Evaluation of Friction Forces in the Joints of Gough-Stewart Manipulator

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ABSTRACT:

Many of researchers neglected the effect of friction phenomena in the robotics analysis and the others investigated and studied the behavior of friction phenomena in robot joints with one type of friction. The aims of this paper is to account and investigate the friction forces in all the joints of Gough-Stewart manipulator taking into consideration two types of friction(i.e. viscous and coulomb friction) . A mathematical model is derived to evaluate the reaction forces developed in robot joints due to movement of robot. Computer codes are written using MATLAB software to solve the equations derived to simulate the friction force in the joints.

Keywords: Robot, Gough – Stewart, Friction Force, Friction Moment, Coulomb friction, viscous friction.

Nomenclature:

SRB: single rigid body.
MP: moving platform.
FP: fixed platform.
GCS: global coordinate system.

INTRODUCTION

Many types of forces developed in the joints of robot. Reaction forces and friction forces are the main types of the forces developed in the joints. Friction force and friction moment in case of translation and rotation, respectively are calculated. The friction force due to the contact surfaces affects the behavior of robot because of its effect on the resultant force developed in the joints. In 2002 Y. Zhang et,al**[1]** estimated the friction force with low joints velocity. In 2010, Xabier Iriarte and Javier Ros **[2]**, derived a model reduction method for the case in which any friction force is modeled as kinetic friction. In 2005, Basilio Bona and Marina Indri **[3]**, overviewed of the main friction compensation techniques that have been developed. In 2011, Andre' Carvalho and Svante Gunnarsson **[4]**, investigated linear and nonlinear functions including typical friction phenomena of robotics. In 1990, Pierre E. Dupont **[5]**, modeled and simulated robot system including friction effect. In 2000[**6**], Nghe H Quach and Ming Liu used Tustin's friction model to develop a novel estimation routine to obtained the dynamical friction forces for the motion control of robot manipulators. In 2010, Hassan M. Alwan and Muhsin N. Hamza[7] used the principle of the virtual work to make the dynamic analysis of the Gough-Stewart manipulator. In 2014, Hassan M. Alwan and Hayder Sabah Ahmed [8] suggested a mathematical solution of parallel manipulator to evaluate the singularity. In the present paper, Gough-Stewart manipulator is the famous traditional type of the parallel robot. It is consist of upper plate (moving platform)"MP", lower plate (fixed platform)"FP" and six extensible legs with six prismatic joints. There are six universal joints connected between the "FP" and the lower part of the legs and there are six spherical joints connected between the "MP" and the upper part of the legs as show in figure(1). The tracking of the robot consist of

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(40) movement steps. In this paper, the general equations are derived to represent the full frictional results in the joints of the Gough-Stewart Platform at each step of the 40 movement steps. Two types of friction considered (i.e. viscous and coulomb friction), to describe the forces resultant in each joint.

2-Joints Reaction Forces Evaluation

To evaluate the reaction forces in the moving, fixed platforms and prismatic joints, a mathematical modeling has been derived. All joints that connected with moving platform consist of three reactions force in space (Rx,Ry,Rz) and each of the six joints that connected with fixed platform, there is moment in Z-Direction (Mz) in additional with three reaction forces. In the prismatic joints, two reactions (Rx, Ry) and three moments in three direction (Mx, My, Mz). The moving platform is assumed as a single rigid body and all points coordination are local and transformed to global as follow at each movement steps[**9**]:

$$[E_i]_j^O = [T].[E_i]_j^1 \qquad (1)$$

Where "i" are number of points and "'j" are number of movement steps.

$$T = R_Z(\gamma).R_X(\beta).R_Z(\alpha)$$

$$R_Y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \quad R_Z(\gamma) = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_X(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$

$$T = \begin{bmatrix} b11 & b12 & b13 \\ b21 & b22 & b23 \\ b31 & b32 & b33 \end{bmatrix}$$

where "T" is the transformation matrix and(Ei) are the joints that connected with moving platform.

$b11 = c(\alpha)c(\gamma) - c(\beta)s(\alpha)s(\gamma)$ $\quad b12 = -s(\alpha)c(\gamma) - c(\beta)c(\alpha)s(\gamma)$ $\quad b13 = s(\beta)s(\gamma)$

$b21 = c(\alpha)s(\gamma) + c(\beta)s(\alpha)c(\gamma)$ $\quad b22 = -s(\alpha)s(\gamma) + c(\beta)c(\alpha)c(\gamma)$ $\quad b23 = -s(\beta)c(\gamma)$

$b31 = s(\beta)s(\alpha)$ $\quad b32 = s(\beta)c(\alpha)$ $\quad b33 = c(\beta)$

(α,β,γ): Euler angles,(c): cosine and (s): sine. All external and internal loads are insert in the equilibrium equations of the moving platform for free body diagram shown in figure (2), with respect to the global coordinate system (GCS) step by step movements using the principle of Euler's angles rotation by assuming the rotation sequence (Z- X- Z). The equations as follows**[10]**:

Σ FX = 0:

$$R_{XE1}^O + R_{XE2}^O + R_{XE3}^O + R_{XE4}^O + R_{XE5}^O + R_{XE6}^O + (m_M^O + m_E^O) * a_x = 0 \qquad (2)$$

