axis of rotations signs,axis/angle (or conversions to Olinde Rodrigues (Axis, Angle) parameters) …

Whichever used technique we will find: A rotation of $\boldsymbol{\theta} = \frac{\mathbf{2\pi}}{\mathbf{3}} = 120\,°$ around the unit axis $\mathrm{n} = \frac{\mathbf{1}}{\sqrt{\mathbf{3}}}\begin{Bmatrix}\mathbf{1}\\ \mathbf{1}\\ \mathbf{-1}\end{Bmatrix}$

To show the anti commutativity of the product let's do the inverse and start by the second rotation instead:

$$\boldsymbol{q_i} = \boldsymbol{q_1 . q_2} = (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0, 0) . (\frac{\sqrt{2}}{2}, 0, \frac{\sqrt{2}}{2}, 0) = (\frac{\mathbf{1}}{\mathbf{2}}, \frac{\mathbf{1}}{\mathbf{2}}, \frac{\mathbf{1}}{\mathbf{2}}, \frac{\mathbf{1}}{\mathbf{2}}) = ((\frac{\mathbf{1}}{\mathbf{2}}, \frac{\sqrt{\mathbf{3}}}{\mathbf{2}}(\frac{\mathbf{1}}{\sqrt{\mathbf{3}}}, \frac{\mathbf{1}}{\sqrt{\mathbf{3}}}, \frac{\mathbf{1}}{\sqrt{\mathbf{3}}})) = \boldsymbol{q_i} = ((\frac{\mathbf{1}}{\mathbf{2}}, -\frac{\sqrt{\mathbf{3}}}{\mathbf{2}}(-\frac{\mathbf{1}}{\sqrt{\mathbf{3}}}, -\frac{\mathbf{1}}{\sqrt{\mathbf{3}}}, -\frac{\mathbf{1}}{\sqrt{\mathbf{3}}}))$$

and that will imply $\theta_i = 120\,°$ around the axis $\mathrm{n} = \frac{1}{\sqrt{3}}\begin{Bmatrix}1\\ 1\\ 1\end{Bmatrix}$, or $\theta_i = -120\,°$ around the axis $(-\mathrm{n}) = \frac{1}{\sqrt{3}}\begin{Bmatrix}-1\\ -1\\ -1\end{Bmatrix}$;

Which of course will imply that: $q_1 . q_2 \neq q_2 . q_1$

Using matrices : $R_i = R_1 R_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \neq R_{ii} = R_2 R_1$ which implies:

A rotation of $\theta = \frac{2\pi}{3} = 120°$ around the unit axis $\mathrm{n} = \frac{1}{\sqrt{3}}\begin{Bmatrix}1\\ 1\\ 1\end{Bmatrix}$ equivalent to a rotation of $\theta = -\frac{2\pi}{3} = -120\,°$ around the unit axis $\mathrm{n} = -\frac{1}{\sqrt{3}}\begin{Bmatrix}1\\ 1\\ 1\end{Bmatrix}$

Using MATLAB (See Appendix 10,1.) we can calculate easily both the two quaternions multiplications: $q = \mathrm{n1} = \mathrm{q2.q1}$ and $q_i = \mathrm{n2} = \mathrm{q1.q2}$ and the two equivalent product of matrices $R_{21} = R_2 R_1$ and $R_i = R_1 R_2$.

IV. Important Notes: What about Translations?

We must recall that rotations act on translations, the reverse being not true; in fact when multiplying by blocks:

For a rotation followed by a translation: $\begin{pmatrix} I & t \\ 0 & 1 \end{pmatrix}\begin{pmatrix} R & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}$; the rotation is not affected by the translation.

While for a translation followed by a rotation: $\begin{pmatrix} R & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} I & t \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R & Rt \\ 0 & 1 \end{pmatrix}$; the translation is affected by the rotation.

When translations are performed first we can thus assume that the translation vector of the resulting matrix product; *Rt* acts as the translation vector *t* of a rotation followed by a translation .Or more generally speaking considering two six degree of freedom general rigid body transformations T_1 followed by T_2 we will have:

$$T_2 .T_1 = \begin{pmatrix} R_2 & t_2 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} R_1 & t_1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R_2R_1 & R_2t_1 + t_2 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}$$

The translation vector *t* of the product of the two transformations is $\begin{Bmatrix} t \\ 1 \end{Bmatrix} = R_2t_1 + t_2 = \begin{pmatrix} R_2 & 0 \\ 0 & 1 \end{pmatrix}\begin{Bmatrix} t_1 \\ 1 \end{Bmatrix} + \begin{Bmatrix} t_2 \\ 1 \end{Bmatrix}$

The same analysis as the last one could then be done whatever the order and the number of the successive transformations being performed over the rigid body: The final result of the products of all the undertaken rigid body transformations will be finally the helicoidal, the helical or the screw motion given by the (4x4) matrix:

$$[T] = T_n \ldots T_i \ldots T_2 .T_1 = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} \tag{3}$$

With T_i representing either a rotation, a translation, a rotation followed by a translation, a translation followed by a rotation or even simply a no movement (ie: the 4x4 identity matrix I).

V. Screw Motion

Any screw motion would be given by the following (4x4) matrix [*T*]:

$$\begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} I & u \\ 0 & 1 \end{pmatrix}\begin{pmatrix} R(\theta,n) & \frac{\theta\, p}{2\pi}n \\ 0 & 1 \end{pmatrix}\begin{pmatrix} I & -u \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R(\theta,n) & \frac{\theta\, p}{2\pi}n + (I - R(\theta,n)u \\ 0 & 1 \end{pmatrix} = [T] \tag{3}$$

The middle matrix is a screw about a line through the origin; that is, a rotation of $\boldsymbol{\theta}$ radians around the axis *n* followed by a translation along *n.* The outer matrices conjugate the screw and serve to place the line at an arbitrary position in space. The parameter p is the pitch of the screw, it gives the distance advanced along the axis for every complete turn, exactly like the pitch on the thread of an ordinary nut or bolt. When the pitch is zero the screw is a pure rotation, positive pitches correspond to right hand threads and negative pitches to left handed threads.

To show that a general rigid motion is a screw motion, we must show how to put a general transformation into the form derived above. The unit vector in the direction of the line *n* is easy since it must be the eigenvector of the rotation matrix corresponding to the unit eigenvalue.(This fails if $R = I$, that is if the motion is a pure translation). The vector *u* is more difficult to find since it is the position vector of any point on the rotation axis. However we can uniquely specify *u* by requiring that it is normal to the rotation axis. So we impose the extra restriction that $n.u = 0$. So to put the general matrix $\begin{pmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0} & \boldsymbol{1} \end{pmatrix}$ into the above form we must solve the following system of linear equations:

$$\frac{\boldsymbol{\theta}\,\mathbf{p}}{\boldsymbol{2\pi}}\boldsymbol{n} + (\boldsymbol{I} - \boldsymbol{R})\boldsymbol{u} = t$$

Now $n.Ru = n.u = 0$, since the rotation is about n. So we can dot the above equation with n to give: $0 = n.(t - \frac{\boldsymbol{\theta}\,\mathbf{p}}{\boldsymbol{2\pi}})$ this enables us to find the pitch: $\mathrm{p} = \frac{\boldsymbol{2\pi}}{\boldsymbol{\theta}}\boldsymbol{n}.t$

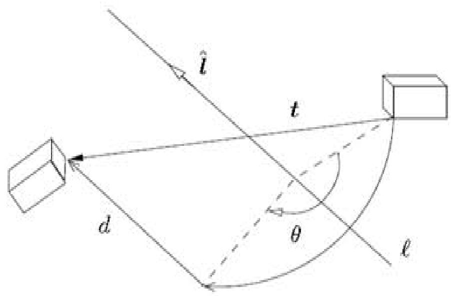
All we need to do now is to solve the equation system: $(\boldsymbol{I} - \boldsymbol{R})\boldsymbol{u} = (t - (\boldsymbol{n}.t)\,\boldsymbol{n})$;

This is possible even though $\det(\boldsymbol{I} - \boldsymbol{R}) = 0$, since the equations will be consistent.

This entire analysis established through this long paragraph concerning the helicoidal motion or rigid (4x4) transformation matrix [T] is contained in only one line enclosed in its counterpart dual quaternion $\widehat{\boldsymbol{T}}$ of the form:

$\hat{T} = \left\{\cos\frac{\hat{\theta}}{2}, \sin\frac{\hat{\theta}}{2}\hat{w}\right\} = \hat{T}_n..\hat{T}_i..\hat{T}_2.\hat{T}_1 = \left\{\cos\frac{\theta}{2}, \sin\frac{\theta}{2}.n\right\} + \varepsilon\left\{-\frac{d}{2}\sin\frac{\theta}{2}, \left\{\mathrm{m}\sin\frac{\theta}{2} + \frac{d}{2}.n\cos\frac{\theta}{2}\right\}\right\}$ or eq (2) $\equiv$ eq (3)

These equations are best represented by the figures (2,1) or/and (2,2) :



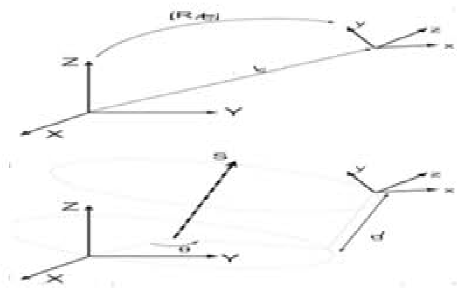


Figure: (2, 1): A semi cubic solid performing simultaneously a rotation θ around the axis $\hat{\imath}$ and a displacement d along the same axis.

Figure: (2, 2): The same rigid (4D) transformation (R,t) represented by its screw axis S and displacement d.

VI. Example 2: General Movement or a Screw Motion

Let's apply two successive screw motions to a rigid body: the first one around the Oy axis of amplitude $\boldsymbol{\theta_1} = \frac{\boldsymbol{\pi}}{\mathbf{2}}$ and of pitch (p $= \frac{\mathbf{2\pi}}{\boldsymbol{\theta}}$ t $=$ 4) followed by a second one around the axis Ox and of the same amplitude $\boldsymbol{\theta_2} = \frac{\boldsymbol{\pi}}{\mathbf{2}}$ and same pitch p = 4 corresponding to a translation of 1 unit along any of the two chosen axes:

$$\mathrm{T}_2.\mathrm{T}_1 = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{4}$$

The rotation part of the product corresponds to that of the precedent example of successive rotations $R_i = R_1\,R_2$ with amplitude $\theta = \frac{2\pi}{3} =$ 120 ° around the unit axis n $= \frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases}$; its translation part being $t = \begin{cases}1\\0\\1\end{cases}$

We can find its pitch p $= \frac{2\pi}{\theta}(\mathrm{n}.t) = \frac{2\pi}{\frac{2\pi}{3}}\frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases}.\begin{cases}1\\0\\1\end{cases} = \frac{6}{\sqrt{3}} = 2\sqrt{3}$

The axis of rotation will keep its same original direction n $= \frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases}$, it will go through a new centre C given by the shifting vector u which could be found by the linear equations system : $(I - R)\,\mathrm{u} = t - \frac{\boldsymbol{\theta}\,\mathbf{p}}{\mathbf{2\pi}}\,\mathrm{n}$

$$\begin{pmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{pmatrix}\begin{Bmatrix} u_x \\ u_y \\ u_z \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0 \\ 1 \end{Bmatrix} - \frac{2\pi}{3.2\pi}\frac{6}{\sqrt{3}}\begin{Bmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0 \\ 1 \end{Bmatrix} - \frac{2}{\sqrt{3}}\begin{Bmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \end{Bmatrix} = \begin{Bmatrix} \frac{1}{3} \\ -\frac{2}{3} \\ \frac{1}{3} \end{Bmatrix}$$

The vector translation T (or t) of the movement $\begin{cases}1\\0\\1\end{cases}$ is the sum of the two main perpendicular vectors $\mathrm{T}_1 + \mathrm{T}_2$ such as T_1 is to be chosen parallel to n while the rest T_2 is the translation vector part responsible for the shifting of the axis to its final position through the new center C as such we have:

$\mathrm{T}_1 = \begin{cases}\mathbf{\frac{2}{3}}\\\mathbf{\frac{2}{3}}\\\mathbf{\frac{2}{3}}\end{cases}$ and $\mathrm{T}_2 = \begin{cases}\mathbf{\frac{1}{3}}\\-\mathbf{\frac{2}{3}}\\\mathbf{\frac{1}{3}}\end{cases}$; T_1 being the translation part parallel to n while T_2 being the perpendicular part with n.

