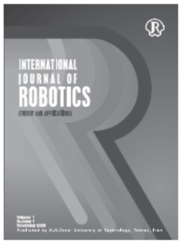

INTERNATIONAL JOURNAL OF ROBOTICS
(THEORY AND APPLICATIONS)
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Optimal Trajectory Generation for Energy Consumption Minimization and Moving Obstacle Avoidance of SURENA III Robot's Arm

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ARTICLE INFO

Article history:
Received: August 20, 2015.
Received in revised form: October 11, 2015.
Accepted: October 17, 2015.

Keywords:
SURENA III
Minimal Energy Consumption
Trajectory generation
Genetic Algorithms
Optimization

ABSTRACT

In this paper, trajectory generation for the 4 DOF arm of SURENA III humanoid robot with the purpose of optimizing energy and avoiding a moving obstacle is presented. For this purpose, first, kinematic equations for a seven DOF manipulator are derived. Then, using the Lagrange method, an explicit dynamics model for the arm is developed. In the next step, in order to generate the desired trajectory for the arm, two different methods are utilized. In the first method, each joint motion is presented by a quadratic polynomial. In the second one, the end effector's path has been considered as 3 polynomial functions. Also, a known moving spherical obstacle with a linear path and constant velocity is considered in robot workspace. The main goal of optimization is to reduce the consumed energy by the arm in a movement between two known points in a specified time frame to avoid the moving obstacle. Initial and final velocities of the arm are set as zero. To this end, the optimization is carried out using Genetic Algorithm. Finally, in order to obtain the most reliable solutions for trajectory generation, many optimizations with various parameters are conducted and the results are presented and discussed.

1. Introduction

In recent decades, many industries such as car fabrication employed robotic arms instead of human resources. Moreover, these arms are as a part of some more complicated anthropomorphic systems, such as humanoid robots. Therefore, many studies have been carried out on these robots. Design and fabrication, selecting suitable actuator, trajectory generation, controlling the robot etc. are challenges of this field. Normally, humanoid robots arms have four or seven DOF (weather they are equipped with a three DOF wrist or not) that made them redundant.

Selecting suitable actuator and actuators performance are the important issues, while designing the robot. Moreover, due to the usage of batteries in robots, trajectory generation and optimum movement may be important. Therefore many studies have been

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done for optimizing the robots trajectories in terms of energy consumption. In this notion, Field and Stepanenko minimized consumed energy of the robot by a suitable trajectory generation, using a repetitive coding method [1]. Hirakawa and Kawamura introduced a new method for generating trajectory of a redundant robotic arm that could optimize robot energy consumption [2]. Moreover, Saramago and Stefen generated trajectory of a robotic arm by the goal of minimizing energy consumption and traveling time [3]. Furthermore, Ding et al. optimized dynamic of redundant robotic arm, using recurrent neural network [4]. Zhang et al. optimized a 6 DOF robotic arm dynamic, using a GA [5].

Minimizing the actuators applying torque is another optimization problem. Therefore Zhang et al. optimized joint's applied torque of a redundant robotic arm employing A Unified Quadratic-Programming-Based Dynamical System [6]. Also, Ma developed a new formulation technique for local torque optimization of redundant manipulators [7].

Another important issue while generating trajectory of a robotic manipulator is existence of moving or fixed obstacles and collision possibility. Guo and Hsia avoided collision of a redundant arm and obstacle, using joints trajectory generation [8]. Moreover, Baba and Kubota avoided obstacle collision of a robotic arm exploiting Genetic Algorithm [9]. Also, Zhang and Wang did the same procedure, using a dual neural network [10].

Combination of optimizing the energy consumption and obstacle avoidance of a robotic arm is one of the challenges while generating trajectory of manipulators. To do so, Kawato et al. employed Cascade Neural Network Model Based on Minimum Torque-Change Criterion to optimize energy consumption of a manipulator while avoiding obstacle [11]. Deo and Walker minimized energy consumption of a planar robotic arm while avoiding obstacles [12]. Also, Saramago and Steffen avoided a fixed obstacle while minimizing the consumed energy [13]. Zhu et.al minimized consumed energy of a planar robotic arm while avoiding a fixed obstacle [14]. Other studies have been carried in this field [15-17] but none of them considered both the moving obstacle and a robotic arm movement in 3D space. In recent years, different studies have been done in this subject. Serdar Kucuk minimized consumed energy of a 3-RRR fully planar parallel manipulator, using PSO [18]. Also in 2015 Hui and Zhijiang planned a path for a Planar Redundant Manipulators to avoidance obstacles, using Workspace Density [19].