Σ FY = 0:

$$R_{YE1}^O + R_{YE2}^O + R_{YE3}^O + R_{YE4}^O + R_{YE5}^O + R_{YE6}^O + (m_M^O + m_E^O) * a_y = 0 \qquad (3)$$

Σ FZ = 0:

$$R_{ZE1}^O + R_{ZE2}^O + R_{ZE3}^O + R_{ZE4}^O + R_{ZE5}^O + R_{ZYE6}^O + W_T + (m_M^O + m_E^O) * a_Z = 0 \qquad (4)$$

Σ MXE1 = 0:

$$-R^{O}_{ZE2}*(Y_{E2}-Y_{E1})-R^{O}{}_{ZE3}*(Y_{E3}-Y_{E1})-R^{O}{}_{ZE4}*(Y_{E4}-Y_{E1})+R^{0}_{ZE5}*(Y_{E5}-Y_{E1})$$
$$+R^{O}_{ZE6}*(Y_{E6}-Y_{E1})+W_{T}*(Y_{o}-Y_{E1})+R^{O}_{YE2}*(Z_{E2}-Z_{E1})+R^{O}_{YE3}*(Z_{E3}-Z_{E1})$$
$$+R^{O}_{YE4}(Z_{E4}-Z_{E1})+R^{O}_{YE5}*(Z_{E5}-Z_{E1})+R^{O}_{YE6}*(Z_{E6}-Z_{E1})+I_{X}*\alpha_{X}=0 \qquad (5)$$

Σ MYE1 = 0:

$$-R^{O}_{ZE2}*(X_{E2}-X_{E1})-R^{O}_{ZE3}*(X_{E3}-X_{E1})+R^{O}_{ZE4}*(X_{XE4}-X_{E1})+R^{O}_{ZE5}*(X_{E5}-X_{E1})$$
$$+R^{O}_{ZE6}*(X_{E6}-X_{E1})+W^{O}_{T}*(X_{E6}-X_{E1})-R^{O}_{XE2}*(Z_{E2}-Z_{E1})-R^{O}_{XE3}*(Z_{E3}-Z_{E1})$$
$$+R^{O}_{XE5}*(Z_{E5}-Z_{E1})+R^{O}_{XE6}(Z_{E6}-Z_{E6})+I_{Y}*\alpha_{Y}=0 \qquad (6)$$

Σ MZE1 = 0:

$$R^{O}_{XE2}*(Y_{E2}-Y_{E1})-R^{O}_{YE2}(X_{E2}-X_{E1})+R^{O}_{XE3}*(Y_{E3}-Y_{E1})-R^{O}_{YE3}*(X_{E3}-X_{E1})$$
$$+R^{O}_{XE4}*(Y_{E4}-Y_{E1})+R^{O}_{XE5}(Y_{E5}-Y_{E1})-R^{O}_{YE5}*(X_{E5}-X_{E1})+R^{O}_{XE6}*(Y_{E6}-Y_{E1})$$
$$-R_{XE6}*(X_{E6}-X_{E1})+I_{Z}*\alpha_{Z}=0 \qquad (7)$$

Where, (WT): total weight, mM: mass of moving platform, mE: mass of external load, (ax,ay,az): linear acceleration of the moving platform, (αx,αy,αz): angular acceleration of moving platform and (X,Y,Z) represent the distance between each joint and joint number(1) in the three dimensions. Each link denoted with symbol (i) divided into five segments to represent the forces, as show in Figure (3):

Zone (Ci): universal joints connected the link with the base.

Zone (Ei): spherical joints connected the link with the moving platform.

Zone (2i): linkage body part located between spherical joint on the moving platform and the prismatic joint. The center of zone (2i) is located at (0.75*Di) measured from the (Ci)

Zone (3i): The prismatic joint. It is located at (0.5*Di).

Zone (4i): the linkage body part located between the spherical joint connected with the fixed and the prismatic joints. The center of zone (4i) is located at (0.25*Di) measured from the point (Ci).

The angles of inclination of each link (i) are evaluated with respect to X-axis, Y-axis, Z-axis by the following formulation as :

$$COS(\theta_{Xi})=\frac{X_{Ei}-X_{Ci}}{D_{i}} \qquad (8)$$

$$COS(\theta_{Yi})=\frac{Y_{Ei}-Y_{Ci}}{D_{i}} \qquad (9)$$

$$COS(\theta_{Zi})=\frac{Z_{Ei}-Z_{Ci}}{D_{i}} \qquad (10)$$

The equations mentioned above are applied for each link and repeated for each movement step. The free- forces body diagram of each link are shown in Figure (4) and denoted as the following:

$R^{O}_{XCi}, R^{O}_{YCi}, R^{O}_{ZCi}, M^{O}_{ZCi}$: Reaction forces and moments for the spherical joints connected the links with the base.

$R^{O}_{XEi}, R^{O}_{YEi}, R^{O}_{ZEi}$; Reaction forces of the spherical joints connected the links with the mobile platform.

$F^O_{X2i}, F^O_{Y2i}, F^O_{Z2i}, M^O_{X2i}, M^O_{Y2i}, M^O_{Z2i}$: Inertia forces and moments of the (2i) part of the link.

$F^O_{X4i}, F^O_{Y4i}, F^O_{Z4i}, M^O_{X4i}, M^O_{Y4i}, M^O_{Z4i}$: Inertia forces and moments of the (4i) part of the link.

