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Procedia Engineering 100 (2015) 206 – 212

Procedia Engineering

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25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Propulsion Effect Analysis of 3Dof Robot under Gravity

Ahmet Shala, Rame Likaj*, Mirlind Bruqi, Xhevahir Bajrami

University of Prishtina, Faculty of Mechanical Engineering, Bregu i diellit PN, Prishtina, Kosovo

Abstract

Modeling, Analysis and Control of robotic systems usually requires that initially the Dynamical Modeling to be carried out. In this paper is used Denavit-Hartenberg (DH) convention for kinematics and Newton-Euler formulations for dynamical modeling of 3DOF robot (3 degree of freedom). Dynamical model is derived by using Software Maple. Simulations for the analysis of propulsion effect under gravity are done using Matlab/Simulink, where Link 1 rotates with 1000 rpm, Link 2 can move freely in vertical direction and Link 3 can rotate freely around its rotation axle. Simulation results show that propulsion of the proposed 3DOF robot is very good. Results are verified-compared with the constructed model of 3DOF robot by using Working Model 3D.
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Keywords: Modeling; Kinematics; Dynamics; Robot; Propulsion

1. Introductions

The idea for design of mechanisms for on “antigravity” propulsion effect based on produced inertial forces is very old, but results on this field are considerable. In this paper is presented modelling and analysis of a 3 Dof (degree of freedom) robot, which consists of three links: Rotational-Translative-Rotational. The problem statement is to analyse the possible propulsion effect for the case when first link rotates i.e. with 1000 rpm, second prismatic link can move free up-down and third link can rotate free from its initial position as is shown in Fig. 1.

Too many authors have work on design of the mechanism which produces propulsion effect such as Hoshino on his patent [2], Provaditis [3] or Dean’s patent [1]. Synthesis of mechanisms is base for study of propulsion [10]. Propulsion effect is enough studied for different uses on robotic systems, see e.g. [4, 5, 6, 7, 8, 9]. Different proposed mechanisms have their advantages and disadvantages based on proposed use of robotic systems.

* Corresponding author. Tel.: +377-44-214-947.
E-mail address: rame.likaj@uni-pr.edu

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doi:10.1016/j.proeng.2015.01.359

2. Modeling of 3 Dof robot

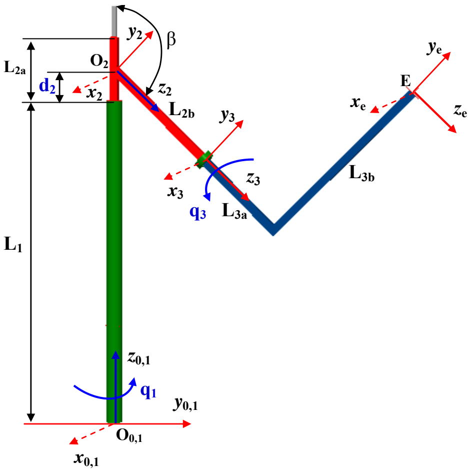

Fig. 1. View of proposed 3 Dof robot and symbolic representation of Denavit-Hartenberg parameters.

Our designed 3 DOF robot shows very high propulsion effect, but it depends from initial position of the third link. Based on Fig. 1 are chosen Denavit-Hartenberg parameters for all three links, which are shown in Table 1.

Table 1. Denavit-Hartenberg parameters for 3 Dof robot.