The solutions to the system of linear equations are: $\boldsymbol{u_x} - \boldsymbol{u_z} = \frac{1}{3}$; $-\boldsymbol{u_x} + \boldsymbol{u_y} = -\frac{2}{3}$; and $-\boldsymbol{u_y} + \boldsymbol{u_z} = \frac{1}{3}$ (5)
Choosing the centre C to belong to the plane (y-z); $\boldsymbol{u_x} = 0$ or ($C_x = 0$) would imply the two coordinates representing the point C intersection of the shifted axis n with the (y-z) plane to be:

$$C_y = -\frac{2}{3} \quad \text{and} \quad C_z = -\frac{1}{3}.$$

For the (z-x) plane ; $\boldsymbol{u_y} = 0$ or ($C_y = 0$) : $C_z = \frac{1}{3}$ and $C_x = \frac{2}{3}$.
And finally considering the (x-y) plane ; $\boldsymbol{u_z} = 0$ or ($C_z = 0$): $C_x = \frac{1}{3}$ and $C_y = -\frac{1}{3}$
So that to confirm these results ; we can finally check the following conjugation matrices :

$$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & \frac{-2}{3} \\ 0 & 1 & 0 & \frac{-1}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & \frac{2}{3} \\ 1 & 0 & 0 & \frac{2}{3} \\ 0 & 1 & 0 & \frac{2}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & \frac{2}{3} \\ 0 & 1 & 0 & \frac{1}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \equiv (4) \quad \text{Or,}$$

$$\begin{pmatrix} 0 & 0 & 1 & \frac{2}{3} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & \frac{1}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & \frac{2}{3} \\ 1 & 0 & 0 & \frac{2}{3} \\ 0 & 1 & 0 & \frac{2}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & \frac{-2}{3} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & \frac{-1}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \equiv (4)$$

Or finally; $$\begin{pmatrix} 0 & 0 & 1 & \frac{1}{3} \\ 1 & 0 & 0 & \frac{-1}{3} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & \frac{2}{3} \\ 1 & 0 & 0 & \frac{2}{3} \\ 0 & 1 & 0 & \frac{2}{3} \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & 0 & 1 & \frac{-1}{3} \\ 1 & 0 & 0 & \frac{1}{3} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \equiv (4)$$

Whenever necessary, Matlab was, throughout the chapter implemented, concerning all kinds of products or multiplication of quaternions or matrices.

VII. The Same General Example using Dual Quaternions

$$\hat{q} = q + \varepsilon q_\varepsilon = q_R + \frac{\varepsilon}{2}(t_x i + t_y j + t_z k) \otimes q_R = R + \varepsilon\frac{TR}{2}$$

The two transformations T_1 and T_2 are basic centered helicoidal movements through the origin O of the axes, that can be written:

For the first movement around and along Oy: $\hat{q}_1 = q_1 + \frac{\varepsilon}{2} q_{\varepsilon_1} = \hat{q}_y =$ (c , 0 , s , 0) $+ \frac{\varepsilon}{2}(-\text{s}t_y , 0 , \text{c}\, t_y , 0) =$ $(\cos\frac{\pi}{4} , 0 , \sin\frac{\pi}{4}, 0) + \frac{\varepsilon}{2}(-\sin\frac{\pi}{4}.1 , 0 , \cos\frac{\pi}{4}.1 , 0) = (\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0) + \frac{\varepsilon}{2}(-\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0)$

followed by the second movement around and along Ox: $\hat{q}_2 = q_2 + \frac{\varepsilon}{2} q_{\varepsilon_2} = \hat{q}_z =$ (c , s , 0 , 0) $+ \frac{\varepsilon}{2}(-\text{s}t_z , \text{c}\, t_z , 0 , 0) = (\cos\frac{\pi}{4} , \sin\frac{\pi}{4} , 0, 0) + \frac{\varepsilon}{2}(-\sin\frac{\pi}{4}.1 , \cos\frac{\pi}{4}.1 , 0, 0) = (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 , 0) + \frac{\varepsilon}{2}(-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 , 0)$

The dual quaternion product of the two screw movements is:

$$\hat{q}_2 . \hat{q}_1 = (q_2 + \frac{\varepsilon}{2} q_{\varepsilon_2}).(q_1 + \frac{\varepsilon}{2} q_{\varepsilon_1}) = q_2 . q_1 + \frac{\varepsilon}{2}(q_2 . q_{\varepsilon_1} + q_{\varepsilon_2} . q_1) =$$

$$[(\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0, 0) + \frac{\varepsilon}{2}(-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 .0)]. [(\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0) + \frac{\varepsilon}{2}(-\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0)] =$$

$$(\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 , 0).(\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0) + \frac{\varepsilon}{2}[(\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 , 0).(-\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0) + (-\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0 .0). (\frac{\sqrt{2}}{2}, 0 , \frac{\sqrt{2}}{2}, 0)] =$$

$$(\frac{1}{2}, (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})) + \frac{\varepsilon}{2}[(-\frac{1}{2}, (-\frac{1}{2}, \frac{1}{2} , \frac{1}{2})) + (-\frac{1}{2} , (\frac{1}{2} , -\frac{1}{2} . \frac{1}{2}))] =$$

$$(\frac{1}{2}, \frac{\sqrt{3}}{2}(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}})) + \frac{\varepsilon}{2} (-1, (0 , 0 , 1)) \tag{6}$$

Another way of doing it: We could get this same result starting from the (4x4) rigid transformation eq(4) matrix defined before: A rotation of amplitude $\theta = \frac{2\pi}{3} =$ 120 ° around the unit axis n = $\frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases}$ followed by a translation $t = \begin{cases}1\\0\\1\end{cases}$ such that : $\hat{q} = q + \varepsilon q_\varepsilon = q_R + \frac{\varepsilon}{2}(t_x i + t_y j + t_z k) \otimes q_R = R + \varepsilon \frac{TR}{2} =$

$$\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)\right) + \frac{\varepsilon}{2}\left[(0, 1, 0, 1)\left(\frac{1}{2}, \left(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}\right)\right)\right] =$$

$$\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)\right) + \frac{\varepsilon}{2}\left[(-1, (0, 0, 0)) + \left(0, \left(\frac{1}{2}, 0, \frac{1}{2}\right)\right) + \left(0, \left(-\frac{1}{2}, 0, \frac{1}{2}\right)\right)\right] =$$

$$\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)\right) + \frac{\varepsilon}{2}\left(-1, (0, 0, 1)\right) \tag{6}$$

At this stage we know the complete integrality of informations concerning this movement thanks to our magic, rapid and powerful dual quaternion :The rotation part, as seen before, having amplitude $\theta = \frac{2\pi}{3} =$ 120 ° around the unit axis n; n = $\frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases}$; the dual part will provide us gratefully with the translation along the axis of rotation; using eq (2): $\varepsilon\left\{-\frac{d}{2}\sin\frac{\theta}{2}, \left\{m\sin\frac{\theta}{2} + \frac{d}{2}n\cos\frac{\theta}{2}\right\}\right\} = \frac{\varepsilon}{2}(-1, (0, 0, 1)) = \varepsilon\left(-\frac{1}{2}, \left(0, 0, \frac{1}{2}\right)\right)$

We thus have the scalar part: $-\frac{d}{2}\sin\frac{\theta}{2} = -\frac{d}{2}\frac{\sqrt{3}}{2} = -\frac{1}{2}$ implying that $d = \frac{2}{\sqrt{3}} = \frac{2\sqrt{3}}{3}$ and pitch $p = 2\sqrt{3}$

We can also have the vector part: $\left\{m\sin\frac{\theta}{2} + \frac{d}{2}n\cos\frac{\theta}{2}\right\} = \left(0, 0, \frac{1}{2}\right)$ which implies:

$m_x \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{3}\frac{1}{\sqrt{3}}\frac{1}{2} = m_x \frac{\sqrt{3}}{2} + \frac{1}{6} = 0$; $m_y \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{3}\frac{1}{\sqrt{3}}\frac{1}{2} = m_y \frac{\sqrt{3}}{2} + \frac{1}{6} = 0$ and $m_z \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{3}\frac{1}{\sqrt{3}}\frac{1}{2} = m_z \frac{\sqrt{3}}{2} + \frac{1}{6} = \frac{1}{2}$

We can then deduce the vector moment $m = \begin{cases}\frac{-1}{3\sqrt{3}}\\ \frac{-1}{3\sqrt{3}}\\ \frac{2}{3\sqrt{3}}\end{cases}$

Finally we can have the right position of the shifted axis u that have the same direction as the rotation axis n by defining the coordinates u_x ,u_y and u_z of a point or a center C belonging to it so that: $m = u \wedge n$

Or $\begin{cases}\frac{-1}{3\sqrt{3}}\\ \frac{-1}{3\sqrt{3}}\\ \frac{2}{3\sqrt{3}}\end{cases} = \begin{cases}u_x\\u_y\\u_z\end{cases} \wedge \frac{1}{\sqrt{3}}\begin{cases}1\\1\\1\end{cases} = \frac{1}{\sqrt{3}}\begin{cases}u_y - u_z\\u_z - u_x\\u_x - u_y\end{cases}$ implying that: $u_y - u_z = \frac{-1}{3}$; $u_z - u_x = \frac{-1}{3}$ and $u_x - u_y = \frac{2}{3}$

Which confirm the same obtained results eq (5) using the (4x4) rigid transformation matrix:

$$u_x - u_z = \frac{1}{3}; \quad -u_x + u_y = -\frac{2}{3}; \quad \text{and} \quad -u_y + u_z = \frac{1}{3} \tag{5}$$

VIII. Application 2: Kinematics of the Puma 560 Robot

The first three joints of this manipulator (Waist, Shoulder, Elbow) characterize for the first joint to be a rotation about a vertical axis , for the second and the third rotations about horizontal axes whose movements are identified by the variables q_1 , q_2, and q_3. The last three joints, which constitute the wrist of the robot arm, are characterized by the rotations q_4 , q_5, and q_6 whose axes intersect at the center of the wrist (See appendix 10,3. Figures (3),(4) and Table 1 for the forward kinematic solution using the Denavit and Hartenberg convention.

The elegant , most accurate , rapid and finally the best manner to get the forward kinematic solutions of this Puma 560 robot is to use the dual quaternions:

For the sake of comparaison let us choose the same home position for the robot with its geometry (a_i and d_i) given in table (1) and the same absolute home initial frame (x_0 ,y_0 ,z_0) with its origin O taken in link1 at the intersection of the base axis with the link1 axis (see figure (3)), assuming mobile frames at the centers of the six rotations: (x_n ,y_n ,z_n) which axes remain parallel to the

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'home position' or initial axes (x_0 ,y_0 ,z_0). Let us begin, with the first two rotations using either equations A3 or A14 from appendix 10,2,1. to find the new vector position of the center O_3 (a_2 , d_2 , 0):

$$\hat{q}_1\,\hat{q}_2\,\hat{q}_v\,\overline{\hat{q}}_2^*\,\overline{\hat{q}}_1^* = \hat{q}_1\,(\hat{q}_2\,(\hat{q}_v)\,\overline{\hat{q}}_2^*\,)\overline{\hat{q}}_1^* \quad (7)$$

$$\hat{q}_2\,\hat{q}_v\,\overline{\hat{q}}_2^* = (c_2\,,0\,,s_2\,,0)\;[\,1+\varepsilon\,(a_2,d_2,0\,)]\;(c_2\,,0\,,-s_2\,,0)$$

Using correctly the rules for both quaternions eq (A1) and dual quaternions multiplications eq (A7) we have :

$$\hat{q}_2\,\hat{q}_v = (c_2\,,0\,,s_2\,,0) + \varepsilon\,(-s_2\,d_2\,,c_2\,a_2,c_2d_2,-s_2\,a_2\,) \quad \text{and}$$

$$\hat{q}_2\,\hat{q}_v\,\overline{\hat{q}}_2^* = 1+\varepsilon\,(0\,,a_2\cos\theta_2\,,d_2\,,-a_2\sin\theta_2) \quad \text{thus}$$

$$\hat{q}_1\,\hat{q}_2\,\hat{q}_v\,\overline{\hat{q}}_2^*\,\overline{\hat{q}}_1^* = (c_1\,,0\,,0\,,s_1)[\,1+\varepsilon\,(0\,,a_2\cos\theta_2\,,d_2\,,-a_2\sin\theta_2)]\;(c_1\,,0\,,0\,,-s_1)$$

Performing the product and using the trigonometric properties we can have the new quaternion vector position:

$$1+\varepsilon\,(0\,,a_2\cos\theta_2\cos\theta_1 - d_2\sin\theta_1,\,a_2\cos\theta_2\sin\theta_1 + d_2\cos\theta_1,-a_2\sin\theta_2\,)$$

or the three coordinates vector: $\begin{cases} a_2\cos\theta_2\cos\theta_1 - d_2\sin\theta_1 \\ a_2\cos\theta_2\sin\theta_1 + d_2\cos\theta_1 \\ -a_2\sin\theta_2 \end{cases}$ (8)

This result is confirmed (see appendix 10,3,2.) by the fourth or last column of the matrix T_0^2 :

$$= T_0^1 T_1^2 = R_1\,R_2 = \begin{pmatrix} c_1 & 0 - s_1 & 0 \\ s_1 & 0 \quad c_1 & 0 \\ 0 & -1 \quad 0 & 0 \\ 0 & 0 \quad 0 & 1 \end{pmatrix}\begin{pmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_1c_2 & -c_1s_2 & -s_1 & a_2c_1c_2 - d_2s_1 \\ s_1c_2 & -s_1s_2 & c_1 & a_2c_2s_1 + d_2c_1 \\ -s_2 & -c_2 & 0 & -a_2s_2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The third rotation of the third link is around the axis O_3y_3 , with the center O_3 being displaced or shifted and thus having the position coordinates with respect to the asolute frame O_3 (a_2, d_2, 0).