Equilibrium equations have been applied for each link(i) as bellow:

Σ FX = 0:

$$R^O_{XCi} - R^O_{XEi} + F^O_{X2i} + F^O_{X4i} = 0 \quad (11)$$

Σ FY = 0:

$$R^O_{YCi} - R^O_{YEi} + F^O_{Y2i} + F^O_{Y4i} = 0 \quad (12)$$

Σ FZ = 0:

$$R^O_{ZCi} - R^O_{ZEi} + F^O_{Z2i} + F^O_{Z4i} = 0 \quad (13)$$

Σ MXCi = 0:

$$R^O_{ZEi} * (Y_{Ei} - Y_{Ci}) - F^O_{Z2i} * (0.75 * D_i * \cos_{\theta Y i}) - F^O_{Z4i} * (0.25 * D_i * \cos_{\theta Y i})$$
$$- R^O_{YEi} * (Z_{Ei} - Z_{Ci}) + F_{Y2i} * (0.75 * D_i * \cos_{\theta Z i}) + F^O_{Y4i} * (0.25 * D_i * \cos_{\theta Z i})$$
$$M^O_{X2i} + M^O_{X4i} = 0 \quad (14)$$

Σ MYCi = 0:

$$R^O_{XEi} * (Z_{EI} - Z_{Ci}) - F^O_{X2i} * (0.75 * D_i * \cos_{\theta Z i}) - F^O_{X4i} * (0.25 * D_i * \cos_{\theta Z i})$$
$$+ R^O_{ZEi} * (X_{Ei} - X_{Ci}) - F^O_{Z2i} * (0.75 * D_i * \cos_{\theta X i}) - F^O_{Z4i} * (0.25 * D_i * \cos_{\theta X i})$$
$$M_{Y2i} + M_{Y4i} = 0 \quad (15)$$

Σ MZCi = 0:

$$- R^O_{YEi} * (X_{Ei} - X_{Ei}) + F^O_{Y2i} * (0.75 * \cos_{\theta X i}) + F^O_{Y4i} * (0.25 * D_i * \cos_{\theta X i})$$
$$R^O_{XEi} * (Y_{Ei} - Y_{Ci}) + F^O_{X2i} * (0.75 * \cos_{\theta Y i}) + F^O_{X4i} * (0.25 * \cos_{\theta Y i}) + M^O_{ZCi}$$
$$M^O_{Z2i} + M^O_{Z4i} \quad (16)$$

The values of inertia forces and moments for zones (2i) and (4i) for all links with respect to global coordinate system are expressed as:

$$F_{2i} = \begin{bmatrix} F_X = m.a_{Xleg} \\ F_Y = m.a_{Yleg} \\ F_Z = m.a_{Zleg} \\ M_X = I_X.\alpha_X \\ M_Y = I_Y.\alpha_Y \\ M_Z = I_Z.\alpha_Z \end{bmatrix}. \qquad F_{4i} = \begin{bmatrix} F_X = m.a_{Xleg} \\ F_Y = m.a_{Yleg} \\ F_Z = m.a_{Yleg} \\ M_X = I_X.\alpha_X \\ M_Y = I_Y.\alpha_Y \\ M_Z = I_Z.\alpha_Z \end{bmatrix}. \quad (17)$$

The equations from (11) to (16) are repeated for each link and for each step. These thirty six equations in addition with the six equations from (2) to (7) are forty two equations containing all the (42) unknown reactions forces of the joints that connected with moving and fixed platforms.

Transformation of the Joints Reaction Forces

Reaction forces of the upper and lower platforms form are in global coordinate system, so that to transfer these forces to the linkage direction coordinate system, the following technique has been adopted which is relay on the principle of the vector analysis **[11]** where z-direction lies along the link direction.

The direction of (Zθ) expressed as follow:

$$\overline{Z^{\theta}} = (X_{Ci} - X_{Ei})i + (Y_{Ci} - Y_{Ei})j + (Z_{Ci} - Z_{Ei})k \quad (18)$$

Vector connected (E1) and (E2) is expressed by:

$$\overline{V_{E1E2}} = (X_{Ei+1} - X_{Ei})i + (Y_{Ei+1} - Y_{Ei})j + (Z_{Ei+1} - Z_{Ei})k \quad (19)$$

the direction of (Xθ) is perpendicular to the plane that containing the vectors ($\overline{Z^{\theta}}$) , so that:

$$\overline{X_i^{\theta}} = \overline{Z_i^{\theta}} \text{ x } \overline{V_{Ei+1Ei}} \quad (20)$$

and the unit vector of (Zθ), (Xθ) and (Yθ) calculated:

$$\overline{U_{X_i^{\theta}}} = \frac{\overline{X_i}}{\left|X_i\right|} \quad (21)$$

$$\overline{U_{Z_i^{\theta}}} = \frac{\overline{Z_i}}{\left|Z_i\right|} \quad (22)$$

$$\overline{Y_i^{\theta}} = \overline{Z_i^{\theta}} \text{ x } \overline{X^{\theta}} \quad (23)$$

$$\overline{U_{Y^{\theta}}} = \frac{\overline{Y_i}}{\left|Y_i\right|} \quad (24)$$

and the transformation equations are:

$$R_{Z_i}^{\theta} = \overline{R_{Z_i}^{O}} . \overline{U_{Z_i^{\theta}}} . + \overline{R_{Y_i}^{O}} . \overline{U_{Z_i^{\theta}}} + \overline{R_{Xi}^{O}} . \overline{U_{Zi^{\theta}}} \quad (25)$$

$$R_{Yi}^{\theta} = \overline{R_{Zi}^{O}} . \overline{U_{Yi^{\theta}}} . + \overline{R_{Yi}^{O}} . \overline{U_{Yi^{\theta}}} + \overline{R_{Xi}^{O}} . \overline{U_{Yi^{\theta}}} \quad (26)$$

$$R_{Xi}^{\theta} = \overline{R_{Zi}^{O}} . \overline{U_{Xi^{\theta}}} + \overline{R_{Yi}^{O}} . \overline{U_{Xi^{\theta}}} + \overline{R_{Xi}^{O}} . \overline{U_{Xi^{\theta}}} \quad (27)$$