Link #	a_i	α_i	d_i	θ_i
1	0	0	d_1	q_1^*
2	0	$-\beta$	d_2^*	0
3	0	0	L_{3a}	q_3^*

2.1. Dynamical modeling of 3 Dof robot using Maple software

> *restart* :
> *with*(*LinearAlgebra*) :
> # Joint variables (degrees of freedom)
> $q := Vector([[q1],[d2],[q3]])$: > $dq := Vector([[dq1],[dd2],[dq3]])$: > $ddq := Vector([[ddq1],[ddd2],[ddq3]])$:
> # Link length vectors and vectors to the centers of mass
> $s1 := Vector([[0],[0],[0]])$: > $s2 := Vector([[0],[0],[zC2]])$: > $s3 := Vector([[xC3],[0],[zC3]])$: > $\beta := \frac{3\cdot\pi}{4}$:
> # Rotation matrices
> $R1 := \begin{bmatrix} \cos(q[1]) & -\sin(q[1]) & 0 \\ \sin(q[1]) & \cos(q[1]) & 0 \\ 0 & 0 & 1 \end{bmatrix}$: > $R2 := \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\sin(\pi-\beta) & \cos(\pi-\beta) \\ 0 & -\cos(\pi-\beta) & -\sin(\pi-\beta) \end{bmatrix}$: > $R3 := \begin{bmatrix} \cos(q[3]) & -\sin(q[3]) & 0 \\ \sin(q[3]) & \cos(q[3]) & 0 \\ 0 & 0 & 1 \end{bmatrix}$:
> # Initial conditions
> $z0 := Vector([[0],[0],[1]])$: > $\omega 0 := Vector([[0],[0],[0]])$: > $d\omega 0 := Vector([[0],[0],[0]])$:
> $v0 := Vector([0],[0],[0])$: > $dv0 := Vector([[0],[0],[g]])$:
> # Forward recursions(i=1,2,3)
> # Angular velocity of the i-th coordinate frame
> $\omega 1 := combine(MatrixVectorMultiply(Transpose(R1), (\omega 0 + z0\cdot dq[1])))$:
> $\omega 2 := combine(MatrixVectorMultiply(Transpose(R2), \omega 1))$:
> $\omega 3 := combine(MatrixVectorMultiply(Transpose(R3), (\omega 2 + z0\cdot dq[3])))$:

```
> # Angular acceleration of the i-th coordinate frame
> dω1 := combine(MatrixVectorMultiply(Transpose(R1), (dω0 + z0·ddq[1] + CrossProduct(ω0,z0·dq[1])))) :
> dω2 := combine(MatrixVectorMultiply(Transpose(R2), dω1)) :
> dω3 := combine(MatrixVectorMultiply(Transpose(R3), (dω2 + z0·ddq[3] + CrossProduct(ω2,z0·dq[3])))) :
> # Position of the i-th coordinate frame with respect to the (i-1)-th coordinate frame
> p1 := Vector([[0],[0],[d1]]) :
> p2 := Vector([[0],[-d2·sin(π/4)],[-d2·sin(π/4)]]) :
> p3 := Vector([[0],[0],[L3]]) :
> # Linear acceleration of the i-th coordinate frame
> dv1 := combine(MatrixVectorMultiply(Transpose(R1), dv0) + CrossProduct(dω1,p1) + CrossProduct(ω1,CrossProduct(ω1,p1))) :
> dv2 := combine(MatrixVectorMultiply(Transpose(R2), dv1 + z0·ddq[2] + CrossProduct(2·ω1,z0·dq[2]))
      + CrossProduct(dω2,p2) + CrossProduct(ω2,CrossProduct(ω2,p2))):
> dv3 := combine(MatrixVectorMultiply(Transpose(R3), dv2) + CrossProduct(dω3,p3) + CrossProduct(ω3,CrossProduct(ω3,p3))) :
> # Linear acceleration of the center-of-mass of link i
> da1 := combine(CrossProduct(dω1,s1) + CrossProduct(ω1,CrossProduct(ω1,s1)) + dv1) :
> da2 := combine(CrossProduct(dω2,s2) + CrossProduct(ω2,CrossProduct(ω2,s2)) + dv2) :
> da3 := combine(CrossProduct(dω3,s3) + CrossProduct(ω3,CrossProduct(ω3,s3)) + dv3) :
> # Moment of inertia tensor of link i about the center-of-mass of link i.
> I1 := [I1xx 0 0; 0 I1yy 0; 0 0 I1zz] :  > I2 := [I2xx 0 0; 0 I2yy 0; 0 0 I2zz] :  > I3 := [I3xx 0 0; 0 I3yy 0; 0 0 I3zz] :
> # Net force and moment exerted on link i
> F1 := m1·da1 :  > F2 := m2·da2 :  > F3 := m3·da3 :
> N1 := combine(MatrixVectorMultiply(I1, dω1) + CrossProduct(ω1,MatrixVectorMultiply(I1, ω1))) :
> N2 := combine(MatrixVectorMultiply(I2, dω2) + CrossProduct(ω2,MatrixVectorMultiply(I2, ω2))) :
> N3 := combine(MatrixVectorMultiply(I3, dω3) + CrossProduct(ω3,MatrixVectorMultiply(I3, ω3))) :
> # Backward recursion (i=3,2,1); Force and moment exerted on link i by link i-1
> # Supposing that there are no outside load on end-effector
> f4 := [0; 0; 0] :  > n4 := [0; 0; 0] :  > R4 := [1 0 0; 0 1 0; 0 0 1] :
> τ4 := MatrixVectorMultiply(Transpose(n4),MatrixVectorMultiply(Transpose(R4),z0)) :
> # Link #3
> f3 := MatrixVectorMultiply(R4,f4) + F3 :  > n3 := MatrixVectorMultiply(R4,n4) + CrossProduct(p3,f3) + N3 + CrossProduct(s3,F3) :
> # Torque at joint 3
> τ3 := MatrixVectorMultiply(Transpose(n3),MatrixVectorMultiply(Transpose(R3),z0)) :
> # Link #2
> f2 := MatrixVectorMultiply(R3,f3) + F2 :  > n2 := MatrixVectorMultiply(R3,n3) + CrossProduct(p2,f2) + N2 + CrossProduct(s2,F2) :
> # Force at joint 2
> τ2 := MatrixVectorMultiply(Transpose(f2),MatrixVectorMultiply(Transpose(R2),z0)) :
> # Link #1
> f1 := MatrixVectorMultiply(R2,f2) + F1 :  > n1 := MatrixVectorMultiply(R2,n2) + CrossProduct(p1,f1) + N1 + CrossProduct(s1,F1) :
> # Torque at joint 1
> τ1 := MatrixVectorMultiply(Transpose(n1),MatrixVectorMultiply(Transpose(R1),z0)) :
> τ := Vector([[expand(τ1)],[expand(τ2)],[expand(τ3)]]) :
> with(CodeGeneration) :
> # Dynamical model of 3 Dof robot in form Tau=M*ddq+CG
> Matlab(simplify(τ1),resultname="T1") :
> Matlab(simplify(τ2),resultname="T2") :
> Matlab(simplify(τ3),resultname="T3") :
```