Note: The conjugation (TRT^{-1}) technique could be used in its dual quaternion form or its (4x4) rigid transformation form.

The dual quaternion ($\hat{q}$) definition (2) may be used instead;

$$\hat{q} = \hat{T} = \left\{\cos\frac{\hat{\theta}}{2},\ \sin\frac{\hat{\theta}}{2}\hat{w}\right\} = \left\{\cos\frac{\theta}{2},\sin\frac{\theta}{2}n\right\} + \varepsilon\left\{-\frac{d}{2}\sin\frac{\theta}{2}\,,\left\{\mathrm{m}\sin\frac{\theta}{2} + \frac{d}{2}n\cos\frac{\theta}{2}\right\}\right\} \quad << dual\ type >> \quad (2)$$

So replacing $d = 0$ in eq (2), will give: $\hat{q}_3 = \left\{\cos\frac{\hat{\theta}}{2},\ \sin\frac{\hat{\theta}}{2}\hat{w}\right\} = [c_3,(0,s_3,0)] + \varepsilon\{0\,,\{\mathrm{m}\,s_3\}\}$

The moment m, w- r - t the axis of rotation y_3 , is $\mathrm{m} = \begin{cases} a_2 \\ d_2 \\ 0 \end{cases} \wedge \begin{cases} 0 \\ 1 \\ 0 \end{cases} = \begin{cases} 0 \\ 0 \\ a_2 \end{cases}$ so that $\hat{q}_3 = [c_3,(0,s_3,0)] + \varepsilon\{0,\{(0,0,a_2s_3\}\}$

$$(\hat{q}_1\,\hat{q}_2\,)\hat{q}_3\,\hat{q}_v\,\overline{\hat{q}}_3^*\;(\overline{\hat{q}}_2^*\,\overline{\hat{q}}_1^*) = (c_1,0,0,s_1)\,(c_2,0,s_2,0)\,\hat{q}_3\,\hat{q}_v\,\overline{\hat{q}}_3^*\,(c_2\,,0\,,-s_2\,,0)\;(c_1\,,0\,,\;0,-s_1)$$

To find the new vector position of the wrist center O_4 :($a_2 + a_3$, $d_2 + d_3$, 0) = (A, D, 0) result of the three successives rotations we must start from the central operation namely :

$$\hat{q}_{\,v3} = \hat{q}_3\,\hat{q}_v\,\overline{\hat{q}}_3^* = [(c_3,0,s_3,0\,) + \boldsymbol{\varepsilon}\,(\,0,0,a_2s_3)]\;[(1+\boldsymbol{\varepsilon}\,(\,\mathrm{A},\mathrm{D},0))]\;[\,\overline{\hat{q}}_3^*\,] =$$

$$[(c_3,0,s_3,0\,) + \boldsymbol{\varepsilon}(\,0,0,a_2s_3) + \varepsilon(-s_3\mathrm{D},\,c_3\mathrm{A}\,,\,c_3\mathrm{D},-s_3\mathrm{A})]\;[\,\overline{\hat{q}}_3^*\,] =$$

$$[(c_3,0,s_3,0 + \varepsilon(-s_3\mathrm{D},\,c_3\mathrm{A}\,,\,c_3\mathrm{D}\;,\,s_3(-\mathrm{A})]\;[(c_3,0,-s_3,0\,) + \boldsymbol{\varepsilon}\,(\,0,0,a_2s_3)] =$$

$$(c_3{}^2 + s_3{}^2,\,0,\,-c_3s_3 + c_3s_3\;,\,0) + \varepsilon(-c_3s_3\mathrm{D} + s_3c_3\mathrm{D}\;,\,s_3{}^2a_2 + c_3{}^2\mathrm{A} + s_3{}^2\,(a_2 - \mathrm{A}),\,s_3{}^2\mathrm{D} + c_3{}^2\mathrm{D}\;,\,c_3s_3a_2 - c_3s_3\,\mathrm{A} + a_2c_3s_3 - c_3s_3\,\mathrm{A}\,)$$

Using the basic trigonometric rules and properties we can write the solution vector:

$$\hat{q}_{\,v3} = \hat{q}_3\,\hat{q}_v\,\overline{\hat{q}}_3^* = 1+\varepsilon\,(0\,,a_2 + a_3\cos\theta_3\,,d_2 + d_3\,,-a_3\sin\theta_3\,) = 1+\varepsilon\,(a_2 + a_3\cos\theta_3\,,d_2 + d_3\,,-a_3\sin\theta_3\,)$$

For a better use of space we may adopt to write our result dual quaternions vectors under the form: $\begin{cases}\text{scalar part}\\ O_x \text{ coord.}\\ O_y \text{ coord.}\\ O_z \text{ coord.}\end{cases}$

So that the precedent result could be written $\hat{q}_{v3} = \begin{pmatrix} 0 \\ a_2 + a_3\cos\theta_3 \\ d_2 + d_3 \\ -a_3\sin\theta_3 \end{pmatrix}$ or simply as a vector $\begin{pmatrix} a_2 + a_3\cos\theta_3 \\ d_2 + d_3 \\ -a_3\sin\theta_3 \end{pmatrix}$

Following the second transformation we have: $(c_2, 0, s_2, 0)\,\hat{q}_{v3}(c_2, 0, -s_2, 0) =$

$$\hat{q}_{v2} = (c_2, 0, s_2, 0)[\,1 + \varepsilon\,(0, a_2 + a_3\cos\theta_3, d_2 + d_3, -a_3\sin\theta_3)\,](c_2, 0, -s_2, 0) =$$

$$(c_2, 0, s_2, 0)\left[1 + \varepsilon\begin{pmatrix} 0 \\ a_2 + a_3\cos\theta_3 \\ d_2 + d_3 \\ -a_3\sin\theta_3 \end{pmatrix}\right][\,\bar{\hat{q}}_2^*\,] =$$

$$\left[(c_2, 0, s_2, 0) + \varepsilon\begin{pmatrix} -s_2(d_2 + d_3) \\ c_2(a_2 + a_3\cos\theta_3) - s_2 a_3\sin\theta_3 \\ c_2(d_2 + d_3) \\ -c_2 a_3\sin\theta_3 - s_2(a_2 + a_3\cos\theta_3) \end{pmatrix}\right](c_2, 0, -s_2, 0) =$$

$$({c_2}^2 + {s_2}^2, 0, -c_2 s_2 + c_2 s_2, 0) + \varepsilon\begin{pmatrix} -c_2 s_2(d_2 + d_3) + c_2 s_2(d_2 + d_3) \\ {c_2}^2(a_2 + a_3\cos\theta_3) - c_2 s_2 a_3\sin\theta_3 - c_2 s_2 a_3\sin\theta_3 - {s_2}^2(a_2 + a_3\cos\theta_3) \\ {c_2}^2(d_2 + d_3) + {s_2}^2(d_2 + d_3) \\ -{c_2}^2 a_3\sin\theta_3 - c_2 s_2(a_2 + a_3\cos\theta_3) - c_2 s_2(a_2 + a_3\cos\theta_3) + {s_2}^2 a_3\sin\theta_3 \end{pmatrix} =$$

$$1 + \varepsilon\begin{pmatrix} 0 \\ {c_2}^2(a_2 + a_3\cos\theta_3) - c_2 s_2 a_3\sin\theta_3 - c_2 s_2 a_3\sin\theta_3 - {s_2}^2(a_2 + a_3\cos\theta_3) \\ {c_2}^2(d_2 + d_3) + {s_2}^2(d_2 + d_3) \\ -{c_2}^2 a_3\sin\theta_3 - c_2 s_2(a_2 + a_3\cos\theta_3) - c_2 s_2(a_2 + a_3\cos\theta_3) + {s_2}^2 a_3\sin\theta_3 \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ \cos\theta_2(a_2 + a_3\cos\theta_3) - a_3\sin\theta_2\sin\theta_3 \\ (d_2 + d_3) \\ -a_3\cos\theta_2\sin\theta_3 - \sin\theta_2(a_2 + a_3\cos\theta_3) \end{pmatrix} =$$

We can finally get the transformed vector $\hat{q}_{v2}$:

$$\hat{q}_{v2} = 1 + \varepsilon\,[(a_3\cos(\theta_2 + \theta_3) + a_2\cos\theta_2,\ (d_2 + d_3),\ -a_3\sin(\theta_2 + \theta_3) - a_2\sin\theta_2)]$$

We can finally perform the first but last transformation given by the following dual quaternions products:

$$(c_1, 0, 0, s_1)\,(c_2, 0, s_2, 0)\,\hat{q}_3\,\hat{q}_v\,\bar{\hat{q}}_3^*\,(c_2, 0, -s_2, 0)(c_1, 0, 0, -s_1) =$$

$$(c_1, 0, 0, s_1)\,\hat{q}_{v2}\,(c_1, 0, 0, -s_1) =$$

$$(c_1, 0, 0, s_1)\,[1 + \varepsilon\,(a_3\cos(\theta_2 + \theta_3) + a_2\cos\theta_2,\ (d_2 + d_3),\ -a_3\sin(\theta_2 + \theta_3) - a_2\sin\theta_2)]\,\bar{\hat{q}}_1^*$$

$$(c_1, 0, 0, s_1)\left[1 + \varepsilon\begin{pmatrix} 0 \\ a_3\cos(\theta_2 + \theta_3) + a_2\cos\theta_2 \\ d_2 + d_3 \\ -a_3\sin(\theta_2 + \theta_3) - a_2\sin\theta_2 \end{pmatrix}\right][\,\bar{\hat{q}}_1^*\,] =$$

$$\left[(c_1, 0, 0, s_1) + \varepsilon\begin{pmatrix} a_3 s_1\sin(\theta_2 + \theta_3) + a_2 s_1\sin\theta_2 \\ a_3 c_1\cos(\theta_2 + \theta_3) + a_2 c_1\cos\theta_2 - s_1(d_2 + d_3) \\ c_1(d_2 + d_3) + a_3 s_1\cos(\theta_2 + \theta_3) + a_2 s_1\cos\theta_2 \\ -a_3 c_1\sin(\theta_2 + \theta_3) - a_2 c_1\sin\theta_2) \end{pmatrix}\right][\,\bar{\hat{q}}_1^*\,] =$$

$$\left[(c_1\,, 0\,, \quad 0, s_1) + \varepsilon \begin{pmatrix} a_3\, s_1 \sin(\theta_2+\theta_3) + a_2 s_1 \sin\theta_2 \\ a_3\, c_1 \cos(\theta_2+\theta_3) + a_2 c_1 \cos\theta_2 - s_1(d_2+d_3) \\ c_1(d_2+d_3) + a_3\, s_1 \cos(\theta_2+\theta_3) + a_2 s_1 \cos\theta_2 \\ -a_3 c_1 \sin(\theta_2+\theta_3) - a_2 c_1 \sin\theta_2 \end{pmatrix}\right](c_1\,, 0\,,\ 0, -s_1) =$$

$$(c_1{}^2 + s_1{}^2, 0, -c_1 s_1 + c_1 s_1, 0) +$$

$$\varepsilon \begin{pmatrix} a_3\, c_1 s_1 \sin(\theta_2+\theta_3) + a_2 c_1 s_1 \sin\theta_2 - a_3 c_1\, s_1 \sin(\theta_2+\theta_3) - a_2 c_1\, s_1 \sin\theta_2 \\ a_3\, c_1{}^2 \cos(\theta_2+\theta_3) + a_2 c_1{}^2 \cos\theta_2 - c_1 s_1(d_2+d_3) - s_1 c_1(d_2+d_3) - a_3\, s_1{}^2 \cos(\theta_2+\theta_3) - a_2 s_1{}^2 \cos\theta_2 \\ c_1{}^2(d_2+d_3) + a_3\, c_1 s_1 \cos(\theta_2+\theta_3) + a_2 c_1 s_1 \cos\theta_2 + a_3\, s_1 c_1 \cos(\theta_2+\theta_3) + a_2 s_1 c_1 \cos\theta_2 - s_1{}^2(d_2+d_3) \\ -a_3 c_1{}^2 \sin(\theta_2+\theta_3) - a_2 c_1{}^2 \sin\theta_2 - a_3\, s_1{}^2 \sin(\theta_2+\theta_3) - a_2\, s_1{}^2 \sin\theta_2 \end{pmatrix} =$$

$$1 + \varepsilon \begin{pmatrix} 0 \\ a_3\, c_1{}^2 c_{23} + a_2 c_1{}^2 \cos\theta_2 - c_1 s_1(d_2+d_3) - s_1 c_1(d_2+d_3) - a_3\, s_1{}^2 c_{23} - a_2 s_1{}^2 \cos\theta_2 \\ c_1{}^2(d_2+d_3) + a_3\, c_1 s_1 c_{23} + a_2 c_1 s_1 \cos\theta_2 + a_3\, s_1 c_1 c_{23} + a_2 s_1 c_1 \cos\theta_2 - s_1{}^2(d_2+d_3) \\ -a_3 c_1{}^2 s_{23} - a_2 c_1{}^2 \sin\theta_2 - a_3\, s_1{}^2 s_{23} - a_2\, s_1{}^2 \sin\theta_2 \end{pmatrix}$$

With $c_{23} = \cos(\theta_2+\theta_3)$ and $s_{23} = \sin(\theta_2+\theta_3)$

The result vector is then:

$$\begin{pmatrix} \cos\theta_1\,(a_2\cos\theta_2 + a_3\, c_{23}) - \sin\theta_1(d_2+d_3) \\ \sin\theta_1(a_2\cos\theta_2 + a_3\, c_{23}) + \cos\theta_1((d_2+d_3) \\ -(a_2\sin\theta_2 + a_3\ \ s_{23}) \end{pmatrix}$$

Which is confirmed by the last column (see appendix (10, 3, 2.) of the matrix T_0^3 .