The equations from (18) to (27) are repeated for each movement step.

Reaction Forces In The Prismatic Joints Evaluation

To evaluate the reaction forces in zone (3i) which represent the prismatic joint, the equilibrium equations are applied for the upper part of the linkage that contains the spherical joints that connected with moving platform, center zone (2i) and the prismatic joint (3i) as show in figure(5) and the equations are as bellow:

Σ FX = 0:

$$R_{X3i}^{\theta} + F_{X2i}^{\theta} - R_{XEi}^{\theta} = 0 \quad (28)$$

Σ FY = 0:

$$R_{Y3i}^{\theta} + F_{Y2i}^{\theta} - R_{YEi}^{\theta} = 0 \quad (29)$$

Σ MXEi = 0:

$$-R_{Y3i}^{\theta} * (0.5 * D_i) - R_{Y2i}^{\theta} * (0.25 * D_i) + M_{X2i}^{\theta} + M_{X3i}^{\theta} = 0 \quad (30)$$

Σ MYEi = 0:

$$R_{x3i}^{\theta} * (0.5 * D_i) + R_{x2i}^{\theta} * (0.25 * D_i) + M_{Y2i}^{\theta} + M_{Y3i}^{\theta} = 0 \quad (31)$$

Σ MZEi = 0:

$$M_{Z2i}^{\theta} + M_{Z3i}^{\theta} = 0 \quad (32)$$

Where:

i= 1, 2, …,6, Equations from (28) to (32) are repeated at each movement step.

Evaluation of Friction Forces and Friction Moments

The friction forces and friction moments are evaluated for all the robot joints by using mathematical modeling consist of two types of friction i.e.,(Coulomb and viscous friction). Because of the rotation in the spherical joints (Ei) and the spherical joints (Ci), the frictional effect is evaluated as a friction moments. The friction moment is expressed as follow **[12]**:

$$M^{O}_{frEi} = -\left[c_s\,.\omega^{O}_{1i,i} + \mu\,.r.\sqrt{(R^{O}_{Ei})^{T}\,.(R^{O}_{Ei})}\;.\frac{\omega^{O}_{1i,i}}{\omega^{O}_{1i,i}} \right] \qquad i = 1,2,...,6 \qquad (33)$$

$$M^{O}_{frCi} = -\left[c_s\,.\omega^{O}_{Oi,i} + \mu\,.\,r.\,\sqrt{(R^{\theta}_{Ci})^{T}\,.(R^{\theta}_{Ci})}\;.\frac{\omega^{O}_{Oi,i}}{\omega^{O}_{Oi,i}} \right] \qquad i = 1,2,...,6 \qquad (34)$$

Where :

c_s : - Viscous friction coefficient in the joint (Ei) (N.m.sec/rad) .

μ : – Coulomb friction coefficient of the joint (Ei)

$\omega^{O}_{1i,i}$: – Projection of the relative angular speed of the moving platform to the linkage

Projection of the vector of angular velocity of the link to the fixed platform

$\omega^{O}_{Oi,i}$: – r: Joint radius.

While in the prismatic joint (3i), there is friction force because there is sliding movement along the link. So that, the mathematical model that has been used to evaluate the friction **[12]** is:-

$$F^{\theta}_{fr} = -\left[c_s\,.v + \mu\,\sqrt{(R^{\theta}_{3i})^{T}\,.(R^{\theta}_{3i})}\;.\,\frac{v_i}{|v_i|} \right] \qquad (35)$$

Where:

v : – Projection of the relative linear speed of the link

The set of equations starting from (33) to (35) are repeated at each movement.

RESULTS

By using the equation derived above, a parametric study is done to evaluate the frictional forces and moments, MATLAB software is used to program the equations step by step. The fallowing parameters are as follow:

The weight of moving platform is equal to (10) kg and the weight of the external load (payload) is equal to (3) kg. The acceleration of the moving platform in the three dimensions are (ax=0.07, ay=0.05, az=0.04) m/s2 and the angular acceleration in three dimensions are (αx=0.005,αy=0.003,αz=0.0025) rad/s2 and inertia tenser unit matrix= 0.07kg.m2. the mass of the zones 2i and 4i is equal to (0.5) kg and the acceleration of the zone 2i and 4i in the three dimensions are (ax=0.055, ay=0.042, az=0.027)m/s2 and (αx=0.0032,αy=0.0021,αz=0.0017) and inertia tenser unit matrix =0.035 kg.m2,cs=0.02 N.m.sec/rad, ω=0.02 rad/sec, μ=0.04, r=0.05m. The results tabulated in Table (1) and Table (2) for frictional moments developed in moving and fixed platform, respectively. Table (3) listed the Friction forces of prismatic joints

Table (1) Friction moments in the joints that connected with moving platform with respect to (GCS), (N.m).