3. Simulation results of propulsion effect analysis

Simulations using Matlab/Simulink are done based on Control Scheme shown in Fig. 2.

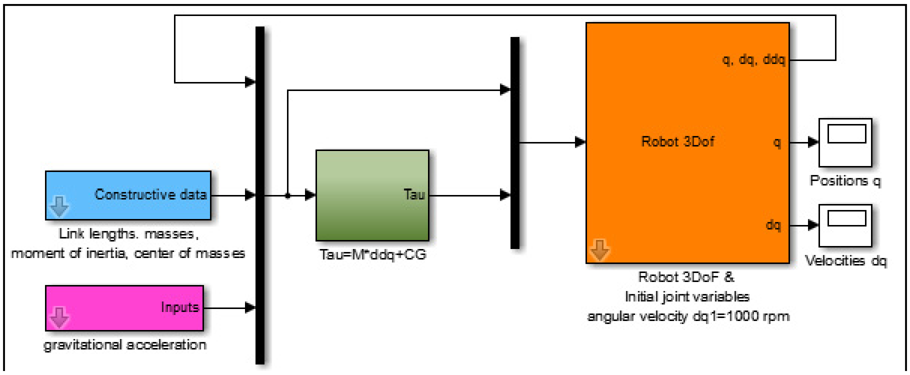

Fig. 2. Simulation scheme of robot, propulsion effect for initial position of Link 3 under q_3=180°.

Conditions for simulation 3 Dof robot:

- Link 1 can rotate freely.
- Link 2 is freely supported on Link 1 and the angle between two parts of Link 2 is fixed to 45°.
- Link 3 starts in vertical position (up normal to x_0-y_0 plane) and swings freely.
- Steel is assumed for the cylinder/prism masses and moments of inertia.