We can also, using the Denavit and Hartenberg formalism or the dual quaternions alike easily calculate the coordinates of the terminal element (or the end effector) and so the final positioning of our Puma 560 robot relative to the base or fixed absolute frame.

IX. Conclusion

We hope that the reader should not get us wrong: We never pretend that the D-H parameters method is wrong or obsolete and that it should be a thing of the past; recognising that this important classical method was the precursor that enlightened the path to modern robotics; we only say that there exist through the DQ parameters another short, free of singularities and easy to work with, when dealing with robot direct kinematics. On the light of the obtained results one has to say that the most perfect (not suffering singularities of any kind), easiest and rapid way to perform a 3D rigid transformation of any sort is to use the dual quaternion that caracterise that movement. Most of all we are free to use the 3D space, being sure that no loss of degree of freedom or guinball lock of any sort can never happen. Using a D-H parameters method or any of its counterparts means a choice of different sort of embarassing and somehow awkward three axes frames to be created and then allocated to each arm/ link; ‘providing’ our robot or mecanism with different direction axes and angles with very much complicated choice of signs (concerning the directions and the angles alike) to be chosen subject to some rules depending on the chosen method and model of robot.

Choosing to use dual quaternions we only need to know the constants or values that concern the construction or space geometry of the given robot (directions (orientations and axes) , rotations ,distances, lengths of links) to evaluate its kinematics without any threat to be lost in the maze or a jungle of choices .Most of all, it will prevent us from using the only other existing method, or one of its options, which is that of the Denavit and Hartenberg parameters that mainly consists of:

1. Choosing 3D frames attached to each link upon certain conditions /conventions,
2. Schematic of the numbering of bodies and joints in a robotic manipulator, following the convention for attaching reference frames to the bodies, this will help to create:
3. A table for exact definition of the four parameters, a_i, α_i, d_i, and θ_i, that locate one frame relative to another,
4. The (4x4) rigid transformation matrix that will have the given form : $\boldsymbol{T_{i\_1}^{i}}$. (See 10,3.)

This chapter provided a taste of the potential advantages of dual-quaternions, and one can only imagine the further future possibilities that they can offer. For example, there is a deeper investigation of the mathematical properties of dual-quaternions (e.g., zero divisions). There is also the concept of dual-dual-quaternions (i.e., dual numbers within dual numbers) and calculus for multi-parametric objects for the reader to pursue if he desires.

We should emphasize on the fact that Matlab software was used, throughout this work and whenever necessary, concerning all kinds of products or multiplication of quaternions or rigid transformation matrices.

Finally we hope all efforts should be conjugated to create a common 'PROJECT MATLAB QUATERNION/MATRIX platform' to be used for the straightforward calculations and manipulation of Quaternions and / or Dual Quaternions as well as conversions from or into 3D or 4D rigid body matrices.

X. Appendices

a) Quaternion-Matlab Implementation Class:

>> % See paragraph 3; Example 1: Rotations represented by Quaternions

>> % A first rotation of angle $\pi/2$ around the x -axis ,q1 , followed by a rotation of angle $\pi/2$ around the y -axis , q2 will result in a rotation given by the product n1 = q2.q1 :

```
>> q1 =[ cos(pi/4) sin(pi/4) 0 0 ];

q2 =[cos(pi/4) 0 sin(pi/4) 0 ];

>> n1 = quatmultiply (q2,q1)

n1 = 0.5000    0.5000    0.5000   -0.5000
```

>> % If the order is inversed the result will be given by the quaternion n2 = q1.q2

```
>> n2 = quatmultiply (q1,q2)

n2 = 0.5000    0.5000    0.5000    0.5000
```

>> % Using 3*3 matrices; if the rotation R1 is performed first the rotation product is R2*R1:

```
R1 = [1 0 0;0 0 -1;0 1 0 ];

R2 = [ 0 0 1; 0 1 0;-1 0 0];

prod1 = R2*R1

prod1 =

     0     1     0
     0     0    -1
    -1     0     0
```

>> % if the order is inversed the multiplication will be R1*R2:

```
prod2 = R1*R2

prod2 =

     0     0     1
     1     0     0
     0     1     0
```

b) Quaternions and Dual Quaternions (Dq)

i. Quaternions or rotation representation

Quaternions were first discovered and described by the Irish mathematician Sir Rowan Hamilton in 1843. Indeed quaternion's representation and axis-angle representation are very similar.

Both are represented by the four dimensional vectors. Quaternions also implicitly represent the rotation of a rigid body about an axis. It also provides better means of key frame interpolation and doesn't suffer from singularity problems.

The definition of a quaternion can be given as (s, m) or (s, q_x, q_y, q_z) where m is a 3D vector, so quaternions are like imaginary (complex) numbers with the real scalar part s and the imaginary vector part m.

Thus it can be also written as: s + $q_x i + q_y j + q_z k$.

There are conversion methods between quaternions, axis-angle and rotation matrix.

Common operations such as addition, inner product etc can be defined over quaternions.

Given the definition of q_1 and q_2 :

$$q_1 = s_1 + q_{x1}\, i + q_{y1}\, j + q_{z1}\, k \ \text{ or } \ q_1 = (s_1, \mathrm{m}_1)$$

$$q_2 = s_2 + q_{x2}\, i + q_{y2}\, j + q_{z2}\, k \ \text{ or } \ q_2 = (s_2, \mathrm{m}_2)$$

Addition operation is defined as:

$$q_1 + q_2 = (s_1 + s_2, \mathrm{m}_1 + \mathrm{m}_2) = (s_1 + s_2) + (q_{x1} + q_{x2})i + (q_{y1} + q_{y2})j + (q_{z1} + q_{z2})k$$

dot (scalar, inner): product operation(.) as:

$$q_1 . q_2 = s_1 . s_2 + \mathrm{m}_1 . \mathrm{m}_2$$

Quaternion multiplication is non commutative, but it is associative.

Multiplication identity element is defined as: (1, (0, 0, 0))

We can also perform the multiplication in the imaginary number domain using the definitions:

$$i^2 = j^2 = k^2 = -1;\ \ i.j = k,\ \ j.k = i,\ \ k.i = j;\ \ j.i = -k,\ \ k.j = -i,\ \ i.k = -j$$

Equations (A1) to (A15) state the definitions, rules and properties of dual quaternion algebra.

Quaternion multiplication (⊗) is defined as:

$$q_1 \otimes q_2 = (s_1 . s_2 - \mathrm{m}_1 . \mathrm{m}_2,\ s_1 . \mathrm{m}_2 + s_2 . \mathrm{m}_1 + \mathrm{m}_1 \wedge \mathrm{m}_2) \tag{A1}$$

Each quaternion has a conjugate q^* (except zero quaternion) defined by:

$$q^* = (s, -\mathrm{m}) \tag{A2}$$

and an inverse $q^{-1} = (\frac{1}{|q|})^2 q^*$; $(q \neq 0)$ Where $|q|^2 = s^2 + q_x{}^2 + q_y{}^2 + q_z{}^2 = q \otimes q^* = q^* \otimes q$

Rotations are defined by unit quaternions. Unit quaternions must satisfy $|q| = 1$. Since multiplication of two unit quaternions will be a unit quaternion, *N* rotations can be combined into one unit quaternion $q_R = q_{R1} . q_{R2} . q_{R3} .... q_{RN}$

It is also possible to rotate a vector directly by using quaternion multiplication. To do this, we must define a 3D vector $V = (v_x, v_y, v_z)$ that we want to rotate in quaternion definition as $q_v = (0, v) = 0 + v_x i + v_y j + v_z k$. The rotated vector $V' = (v_x', v_y', v_z')$ can be defined as $q_{v'} = (0, v') = 0 + v_x' i + v_y' j + v_z' k$

Noting that, in quaternion rotation $q^{-1} = q^*$ (For unit quaternion). So, rotation of q_v by quaternion q can be calculated as:

$$q_{v'} = q \otimes q_v \otimes q^{-1} = q \otimes q_v \otimes q^* \qquad (A3)$$

And, assuming another quaternion rotation p, two rotations can be applied to the vector V such as:

$$q_{v'} = p \otimes (q \otimes q_v \otimes q^{-1}) \otimes p^{-1} = (p \otimes q) \otimes q_v \otimes (q^{-1} \otimes p^{-1}) = C \otimes q_v \otimes C^{-1} \qquad (A4)$$

Providing that quaternion $C = (p \otimes q)$ is a combinaison of the precedent quaternions q and p.

The equation implies that vector V is first rotated by the rotation represented by q followed by the rotation p.

A quaternion q that defines a rotation about (around) the axis n denoted by the unit vector (n_x, n_y, n_z) of an angle θ could be written as :

$$q = \cos\frac{\theta}{2} + \sin\frac{\theta}{2}(n_x i + n_y j + n_z k) \qquad (A5)$$

This same quaternion represents a rotation of amplitude $(-\theta)$ around the opposite axis $(-n)$

ii. *Dual quaternions*

Dual Quaternions (DQ) were proposed by William Kingdom Clifford in 1873.They are an extension of quaternions. They represent both rotations and translations whose composition is defined as a rigid transformation.

They are represented by the following eight dimensional vector:

$$\hat{q} = (\hat{s}, \hat{m}) = (s, q_x, q_y, q_z, q_{\varepsilon_s}, q_{\varepsilon_x}, q_{\varepsilon_y}, q_{\varepsilon_z}) = (\hat{s}, \hat{x}, \hat{y}, \hat{z}) \qquad (A6)$$

Such that: $\hat{q} = q + \varepsilon q_\varepsilon = s + q_x i + q_y j + q_z k + \varepsilon(q_{\varepsilon_s} + q_{\varepsilon_x} + q_{\varepsilon_y} + q_{\varepsilon_z})$

Dual quaternion multiplication is defined by:

$$\hat{q}_1 \otimes \hat{q}_2 = q_1 \otimes q_2 + \varepsilon(q_1 \otimes q_{2_\varepsilon} + q_{1_\varepsilon} \otimes q_2) \qquad (A7)$$

With $\varepsilon^2 = 0$; ε being the second order nilpotent dual factor.
The dual conjugate (analogous to complex conjugate) is denoted by:

$$\bar{\hat{q}} = q - \varepsilon q_\varepsilon \qquad (A8)$$

This conjugate operator can lead to the definition of the inverse of $\hat{q}$ which is:

$\hat{q}^{-1} = \frac{1}{\hat{q}} = \frac{\bar{\hat{q}}}{\bar{\hat{q}}}\frac{1}{\hat{q}} = \frac{1}{q} - \varepsilon\frac{q_\varepsilon}{q^2}$; which means that a pure dual number $(ie{:}\, q = 0)$ does not have an inverse)

$$\hat{q} = = \hat{q} \otimes \hat{q}^{-1} = (q + \varepsilon q_\varepsilon)\left(\frac{1}{q} - \varepsilon\frac{q_\varepsilon}{q^2}\right) = \frac{q}{q} - \varepsilon\frac{q q_\varepsilon}{q^2} + \frac{\varepsilon q_\varepsilon}{q} = \frac{q}{q} - \varepsilon\frac{q_\varepsilon}{q} + \frac{\varepsilon q_\varepsilon}{q} = 1 - 0 = 1$$

A second conjugation operator is defined for DQs. It is the classical quaternion conjugation and is denoted by: $\hat{q}^* = q^* + \varepsilon q_\varepsilon^*$

Combining these two conjugation operators will lead to the formalization of DQ transformation on 3D points. Use of both conjugations on $\hat{q}$ can be denoted $\bar{\hat{q}}^*$.Using definitions (A2), (A6) and (A8) we finally have:

$$\bar{\hat{q}}^* = (s, -q_x, -q_y, -q_z, -q_{\varepsilon_s}, q_{\varepsilon_x}, q_{\varepsilon_y}, q_{\varepsilon_z}) \qquad (A9)$$

It is well know that we can use dual quaternions to represent a general transformation subject to the following constraints:

The DQ screw motion operator $\hat{q}{:} = (q, q_\varepsilon)$ must be of unit magnitude: $|\hat{q}| = (q + \varepsilon q_\varepsilon)^2 = 1$

This requirement means two distinct conditions or constraints:

$$s^2 + q_x^2 + q_y^2 + q_z^2 = 1 \quad \text{and}$$

$$s\, q_{\varepsilon_s} + q_x q_{\varepsilon_x} + q_y q_{\varepsilon_y} + q_z q_{\varepsilon_z} = 0 \qquad (A10)$$

Which imposed on the eight (8) parameters of a general DQ, effectively reduce the number of degree of freedom $(8 - 2) = 6$; equivalent to the degree of freedom of any free rigid body in 3-D space

iii. *Dual Quaternions or general 3D rigid transformation representation*

While equation (A5) defines completely and unambiguously (without any singularity like guimbal lock and other loss of degree of freedom) all 3D rotations in the physical space, dual quaternions can represent translations;

A DQ defined as: $\hat{q}_T = 1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)$ corresponds to the translation vector $\vec{T} = (t_x , t_y , t_z)^t$

which could symbolically be noted *T*; so $\hat{q}_T = 1+\varepsilon \frac{T}{2}$

The translation *T* on the vector $\vec{v}$ can be computed by: $\hat{q}_v' = \hat{q}_T \otimes \hat{q}_v \otimes \bar{\hat{q}}_T^*$

So fortunately using def (A9), we have:

$$\bar{\hat{q}}_T^* = \hat{q}_T = 1+\varepsilon \frac{T}{2}, \text{ then } \hat{q}_v' = \hat{q}_T \otimes \hat{q}_v \otimes \bar{\hat{q}}_T^* = \hat{q}_T \otimes \hat{q}_v \otimes \hat{q}_T = [1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)] \otimes [1+\varepsilon(v_x i + v_y j + v_z k)] \otimes [1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)] =$$

$$1+\varepsilon [(v_x + t_x)i + (v_y + t_y)j + (v_z + t_z)k)]$$

Which correspond to the transformed vector: $\vec{v}' = (v_x + t_x)i + (v_y + t_y)j + (v_z + t_z)k)$

iv. *Combining rotation and translation*

Transformations represented by DQs can be combined into one DQ (similar to quaternions combination Assuming: $\hat{q}$ and then $\hat{p}$, two DQ transformations applied successively and in that order to a DQ position vector $\hat{q}_v$; Their combined DQ transformation $\hat{C}$ applied to $\hat{q}_v$ gives:

$$\hat{q}_v' = \hat{p} \otimes (\hat{q} \otimes \hat{q}_v \otimes \bar{\hat{q}}^*) \otimes \bar{\hat{p}}^* = (\hat{p} \otimes \hat{q}) \otimes \hat{q}_v \otimes (\bar{\hat{q}}^* \otimes \bar{\hat{p}}^*) = \hat{C} \otimes \hat{q}_v \otimes \bar{\hat{C}}^* \quad \text{(A11)}$$

It is very important to notice that the most inner transformation of the equation is applied first with an inside to outside manner.

In eq (22), $\hat{q}$ is the first transformation followed by the second one $\hat{p}$.

The successive composition or combination of unit DQ rotation $\hat{q}_R = R$ followed by a DQ translation $\hat{q}_T = 1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)$ will give:

$$\hat{q}_T \otimes \hat{q}_R = (1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)) \otimes q_R = q_R + \frac{\varepsilon}{2}(t_x i + t_y j + t_z k) \otimes q_R = R + \varepsilon \frac{TR}{2} \quad \text{(A12)}$$

Its inverse being: $(R + \varepsilon \frac{TR}{2})^{-1} = R^* - \frac{R^*T}{2}$

If the translation is applied first:

$$\hat{q}_R \otimes \hat{q}_T = \hat{q}_R \otimes (1+\frac{\varepsilon}{2}(t_x i + t_y j + t_z k)) = q_R + \hat{q}_R \otimes \frac{\varepsilon}{2}(t_x i + t_y j + t_z k) q_R = R + \varepsilon \frac{RT}{2} \quad \text{(A13)}$$

Its inverse being: $(R + \varepsilon \frac{RT}{2})^{-1} = R^* - \frac{TR^*}{2}$

v. *Several transformations*

Suppose that the vector *V* in its dual quaternion form $\hat{q}_v = 1+\varepsilon v$ is under a sequence of rigid transformations represented by the dual quaternions $\hat{q}_1, \hat{q}_2, \ldots, \hat{q}_n$. The resulting vector is encapsulated in the dual quaternion:

$$1+\varepsilon v' = \hat{q}_n \otimes (\hat{q}_{n-1} \otimes \ldots \otimes (\hat{q}_1 \otimes (1+\varepsilon v) \otimes \bar{\hat{q}}^*_1) \otimes \ldots \otimes \bar{\hat{q}}^*_{n-1}) \otimes \bar{\hat{q}}^*_n \quad \text{(A14)}$$

$$= (\hat{q}_n \otimes \ldots \otimes \hat{q}_1) \otimes (1+\varepsilon v) \otimes (\bar{\hat{q}}^*_1 \otimes \ldots \otimes \bar{\hat{q}}^*_n)$$

We denote the product dual quaternion as $\hat{q} = \hat{q}_n \otimes \ldots \otimes \hat{q}_1$. The effect is equivalent to a single rigid transformation represented by $\hat{q}$; namely,

$$1+\varepsilon v' = \hat{q} \otimes (1+\varepsilon v) \otimes \bar{\hat{q}}^*.$$

Using dual numbers and plucker coordinates and introducing the following dual angle and dual vector we can write:

$$\hat{\theta} = \theta + \varepsilon d \quad \text{and}$$

$$\hat{l} = l + \varepsilon m$$

It can be easily shown that:

$$\cos\frac{\theta+\varepsilon d}{2} = \cos\frac{\theta}{2} - \varepsilon\frac{d}{2}\sin\frac{\theta}{2} \quad \text{and}$$

$$\sin\frac{\theta+\varepsilon d}{2} = \sin\frac{\theta}{2} + \varepsilon\frac{d}{2}\cos\frac{\theta}{2} \tag{A15}$$

vi. *D-H Parameters For The Puma 560 Robot*

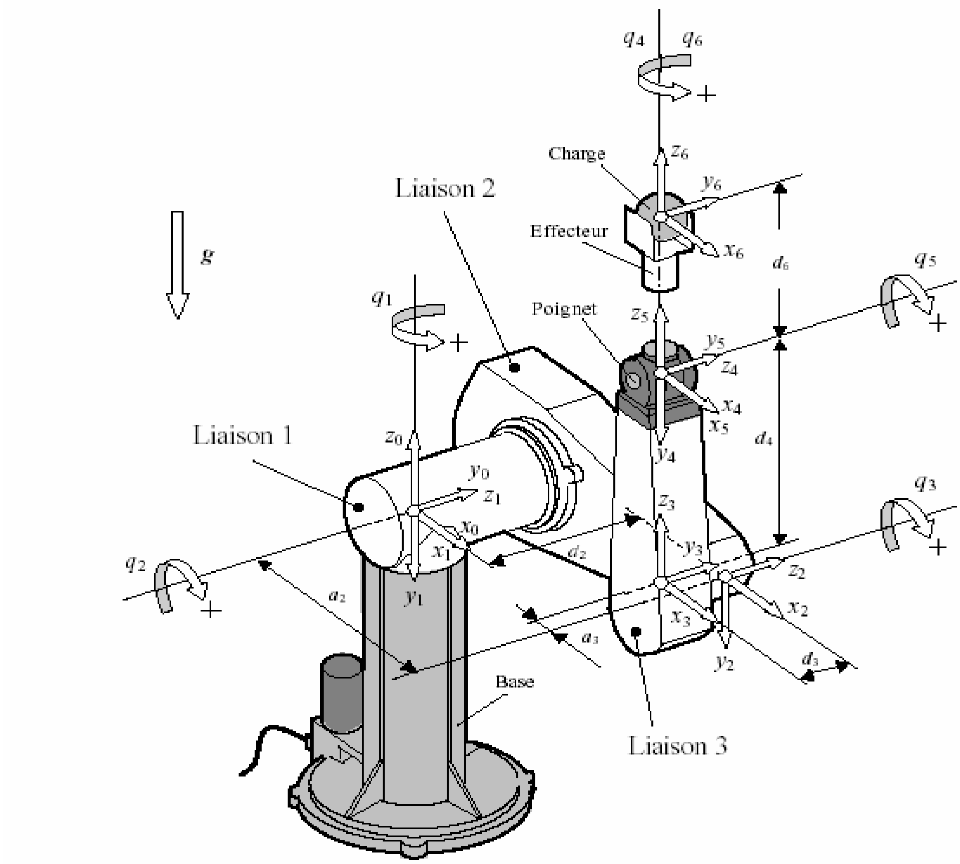

Figure 3: System of connections coordinates and parameters of joints for the PUMA 560 robot arm according to the Denavit and Hartenberg convention

vii. *Parameters of Denavit and Hartenberg*

The Denavit and Hartenberg Convention is a systematic method. It allows the passage between adjacent joints of a robotics system. It relates to the open kinematic chains where the joint possesses only one degree of freedom, and the adjacent surfaces remain in contact. For this aspect the use of hinges or slides is indispensable. The choice of the frames for the links facilitates the calculation of the DH homogeneous matrices and makes it possible to rapidly express information of the terminal element towards the base or the reverse.

The steps for this technique are as follows:

1. Numbering of the constituent segments of the manipulator arm from the base to the terminal element. The zero referential is associated with the base of it, and the order n to the terminal element (end effector);
2. Definition of the main axes of each segment:
   - If z_i and z_{i-1} do not intersect we choose x_i so as to be the parallel with the axis perpendicular to z_i and z_{i-1}.
   - If z_i and z_{i-1} are collinear, x_i is chosen in the plane perpendicular to z_{i-1}.
3. Fix the four geometric parameters: d_i, θ_i, a_i, $\boldsymbol{\alpha_i}$ (see Figure(4)) for each joint such as:

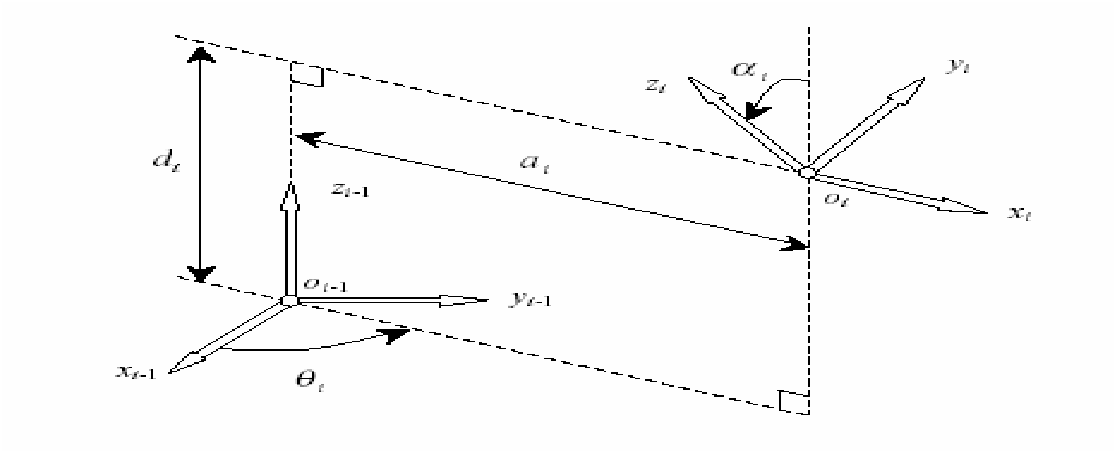

Figure 4: Coordinate systems and parameters of Denavit and Hartenberg

- d_i coordinate of the origin O_i on the axis z_{i-1} For a slide d_i is a variable and for a hinge d_i is a constant.
- θ_i is the angle obtained by screwing x_{i-1} to x_i around the axis z_{i-1}.For a slide $\boldsymbol{q_i}$ is a constant and for a hinge $\boldsymbol{q_i}$ is a variable.
- a_i is the distance between the axes z_i and z_{i-1} measured on the axis x_i negative from its origin up to the intersection with the axis z_{i-1}.
- α_1 is the angle between z_i et z_{i-1} obtained by screwing z_{i-1} to z_i around x_i.