POS	MfrC1	MfrC2	MfrC.3	MfrC4	MfrC5	MfrC6
1	-0.044	-0.131	-0.124	-0.045	-0.046	-0.117
2	-0.133	-0.125	-0.046	-0.043	-0.052	-0.114
3	-0.132	-0.052	-0.070	-0.112	-0.046	-0.135
4	-0.035	-0.125	-0.113	-0.032	-0.119	-0.055
5	-0.035	-0.138	-0.045	-0.041	-0.114	-0.119
6	-0.052	-0.138	-0.121	-0.118	-0.038	-0.041
7	-0.038	-0.126	-0.119	-0.117	-0.042	-0.034
8	-0.042	-0.124	-0.031	-0.042	-0.132	-0.103
9	-0.053	-0.128	-0.116	-0.112	-0.024	-0.042
10	-0.055	-0.126	-0.124	-0.046	-0.0133	-0.118
11	-0.115	-0.053	-0.111	-0.038	-0.123	-0.033
12	-0.0131	-0.130	-0.036	-0.041	-0.105	-0.048
13	-0.137	-0.124	-0.044	-0.112	-0.051	-0.048
14	-0.128	-0.127	-0.050	-0.036	-0.102	-0.046
15	-0.132	-0.051	-0.112	-0.037	-0.118	-0.051
16	-0.037	-0.118	-0.044	-0.117	-0.053	-0.120
17	-0.043	-0.041	-0.126	-0.121	-0.049	-0.123
18	-0.050	-0.048	-0.126	-0.135	-0.112	-0.040
19	-0.043	-0.1430	-0.126	-0.044	-0.036	-0.109
20	-0.044	-0.060	-0.125	-0.126	-0.035	-0.122
21	-0.124	-0.118	-0.039	-0.049	-0.041	-0.118
22	-0.128	-0.049	-0.131	-0.117	-0.058	-0.041
23	-0.128	-0.045	-0.128	-0.121	-0.048	-0.051
24	-0.130	-0.045	-0.124	-0.125	-0.051	-0.042
25	-0.131	-0.126	-0.052	-0.058	-0.121	-0.043
26	-0.128	-0.124	-0.044	-0.045	-0.040	-0.122
27	-0.126	-0.120	-0.064	-0.052	-0.034	-0.122
28	-0.132	-0.130	-0.040	-0.050	-0.044	-0.124
29	-0.130	-0.123	-0.053	-0.042	-0.043	-0.119
30	-0.129	-0.122	-0.055	-0.041	-0.124	-0.042
31	-0.126	-0.129	-0.045	-0.049	-0.118	-0.045
32	-0.130	-0.121	-0.049	-0.050	-0.118	-0.048
33	-0.124	-0.121	-0.040	-0.041	-0.120	-0.049
34	-0.133	-0.117	-0.048	-0.039	-0.119	-0.036
35	-0.129	-0.119	-0.044	-0.037	-0.105	-0.111
36	-0.027	-0.038	-0.107	-0.103	-0.035	-0.102
37	-0.055	-0.031	-0.129	-0.122	-0.046	-0.122
38	-0.050	-0.039	-0.129	-0.122	-0.046	-0.122
39	-0.049	-0.046	-0.126	-0.120	-0.037	-0.120
40	-0.048	-0.040	-0.126	-0.114	-0.041	-0.126

Table (2) Friction moments in the joints connected with fixed platform with respect to the linkage direction, (N.m).

POS	MfrC1	MfrC2	MfrC.3	MfrC4	MfrC5	MfrC6
1	-0.044	-0.095	-0.122	-0.064	-0.051	-0.123
2	-0.133	-0.111	-0.068	-0.073	-0.062	-0.127
3	-0.132	-0.079	-0.086	-0.116	-0.051	-0.128
4	-0.035	-0.128	-0.110	-0.051	-0.112	-0.077
5	-0.030	-0.119	-0.065	-0.051	-0.036	-0.106
6	-0.046	-0.120	-0.118	-0.114	-0.067	-0.071
7	-0.044	-0.107	-0.113	-0.111	-0.070	-0.056
8	-0.037	-0.098	-0.044	-0.072	-0.123	-0.129
9	-0.069	-0.105	-0.108	-0.119	-0.054	-0.042
10	-0.052	-0.137	-0.117	-0.076	-0.050	-0.122
11	-0.109	-0.056	-0.103	-0.066	-0.099	-0.039
12	-0.125	-0.119	-0.053	-0.112	-0.125	-0.064
13	-0.127	-0.117	-0.059	-0.113	-0.066	-0.067
14	-0.107	-0.125	-0.058	-0.052	-0.118	-0.055
15	-0.103	-0.066	-0.080	-0.113	-0.1216	-0.077
16	-0.053	-0.126	-0.131	-0.121	-0.076	-0.128
17	-0.058	-0.067	-0.122	-0.131	-0.067	-0.116
18	-0.070	-0.048	-0.130	-0.072	-0.128	-0.056
19	-0.049	-0.095	-0.142	-0.139	-0.059	-0.117
20	-0.064	-0.068	-0.142	-0.147	-0.057	-0.121
21	-0.118	-0.124	-0.066	-0.061	-0.071	-0.116
22	-0.123	-0.059	-0.127	-0.142	-0.064	-0.053
23	-0.118	-0.065	-0.119	-0.117	-0.052	-0.067
24	-0.115	-0.048	-0.118	-0.116	-0.059	-0.057
25	-0.122	-0.119	-0.052	-0.072	-0.115	-0.056
26	-0.124	-0.102	-0.050	-0.060	-0.056	-0.188
27	-0.131	-0.101	-0.064	-0.068	-0.058	-0.123
28	-0.130	-0.124	-0.053	-0.056	-0.060	-0.122
29	-0.121	-0.118	-0.084	-0.074	-0.058	-0.126
30	-0.115	-0.125	-0.089	-0.075	-0.118	-0.047
31	-0.108	-0.111	-0.061	-0.065	-0.128	-0.045
32	-0.121	-0.108	-0.063	-0.071	-0.117	-0.048
33	-0.109	-0.117	-0.084	-0.063	-0.112	-0.040
34	-0.106	-0.115	-0.074	-0.062	-0.109	-0.034
35	-0.105	-0.116	-0.061	-0.059	-0.105	-0.048
36	-0.040	-0.058	-0.107	-0.101	-0.035	-0.110
37	-0.078	-0.044	-0.115	-0.113	-0.046	-0.118
38	-0.049	-0.076	-0.122	-0.110	-0.043	-0.119
39	-0.049	-0.052	-0.116	-0.124	-0.032	-0.120
40	-0.056	-0.046	-0.085	-0.108	-0.041	-0.118