As it is known that a robot manipulator is basically a positioning device, is analysed firstly the dependence of propulsion effect from initial position of third link, which can rotate freely around its axle. In Fig. 3 is shown a diagram contact force change F_2 of the Link 2, depending on initial position q_3 of the Link 3.

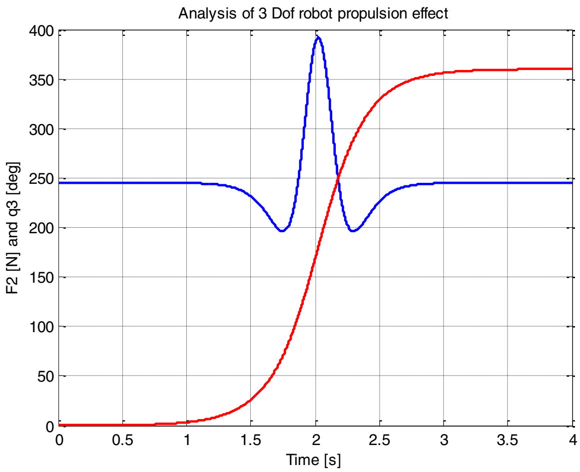

Fig. 3. Contact Force F_2 between Link 2 and Link 1 and orientation q_3 of Link 3.

From Fig. 3 is shown that contact force F_2 has its maximum value F_{2max}=392.16N for q_3=180°.
Conditions for the simulation 3 Dof robot are given in the following:

- Link 3 starts in vertical position and swings freely, initial position q_3 = pi = 180°.
- Link 1 is turned up to 1000 rpm
- Propulsion is result of fast rotation of Link 1, 1000 rpm, and rotation-oscillation of Link 3, and Contact-inertial force between Link 2 and Link 1 exists only for the cases when these two Links are in contact, if there is no contact, this mean that Link 2 starts to move up (d_2>1.1) and the result of the contact force is zero.

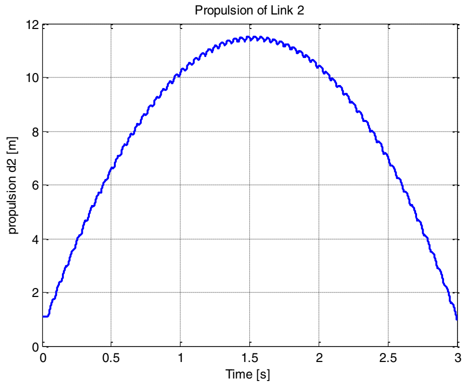

Fig. 4. Vertical propulsion d_2 of Link 2.

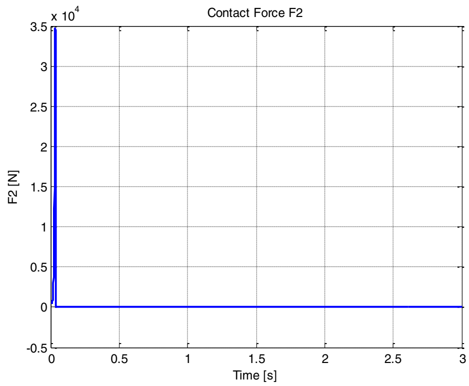

Fig. 5. Contact Force F_{2c} between Link 2 and 1.

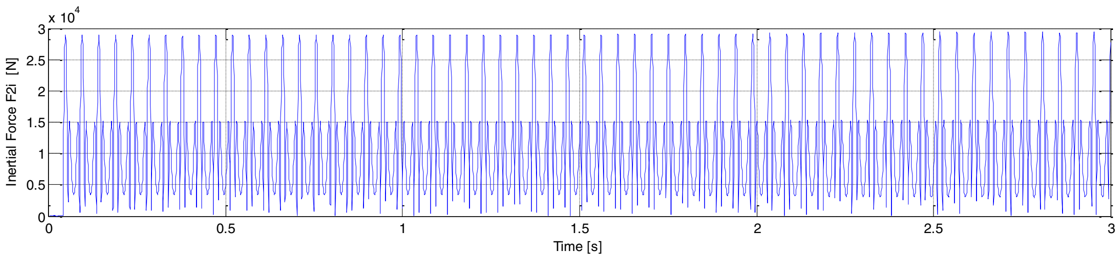

Fig. 6. Inertial Force F_{2i} of Link 2.