Finally, the homogeneous DH displacement matrix $[\boldsymbol{T_{i-1}^{i}}]$ which binds together the rotation and the translation is formed . Its left upper part defines the rotation matrix $\boldsymbol{R_{i-1}^{i}}$ and on its right the translation vector

$$[T_{i-1}^{i}] : \begin{bmatrix} R_{i-1}^{i} & d_{i-1}^{i} \\ 0\ 0\ 0 & 1 \end{bmatrix} \tag{9}$$

With

$$R_{i-1}^{i} = \begin{bmatrix} cos\ \theta_i & -cos\ \alpha_i\ sin\ \theta_i & sin\ \alpha_i\ sin\ \theta_i \\ sin\ \theta_i & cos\ \alpha_i\ cos\ \theta_i & -sin\ \alpha_i\ cos\ \theta_i \\ 0 & sin\ \alpha_i & cos\ \alpha_i \end{bmatrix} \tag{10}$$

And

$$d_{i-1}^{i} = \begin{cases} a_i cos\ \theta_i \\ a_i sin\ \theta_i \\ d_i \end{cases} \tag{11}$$

Figure (4) represents the Denavit and Hartenberg parameters for a two successive frames (x_{i-1}, y_{i-1} , z_{i-1}) and (x_i, y_i , z_i).

And finally the (4x4) rigid transformation matrix will have the form: $\boldsymbol{T_{i-1}^{i}}$

$$\begin{pmatrix} cos\ \theta_i & -cos\ \alpha_i\ sin\ \theta_i & sin\ \alpha_i\ sin\ \theta_i & a_i cos\ \theta_i \\ \sin\theta_i & cos\alpha_i\ cos\ \theta_i & -sin\alpha_i\ cos\ \theta_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & cos\ \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{12}$$

The definition of the frames associated with the links according to the Denavit and Hartenberg convention is as follows:

Link1: Frame (x_0 ,y_0 ,z_0) ;The origin O is taken in link1 at the intersection of the base axis with the link1 axis. z_0 axis of rotation, + z_0 upwards.+ y_0 coincides with the axis of the link 1 and the axis + z_1.y_1 is parallel to the link 2.

Link 2: Frame (x_1 ,y_1 ,z_1) ;The origin coincides with the origin of the frame (x_0 ,y_0 ,z_0,) .z_1 axis of rotation, + z_1 is perpendicular to the link 2 and parallel to the axis + z_2.+ y_1 downwards, superimposed with the axis of the base and parallel with y_2.+ x_1 is parallel to the link 2.

Link 3: Frame (x_2 ,y_2 ,z_2) ;The origin is taken in link 2 at the intersection of the axis of the link 2 with the axis of the joint 3.z_2 axis of rotation, + z_2 is perpendicular to link 2 and axis z_3.+ y_2 downwards, opposite with + z_3.+ x_2 is parallel to the link 2.

Link 4: Frame (x_3, y_3, z_3); The origin is taken in link 3.z_3 axis of rotation, + z_3 towards the wrist and perpendicular to +z_4 .+ y_3 is perpendicular to the link 2, and parallel to +z_4.+ x_3 is parallel to the link 2.

Link 5: Frame (x_4 ,y_4 ,z_4) ;The origin is taken at the center of the wrist.z_4 axis of rotation, + z_4 is perpendicular to link 2 superposed with $+z_5$. + y_4 is opposite to + z_5.+ x_4 is parallel to link 2.

Link 6: Frame (x_5,y_5, z_5) ;The origin coïncides with the origin of the link (x_4,y_4, z_4).z_5 axis of rotation, $+z_5$ towards the effector parallel to $+z_6$.+ y_5 coïncides with the axis of joint 5.+ y_5 is perpendicular to the axis of joint 5.

The end effector: Frame (x_6,y_6,z_6) ;The origin coïncides with the origins of the links (x_4,y_4, z_4) and (x_5, y_5, z_5). $+z_6$ is parallel to $+z_5$. and $+y_6$ is parallel to + y_5 . $+x_6$ is parallel to $+x_5$.

By respecting the original position of the robot and the definition of the links and correspondant frames presented in Figure (3), the parameters of the PUMA 560 robot arm given by the Denavit and Hartenberg Convention are shown in Table (1):

Table 1: Puma 560 Denavit and Hartenberg Parameters

i Numéro de la liaison	α_i (degrés)	θ_i Variable	a_i (mètres)	d_i (mètres)
1	−90	q_1	0	0
2	0	q_2	a_2	d_2
3	+90	q_3	a_3	d_3
4	−90	q_4	0	d_4
5	+90	q_4	0	0
6	0	q_5	0	–

The distance d_6 is not shown in Table (I)..This distance varies according to the effector used for the application (the effector is the tool attached to the wrist on the last articulation of the robot for the manipulation of the objects). In this application the distance between the end of the effector and the axis of the wrist is assumed to be null $d_6 = 0$.

The dynamics of the last three articulations is negligible compared to the first three. Therefore, we have been interested in studying the movement of the three first joints of the PUMA 560 robot arm fixing the others to the original position (i.e., wrist attached to the original position: $q_4 = q_5 = q_6 = 0$).

v. *D-H kinematics of the PUMA 560 ROBOT*

The appropriate transformations for the first three considered articulations are:

$$T_0^1 = \begin{pmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{13}$$

$$T_1^2 = \begin{pmatrix} c_2 & -s_2 & 0 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & a_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{14}$$

Such that we will have : $T_0^2 = T_0^1 T_1^2$

$$= \begin{pmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_1c_2 & -c_1s_2 - s_1 & a_2c_1c_2 - d_2s_1 \\ s_1c_2 & -s_1s_2 \;\; c_1 & a_2c_2s_1 + d_2c_1 \\ -s_2 & -c_2 \;\; 0 & -a_2s_2 \\ 0 & 0 \;\; 0 & 1 \end{pmatrix} \tag{15}$$

We can also write:

$$T_2^3 = \begin{pmatrix} c_3 & -s_3 & 0 & 0 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & a_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_3 & 0 & s_3 & a_3c_3 \\ s_3 & 0 & -c_3 & a_3s_3 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{16}$$

And finally write $T_0^3 = T_0^2 T_2^3 = \begin{pmatrix} c_1c_2 & -c_1s_2 - s_1 & a_2c_1c_2 - d_2s_1 \\ s_1c_2 & -s_1s_2 \;\; c_1 & a_2c_2s_1 + d_2c_1 \\ -s_2 & -c_2 \;\; 0 & -a_2s_2 \\ 0 & 0 \;\; 0 & 1 \end{pmatrix}\begin{pmatrix} c_3 & 0 & s_3 & a_3c_3 \\ s_3 & 0 & -c_3 & a_3s_3 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} =$

$$T_0^3 = \begin{pmatrix} c_1c_{23} & -s_1c_1s_{23} & c_1(a_2c_2 + a_3c_{23}) - (d_2 + d_3)s_1 \\ s_1c_{23} & c_1s_1s_{23} & s_1(a_2c_2 + a_3c_{23}) + (d_2 + d_3)c_1 \\ -s_{23} \quad 0 & c_{23} & -(a_2s_2 + a_3s_{23}) \\ 0 \quad 0 & 0 & 1 \end{pmatrix} \tag{17}$$

With $c_i = \cos\theta_i,\, s_1 = \sin\theta_i, c_{ij} = \cos(\theta_i + \theta_j), s_{ij} = \sin(\theta_i + \theta_j)$

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A Basic Platform and Electronics Interfaces Board for Family Therapeutics Tools to Surgical Robots

By V. Ivanova, D. Batchvarov, A. Boneva & Z. Ilcheva

Abstract- Robotic technologies are advancing in the field of minimally invasive surgery. The last decade, more than 1.5 million laparoscopic surgical procedures, including gynecologic, cardiac, urology, thoracic, and general surgery, have been performed by *popular robotic and mechatronic systems for minimally invasive surgery. In contrast to big popular robot systems* which instruments are designed for manipulation and video observation this paper describes novel instrument for therapy with application in minimally invasive surgery. The aim of the work is design of a compact, convenient, simplified, better possibilities and suitable price devices there by and the small hospitals to have accesses to this systems and patient benefit from it our ultimate aim is radical improvements to the quality and efficiency of our healthcare.

Keywords: robot system; therapeutics tasks; surgical robots, therapeutics tools, laparoscopic surgery.

GJRE-H Classification: FOR Code: 280209

ABASICPLATFORMANDELECTRONICSINTERFACESBOARDFORFAMILYTHERAPEUTICSTOOLSTOSURGICALROBOTS

Strictly as per the compliance and regulations of:

A Basic Platform and Electronics Interfaces Board for Family Therapeutics Tools to Surgical Robots

V. Ivanova α, D. Batchvarov σ, A. Boneva ρ & Z. Ilcheva ω

Abstract- Robotic technologies are advancing in the field of minimally invasive surgery. The last decade, more than 1.5 million laparoscopic surgical procedures, including gynecologic, cardiac, urology, thoracic, and general surgery, have been performed by *popular robotic and mechatronic systems for minimally invasive surgery.* In contrast to *big popular robot systems* which instruments are designed for manipulation and video observation this paper describes novel instrument for therapy with application in minimally invasive surgery. The aim of the work is design of a compact, convenient, simplified, better possibilities and suitable price devices there by and the small hospitals to have accesses to this systems and patient benefit from it our ultimate aim is radical improvements to the quality and efficiency of our healthcare.

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I. Introduction

Robotic technologies are advancing in the field of minimally invasive surgery. The last decade, more than 1.5 million laparoscopic surgical procedures, including gynecologic, cardiac, urology, thoracic, and general surgery, have been performed by daVinchi (Intuitive Surgical Incorporation) [1]. In contrast to daVinchi by Intuitive Surgical Incorporation and Zeus by Computer Motion [2] which instruments are designed for manipulation and video observation this paper describes novel instrument for therapy with application in minimally invasive surgery. The aim of the work is design of a compact, convenient, simplified, better possibilities and suitable price devices thereby and the small hospitals to have accesses to this systems and patient benefit from it Our ultimate aim is radical improvements to the quality and efficiency of our healthcare.

Major diseases of gallbladder are gallbladder stones and carcinoma. Gallbladder and bile duct carcinoma are rare diseases of the biliary tract. Correctly function of gallbladder is essential to the digestive process. When gallbladder cancer is caught early, removing a gallbladder or part of the bile duct may eliminate all the cancerous cells. Gallbladder cancer does not have any proven prevention methods. The causes of the disease, such as gallstones, cannot be prevented from forming in the gallbladder. Two main types of gallbladder cancer tumors are typical, adenocarcinoma and non-adenocarcinoma. There is a lot of methods for diagnostics of gallblader carcenoma: Blood tests, Ultrasound Computerized tomography (CT) scan, Magnetic resonance imaging (MRI) Endoscopic retrograde cholangio pancreatography (ERCP) Biopsy, Laparoscopy, and etc. Tumors tend to be harder than the surrounding tissue, and not possible indicate their presence, size and exact location without tactile sense when diagnostics is performed by laparoscopic procedure. Many gallbladder cancers are discovered after a laboratory examination of a gallbladder that's been removed for other reasons.. Several researchers have also incorporated a direct sensing method for tissue characterization through pressure measurement normal to the surface of the jaws [3] or incorporated the sensors into the handle of the robot instrument [4], [5] We offer family instruments for Therapeutics tasks which is described at the following section.

II. An Instrument for Therapeutics Tasks

On the Fig. 1 is shown a basic structure of the instrument for therapy in laparoscopy. We are applied the construction and principle of the work which is described at [6]. The main elements of the instrument are a step motor by PrimoPall [7], incremental contactless encoder, a force sensors by Honeywell [8] and therapy module mounted on the top of the slider.

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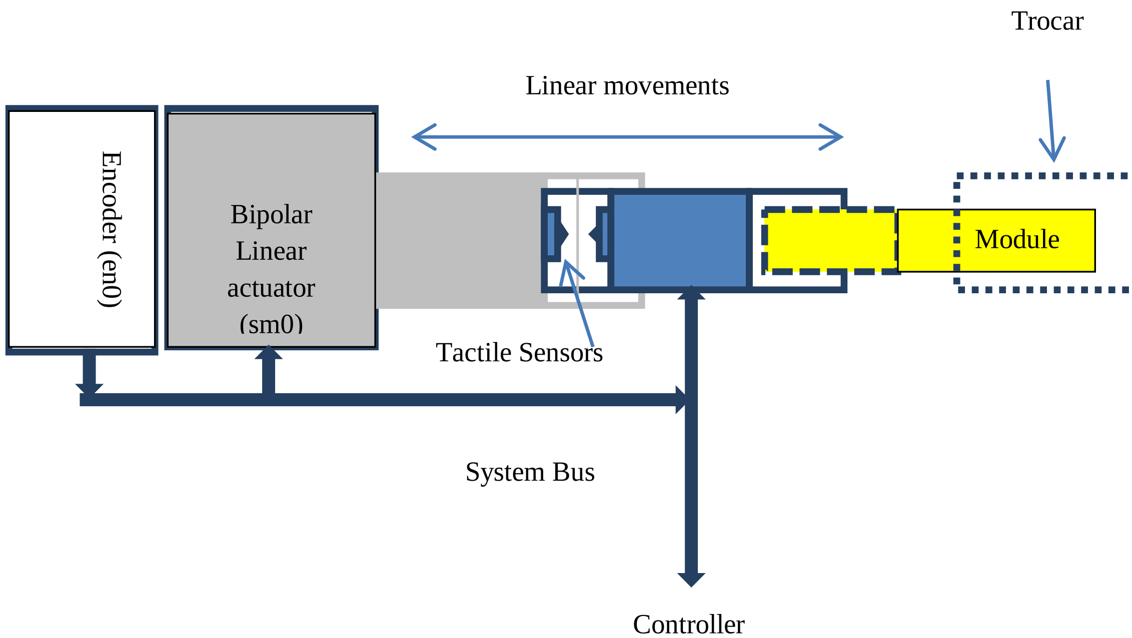


Fig. 1: Basic platform of instrument for therapy

a) *An instrument for mechanical therapy*

An instrument for a therapy (On Fig.2) is a sophisticated module that incorporates engines, sensors for positioning and control of encoders and mechanical structures that perform manipulation on tissues (laparoscopic interventions). It is coupled on the top of the Basic platform slider, having three degrees of freedom: translation, rotation, and jabbing between the jaws and been controlled by Controller.