Table (3) Friction forces in prismatic joints, (N)

POS	Ffr1	Ffr2	Ffr3	Ffr4	Ffr5	Ffr6
1	-0.452	-0.749	-0.751	-0.770	-0.985	-0676
2	-0.698	-1.101	-1.025	-1.024	-0.965	-1.038
3	-1.690	-0.975	-1.162	-0.898	-1.013	-0.769
4	-0.623	-0.770	-0.575	-1.154	-1.013	-0.989
5	-0.480	-1.129	-0.851	-0.808	-0.721	-0.833
6	-0.827	-1.314	-0.688	-0.714	-0.943	-0.845
7	-0.559	-0.746	-0.608	-0.763	-1.130	-0.848
8	-0.593	-0.944	-0.504	-0.870	-0.7247	-0.621
9	-0.838	-0.922	-0.832	-1.011	-0.709	-0.640
10	-0.633	-0.853	-0.825	-1.412	-0.755	-0.709
11	-0.860	-1.082	-0.531	-0.971	-0.657	-0.575
12	-0.823	-0.831	-0.624	-1.051	-0.813	-0.879
13	-1.059	-0.934	-0.630	-1.248	-0.982	-1.256
14	-0.6234	-1.034	-1.171	-0.826	-1.172	-0.985
15	-0.419	-0.820	-1.247	-0.814	-0.847	-1.271
16	-0.789	-0.853	-0.811	-1.202	-0.930	-0.969
17	-0.774	-0.826	-1.199	-1.300	-0.989	-0.851
18	-0.774	-0.966	-0.880	-1.242	-0.919	-0.833
19	-0.534	-0.768	-0.916	-0.863	-0.893	-0.913
20	-0.785	-0.754	-0.913	-1.311	-0.852	-1.202
21	-0.935	-0.795	-1.166	-1.017	-0.867	-0.851
22	-0.997	-0.966	-1.113	-0.904	-0.933	-1.287
23	-0.953	-0.841	-1.141	-1.036	-0.956	-1.132
24	-0.793	-0.782	-1.214	-1.040	-0.899	-0.810
25	-0.997	-1.009	-0.810	-0.991	-0.812	-0.718
26	-0.912	-0.827	-0.601	-0.834	-0.751	-0.833
27	-0.770	-0.828	-1.027	-0.971	-0.0687	-0.878
28	-1.267	-0.948	-0.608	-0.584	-0.791	-0.860
29	-0.790	-0.505	-1.068	-1.120	-0.819	-0.849
30	-0.839	-0.797	-1.476	-1.017	-0.828	-0.642
31	-0.652	-0.822	-0.787	-0.786	-0.942	-0.593
32	-0.572	-0.532	-0.678	-0.898	-0.778	-0.685
33	-0.704	-1.295	-1.065	-0.732	-0.543	-0.635
34	-0.715	-0.913	-1.370	-1.056	-0.801	-0.455
35	-0.703	-0.844	-0.874	-0.621	-0.485	-0.668
36	-0.799	-0.732	-0.785	-0.794	-0.637	-0.543
37	-1.008	-0.792	-0.799	-0.807	-0.755	-0.577
38	-0.449	-1.067	-1.002	-0.641	-0.702	-0.744
39	-0.615	-0.796	-0.863	-0.882	-0.435	-0.446
40	-1.077	-0.690	-0.869	-0.934	-0.655	-0.830

According to the results that listed in the above tables it is noted that there are change in the values of the friction forces and friction moments at each step and that's due to the change of the main variable and that is the reaction forces that developed in the joints in additional with the change in the position, orientation of the moving platform center and the angles of inclination of the linkages at each step of the forty steps.