Modeling and simulations software's provide very good and specialized tools for verification of results [6, 8]. In Fig. 7, is shown modelling and simulation of 3 DOF robot, which is constructed in the Working Model 3D software.

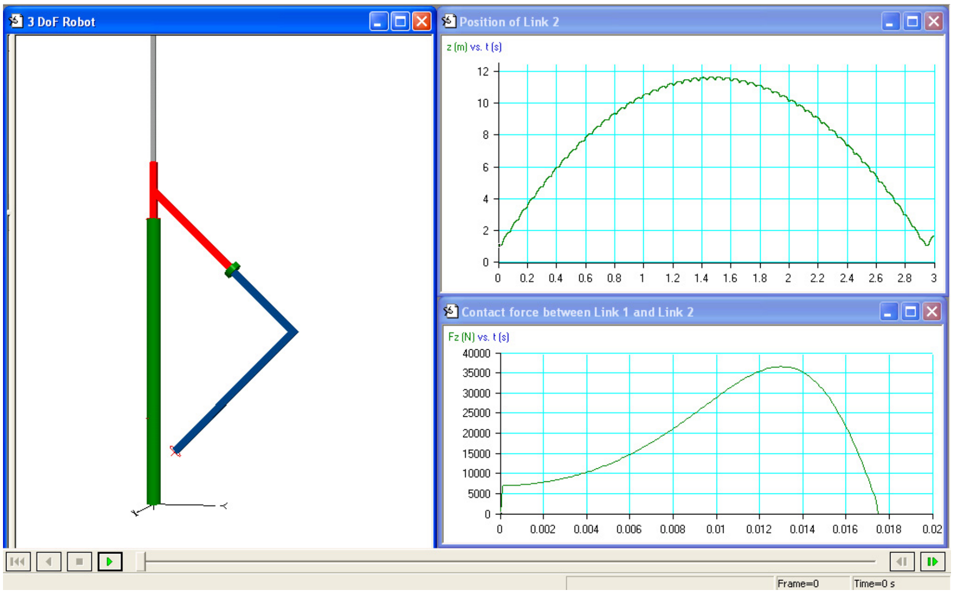

Fig. 7. Modeling and simulations of 3 DOF robot using Working Model 3D software.

Conclusion

This paper describes the design, modelling and simulation of the proposed configuration of 3 DOF robot.

Kinematic analysis of 3 DOF robot is carried out by using Denavit-Hartenberg symbolic representation, as shown in Fig. 1 and Tab. 1.

Dynamical Model for 3 DOF robot is derived based on the Newton-Euler formulations. Dynamical Model is derived by using Maple software which contains very good tools for symbolic calculations and converters for Matlab/Simulink.

Simulations of dynamical model of 3 DOF robot are done using Matlab/Simulink software, based on simulations scheme, which is shown in Fig. 2.

Based on modelling, simulation results and analysis initial position of Link 3 $(q_3)_0=180°$ also have been found, and this represents special position for maximal propulsion of proposed 3 DOF robot (Fig. 3).

Propulsion of Link 2 or vertical position d_2 grows up significantly from its initial position 1.1m up to approximately 11.5m (Fig. 4), while Link 3 oscillates freely around its own oscillation axle.

Special case for $(q_3)_0=180°$, clearly illustrates that propulsion effect exists. Based on the diagram of contact force shown in Fig. 5 and Fig. 7, and by including other simulations tests which are done, we can conclude that this is the biggest propulsion of 3 DOF robot.

The verification of the results for dynamical model simulations in Matlab/Simulink, are verified by using constructed 3 DOF robot in Working Model 3D software (Fig. 7).

Result of rotation of Link 1 with 1000 rpm and contact force F_{2c}, between Link 2 and Link 1, produces the inertial force F_{2i}, Fig. 6, reaching its maximum around $\max(F_{2i})$ = 29 kN. This force is large enough and that can be used for carrying or holding any load.

Our plan for future work is to build and test the designed 3 DOF robot. It might be also of great interest to study the designed robot in relation to the work on zero-gravity working space.

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