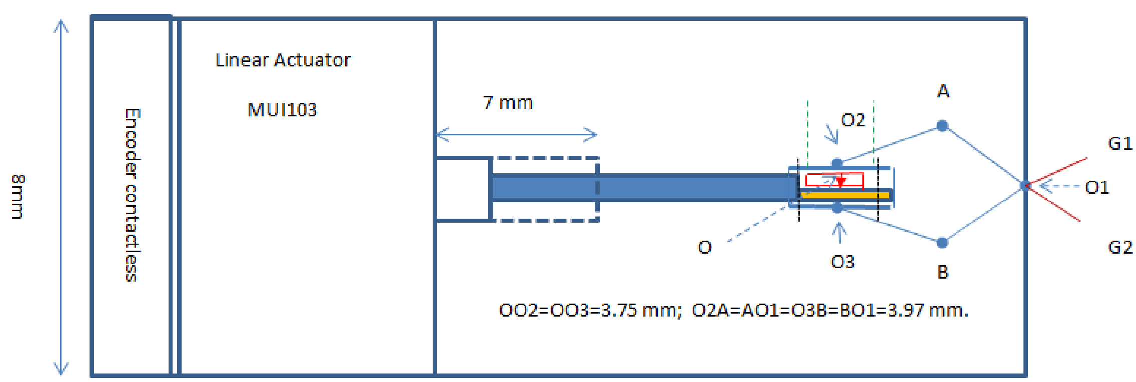


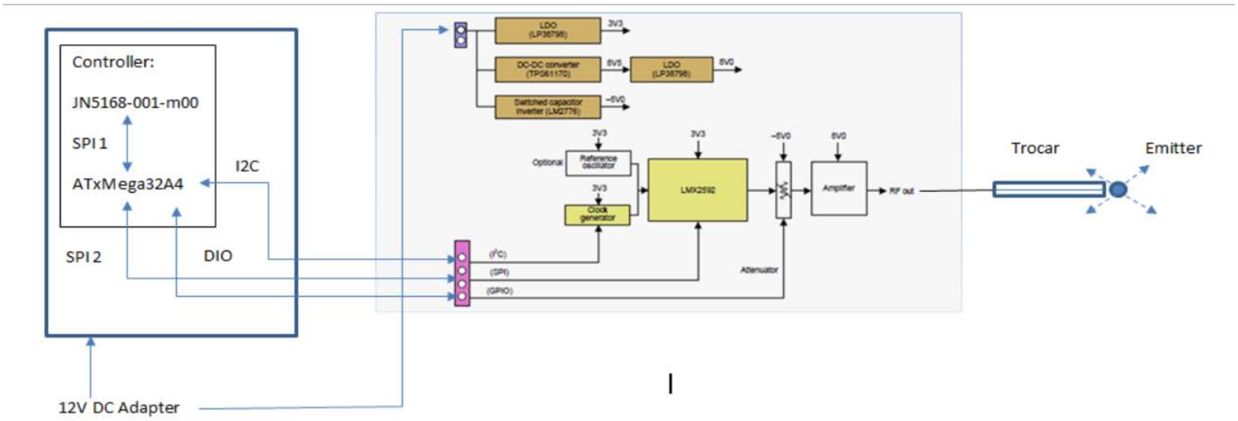
Fig. 2: An instrument for mechanical therapy

b) *An instrument for RF therapy*

This instrument is designed for programmable tissue exposure in the frequency range from 0 Hz to 500MHz or 40MHz **до** 8 GHz. The irradiation is local. A programmed change in the intensity and frequency of the radio signal is a function of time. Main Idea is to transport the end of the tool where is embedded UFR emitter and therapy to be executed locally.

The instrument uses an UHF Generator that generates a programmed frequency, forms the required radio signal through the output stage, and outputs it to an emitter to perform radiotherapy via a wired channel. The linear displacement of the module and its positioning at a set point is provided by the main step motor, taking into account force sensors readings to confirm the contact with the object of the therapy.

The UHF Generator shown on the Fig. 3 is external device, controlled by Controller and generates the signal to the UFR emiter.



LMX2592 Wideband Frequency Synthesizer with Integrated VCO, Min f=20 MHz, Max f=9800 MHz, Texas Instrument. SPI.

AD9915 Clock generator 2.5 GSPS Direct Digital Synthesizer with 12-Bit DAC. Max f=1000 MHz, Analog Devices. I2C.

DIO Input/output signals for the devices control.

Fig. 3: Controller, UHF generator and emitting device

The RF- generator is built on the base of programmable PLL generator LMX 2592, using programmable frequency reference source AD9915. Odd of them are being controlled by SPI and I2C from microcontroller ATxMega32A4, embedded in the main controller. The formed radio- signal is transmitted through wave- channel placed into the slider to the emitting block.

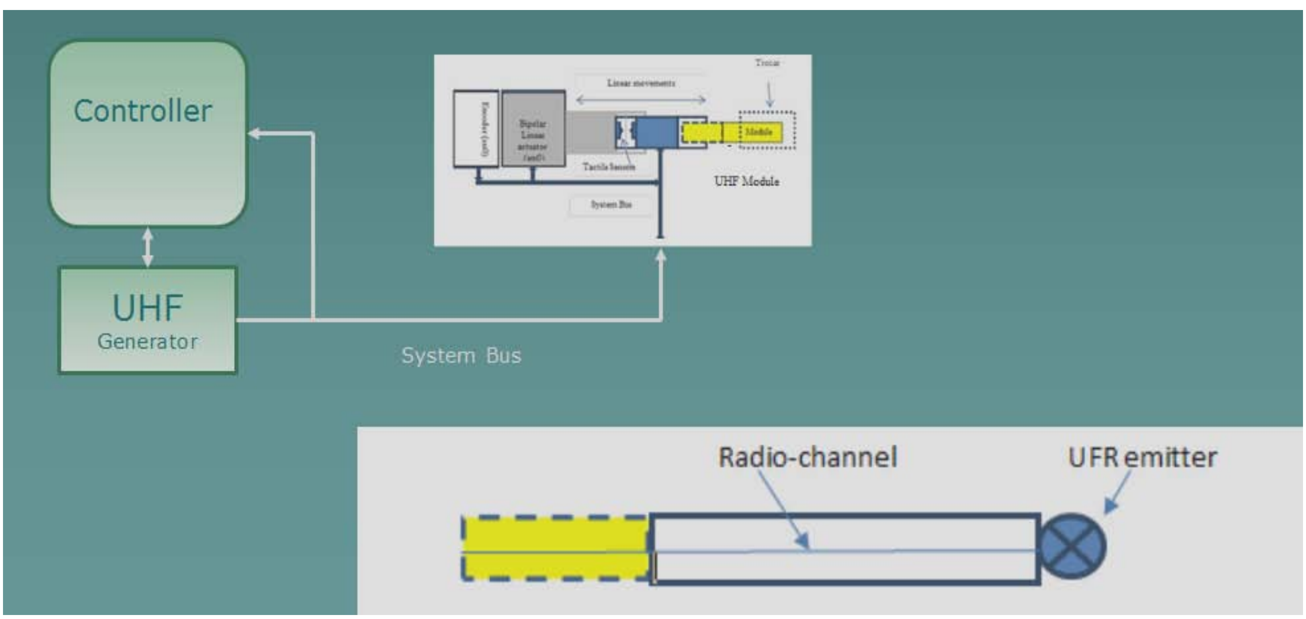


Fig. 4: RF therapy action

III. Electronics Interfaces Board

The electronic interfaces board is two-processors system, including wireless JN5168-001-M00 and industrial ATxMega32A4. The microcontroller JN5168-001-M00 works as a network device in local wireless network and a processor for control of different incorporated electronic modules simultaneously. ATxMega32A4 works as slave coprocessor and is responsible for the encoder's data processing and radio- therapy controlling.

On the Fig 5 is shown the block diagram of the Controller. Odd microcontrollers are connected with SPI bus, JN5168-001-m00 functions as master.

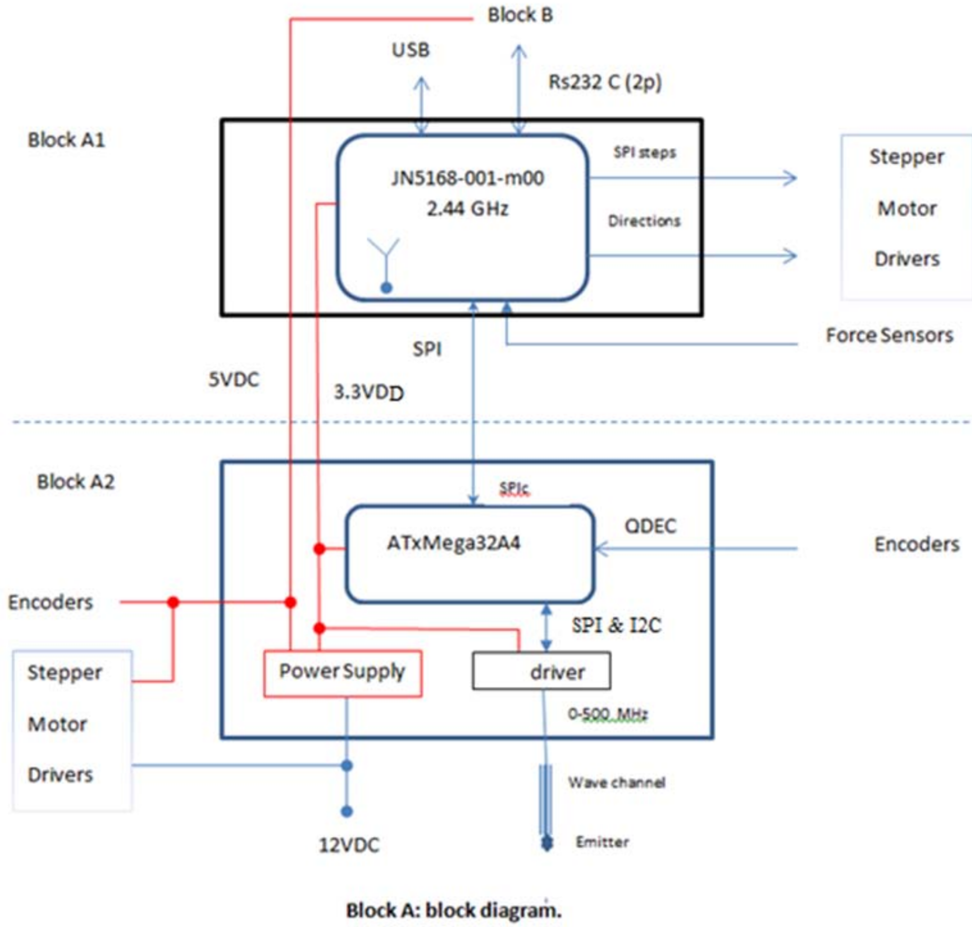


Fig. 5: Block diagram of Controller

The control module includes as coprocessor microcontroller ATxMega32A4. Its architecture is shown on the Fig 6. This microcontroller is responsible for the encoders data processing and radio- therapy controlling. JN5168-001-M00 and ATxMega32A4 [9] ate connected between using on board SPI bus (primary). ATxMega32A4 is controlling the frequency generator module using embedded secondary SPI and I2C busses

On Fig. 6 is shown Block diagram of JN5168-001-M00 architecture.