CONCLUTION

In the present work, a mathematical model has been derived to evaluate the frictional forces and moments that developed in the all robot joints and all the results are listed in tables mentioned above. The values of frictional forces and moments are affected by linear or angular velocity of the joints, the value of coefficient of friction and the values of the reaction forces that developed in the robot joints. The step position values relay on the applied loading which affect on the forces exerted in each joint that make change on the values of forces and moments of friction developed in each joint. Also there is another reason to make this difference in the results that maintained above that is the change in the angle of inclination of each leg. The design of the robot depends on many factors and one of these factors is the resultant forces which affect on the size of the joints.

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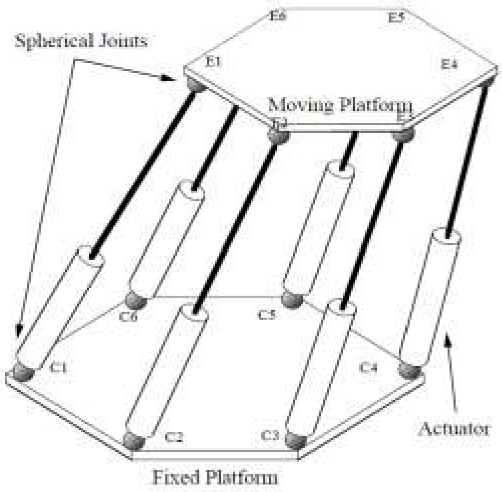

Figure (1) Gough-Stewart mechanism

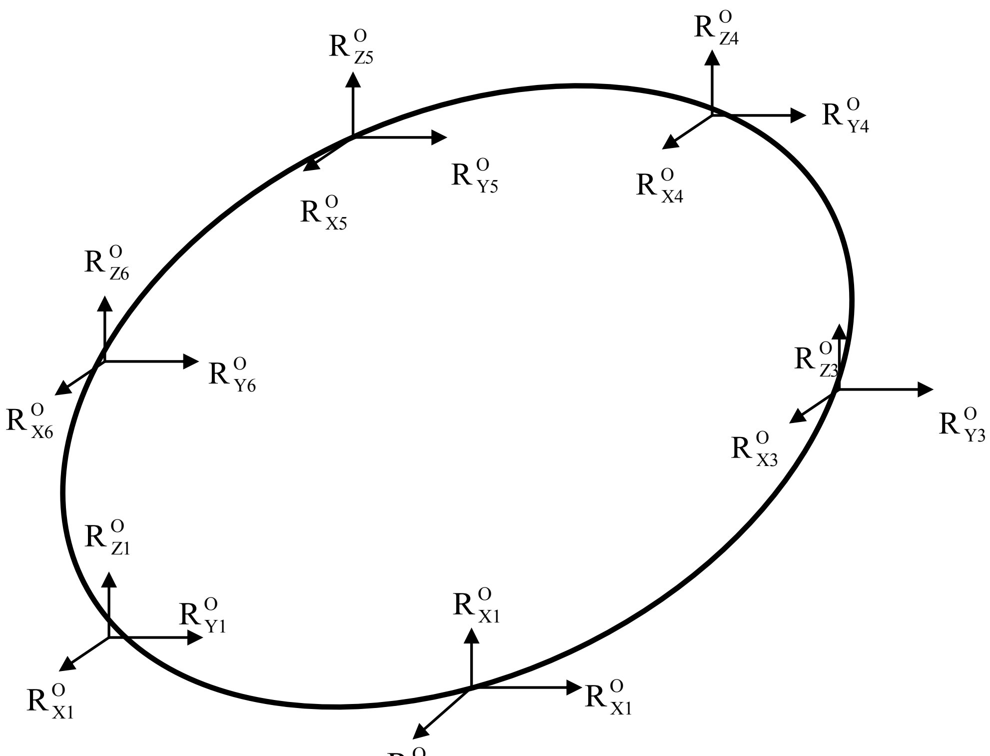

Figure (2): Free body diagram of the upper joints

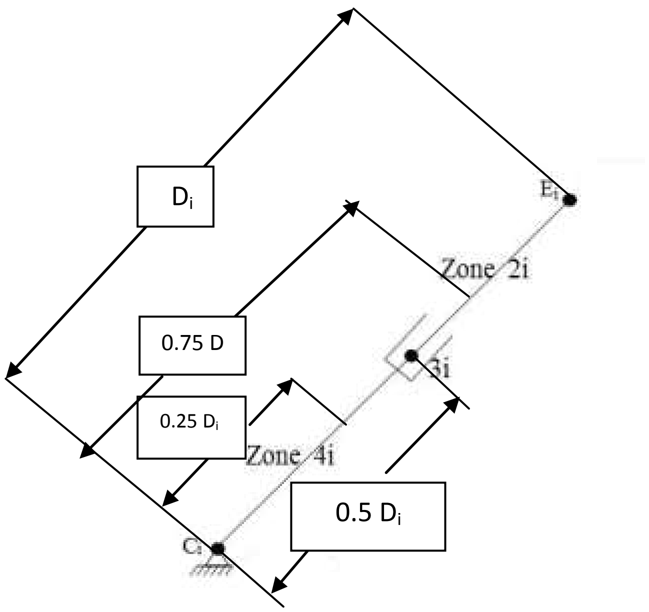

Figure (3) Linkage (i) mechanism

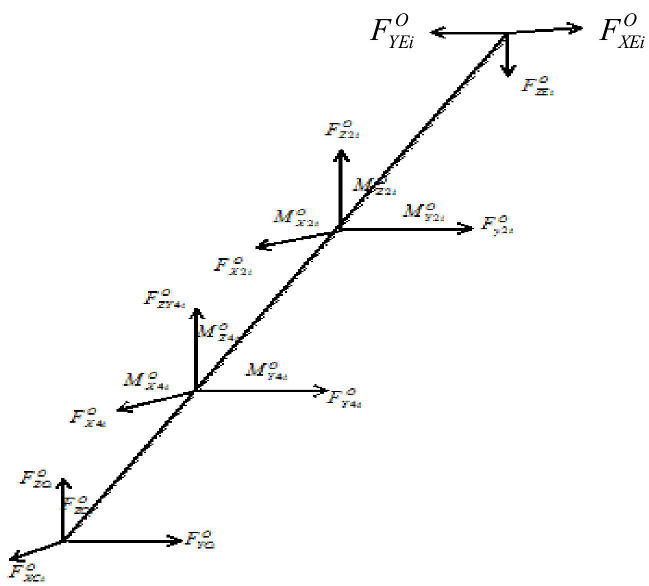

Figure (4) Linkage (i) free body diagram

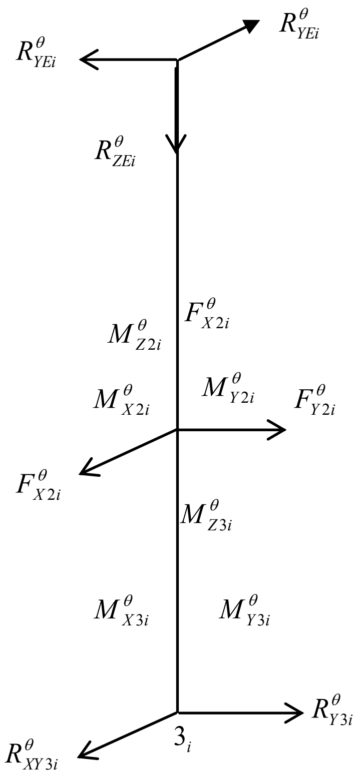

Figure (5) Upper part of the linkage (i)

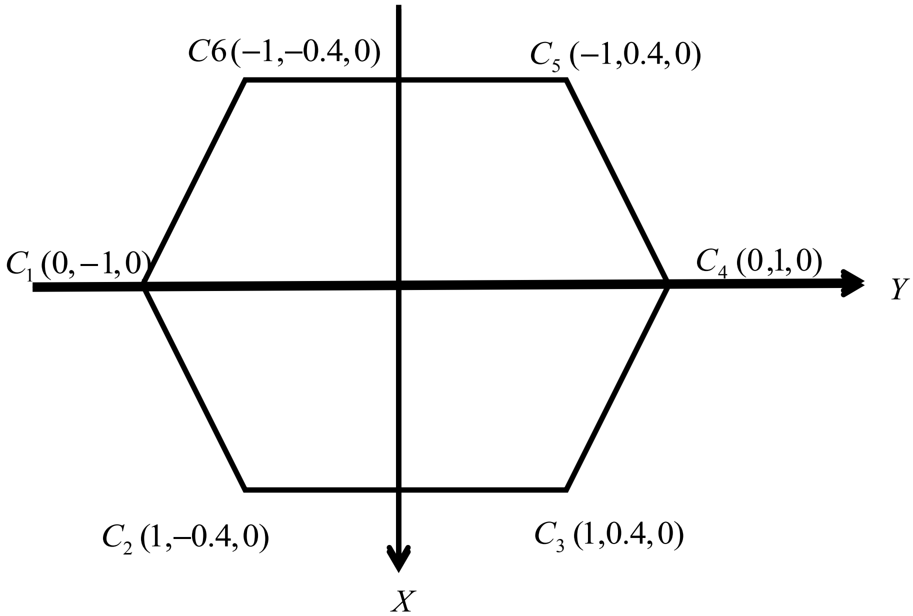

Figure (6): Dimensions of the fixed platform with respect to global coordinate system

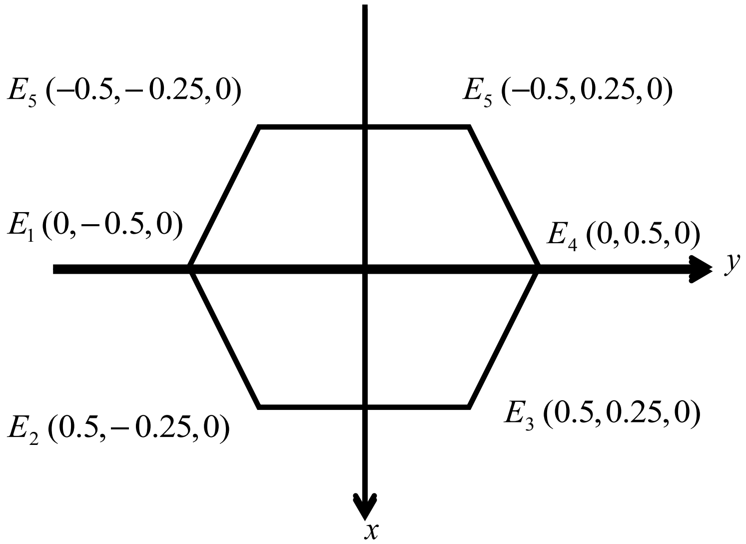

Figure (7): Dimensions of the moving platform with respect to local coordinate system