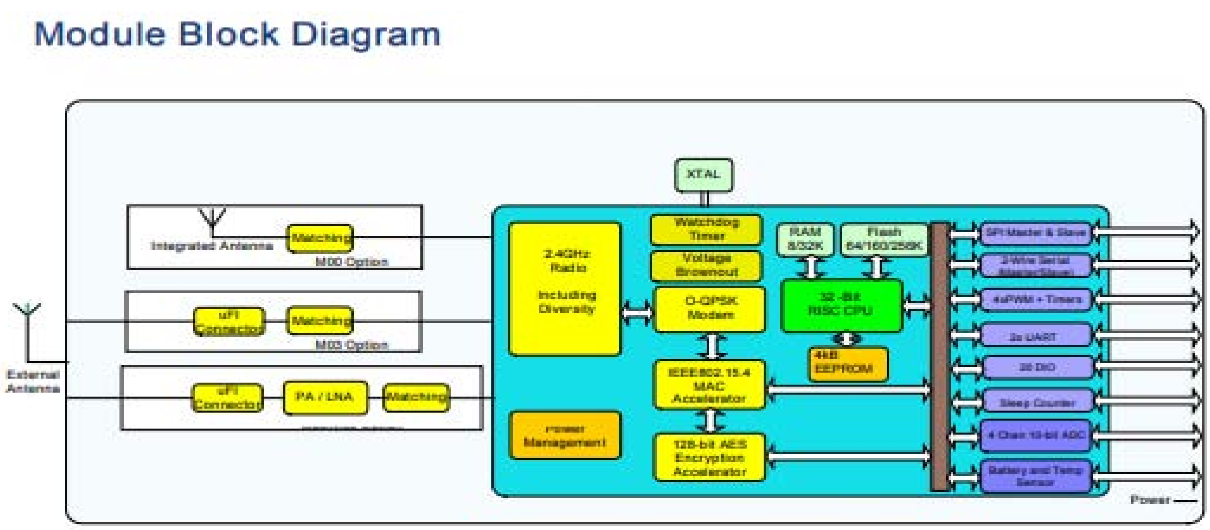


Fig. 6: Block diagram of microcontroller JN5148-01-M00

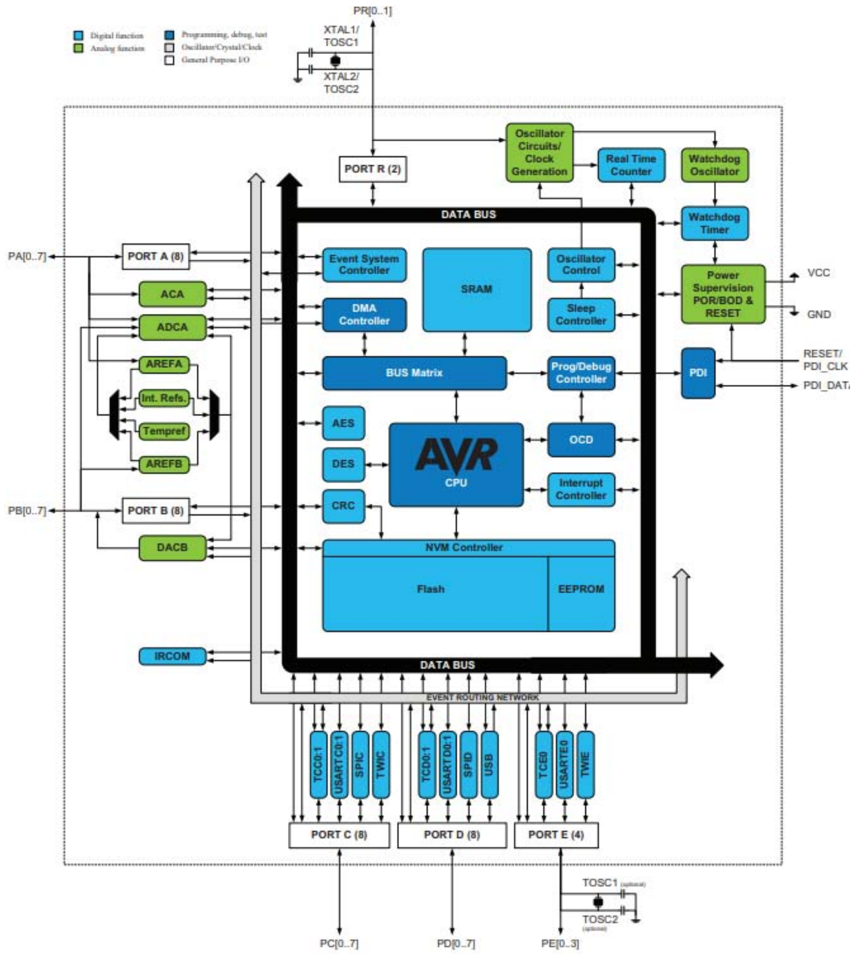


Fig. 7: Block diagram of microcontroller ATx Mega 32A4

Block diagram of microcontroller ATxMega32A4 is shown on the Fig 7.

IV. Quantitative Assessment of Gallbladder Carcinoma by Image Processing

a) Image processing

Tumors tend to be harder than the surrounding tissue. Inicially image processing is performed to get some idea of presence, size and exact location of different tissues. [10]. For example, we are using the laparoscopic image in a 65-year-old man. The procedure of image processing involves the following steps:

1. Preliminary image processing;
2. Image Segmentation;
3. Defining and measuring the features of image;
4. Classification of objects in the image.

Preliminary image processing includes procedures which increase the image quality and prepare suitable images for the next steps. Image segmentation as procedure for separating the image objects from one other and from background -10. There are different approaches for image segmentation: Color-based segmentation, texture segmentation, contour segmentation [15], [16] etc. Defining the features of the image is a basic step in image processing. Be the features image is classified in groups.

Looking at the image we notice that the tumor has a darker (lighter) color. This shows us that we must choose a feature of segmentation of the image intensity threshold. After image segmentation with different thresholds we can calculate the size (area) of whole gall and size of healthy part. We calculate the size by expression:

$$S = \sum_{i=1}^{n-1}(x_i - x_{i+1})(y_i + y_{i+1}) + (x_n - x_1)(y_n + y_1)$$

Where (x_i, y_i) the contour's coordinate points and n are is the number of contour's points on the segmented object.

Fig. 8: Laparoscopic image of gallbladder

The picture of gallbladder is in the Fig 8. After segmentation eith threshold 150 the following image (Fig. 9) is obtained. The size of segmented image is 42692 pixels. In our case the treshold is the feature of the image. From this features the image object (gallbladder) after contour segmentation is separated in health and ill parts

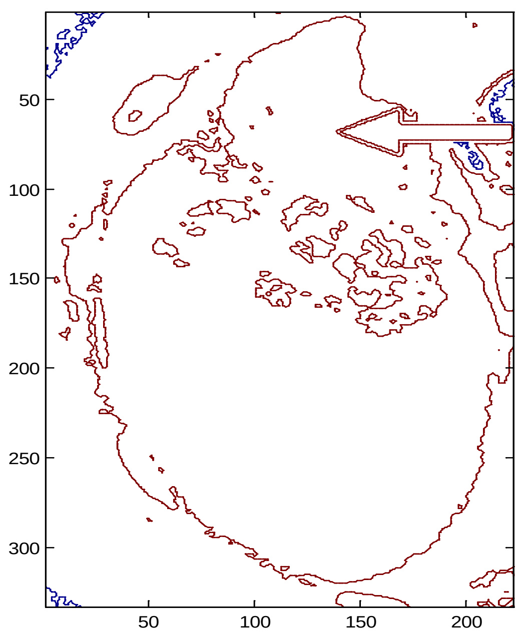


Fig. 9: Segmentation of image

After segmentation with threshold 190 the following segmented image is obtaine (Fig. 10). The size of tumor is 3823 pixels. (16162 pixels). The ratio of ill part to the whole one is 3823/42692. (16162/42692). It is equal to 0.0895 (0.3786).

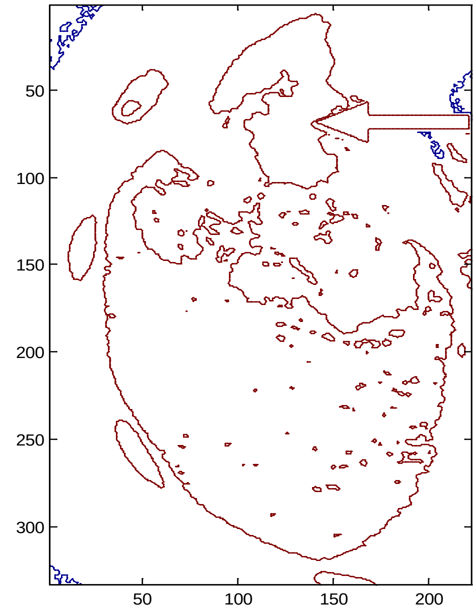


Fig. 10: Image processing

V. Experiments and Analyzes

After image processing we perform experiments and analyses. The purposes of carried out experiments are to verify the functionality and working capacity of the tools, to evaluate practically whether the error introduced by the proposed module during its normal operation is well within the required target, to demonstrate the operation of the tools

The experiment includes a search in the work area for a deviation with a set force value. It is shown in the red graphic. The blue graph shows the frequency of the generated RF signal used to irradiate the subject.

When the deviation is detected, the formation of the micro steps is terminated and the generator starts operating in accordance with the set program. Upon reaching the set frequency, in the case of 434 MHz, radiation is maintained at the set frequency and intensity for the time defined by the therapy program - in this case 10 seconds. After that, the generator turns off and the frequency drops to the minimum.

The number of the micro steps is located along the X axis, along with the time in units of 100 ms.

100 ms is the time to take 1 micro step. Along the Y axis is located the power in grams, along with the frequency of the irradiation signal in megahertz.

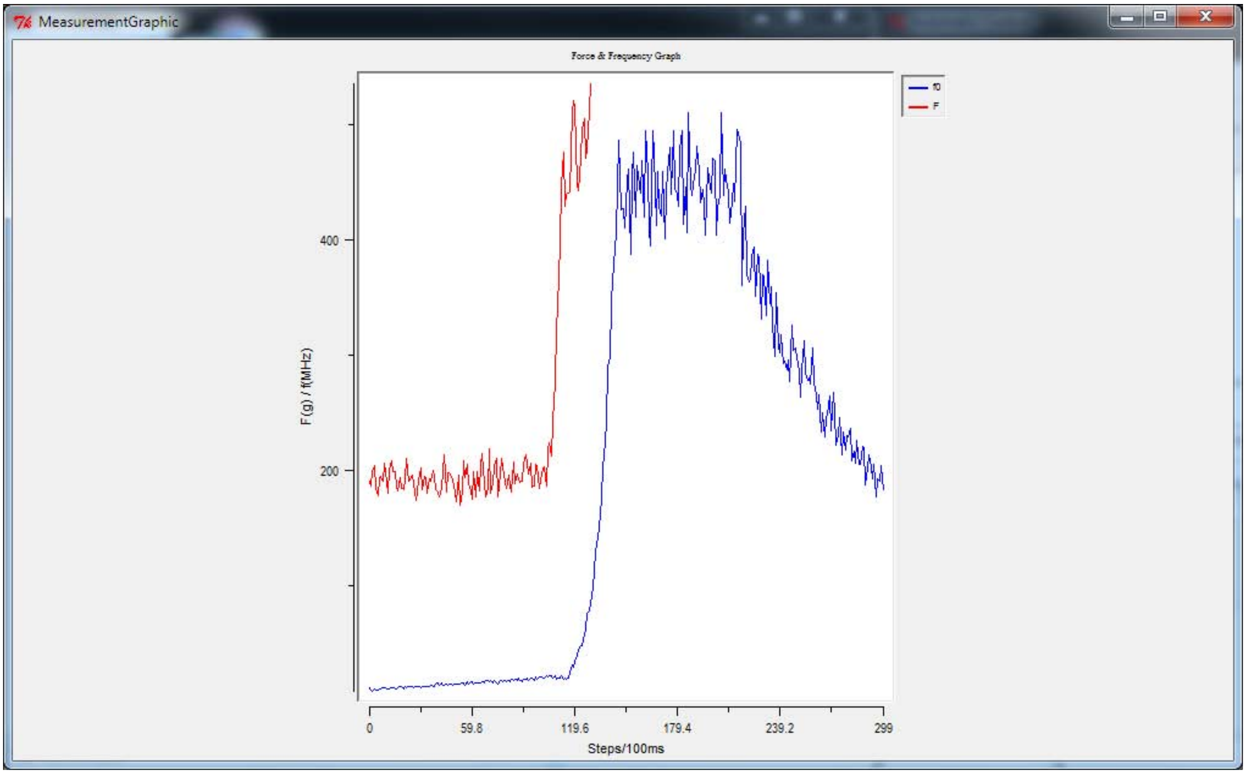


Fig. 11: Graphical presentation of the Experiment

VI. Conclusions and Intentions for Future Work

This paper discussed design and development of family instruments for therapeutics tasks with application of minimally invasive surgery. There are proposed an electronics interfaces board whish includes a block diagram of Controller, a block diagram of microcontroller JN5148-01-M00 and a block diagram of microcontroller ATxMega32A4. They are conducted an experiment to demonstrate a principle of the work of the instruments. Our intention for future work includes some experiments which have to be conducted with various frequency and intensity, and different materials of similar properties of human tissues in order to compare the results.

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19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.
22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

General style:

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear: Adhere to recommended page limits.

Mistakes to avoid:

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

The Administration Rules

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

Written material: You may discuss this with your guides and key sources. Do not copy anyone else's paper, even if this is only imitation, otherwise it will be rejected on the grounds of plagiarism, which is illegal. Various methods to avoid plagiarism are strictly applied by us to every paper, and, if found guilty, you may be blacklisted, which could affect your career adversely. To guard yourself and others from possible illegal use, please do not permit anyone to use or even read your paper and file.

Criterion for Grading a Research Paper (Compilation) by Global Journals

Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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