The main aim of this research is to generate joint trajectories of a robotic arm based on polynomials time functions, while optimizing consumed energy of the robot in the presence of moving obstacles. For this purpose, SURENA III Iranian national humanoid robot's arm have been used.

Figure 1. SURENA III's arm

Figure 2. SURENA III humanoid robot

2. Robotic Arm Kinematic

As it is illustrated schematically in fig1, the SUERNA III robot's arm has 7 DOF which is composed of three DOFs in shoulder, one DOF in elbow and three DOFs in wrist. In order to encapsulate the forward kinematics set of equations, the coordinate axes are attached to the joints based on Denavit-Hartenberg convention and the parameters are calculated and specified in table (1). The numbering and arrangement of the DOFs are specified in table (2).

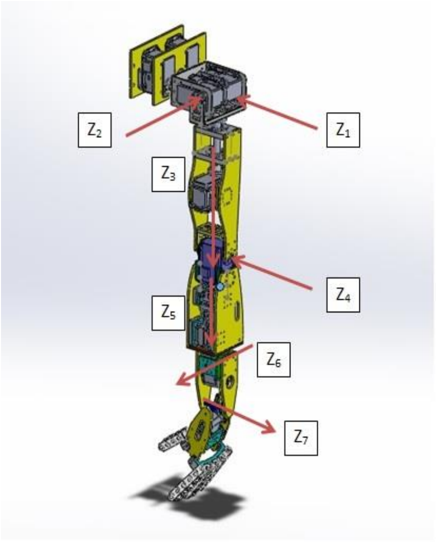

Figure 3. Robot structure

Figure 4. Robotic Arm

Table 1. Robot Denavit-Hartenberg parameters

i	***α_i***	***a_i***	***d_i***	***θ_i***
1	-90	0	0	θ_1
2	-90	0	0	θ_2
3	-90	0	0.25	θ_3
4	90	0	0	θ_4
5	-90	0	0.24	θ_5
6	90	0	0	θ_6
7	0	0	0	θ_7

Table 2. Robot Degrees of Freedom

DOF	Number
Shoulder Flexion/Extension	1
Shoulder Abduction/Adduction	2
Shoulder Rotation	3
Elbow	4
Wrist Rotation	5
Wrist Abduction/Adduction	6
Wrist Flexion/Extension	7

By multiplying the transformation matrices successively, the position and orientation of the end-effector with respect to the base of the arm are calculated.

$$ {}^{B}_{W}P = {}^{B}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{6}T\,{}^{6}_{W}T\;\; {}^{W}_{W}P \tag{1}$$

Where ${}^{B}_{W}P$ represents position of the wrist with respect to base of the arm. The forward kinematics procedure may be carried out to yield posture of the end-effector. Since the object grasping or manipulation are not of concern during obstacle avoidance, the 3 DOFs of the wrist are not included during the modeling and analyses. Therefore, using shoulder and elbow's DOFs, position of end-effector can be achieved:

$$ {}^{B}_{W}P = {}^{B}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{W}T\,{}^{W}_{W}P \tag{2}$$

Using the above equation, position components of the end effector may be obtained as equations below:

$$\begin{aligned} X_{ef} &= -l_2 \sin\theta_4 (\cos\theta_1 \cos\theta_3 \\ &+ \sin\theta_1 \sin\theta_2 \sin\theta_3) - l_1 \cos\theta_2 \sin\theta_1 \\ &- l_2 \cos\theta_2 \cos\theta_4 \sin\theta_1 \end{aligned} \tag{3}$$

$$\begin{aligned} Y_{ef} &= l_1 \sin\theta_2 + l_2 \cos\theta_4 \sin\theta_2 \\ &- l_2 \cos\theta_2 \sin\theta_3 \sin\theta_4 + 0.065 \end{aligned} \tag{4}$$

$$\begin{aligned} Z_{ef} &= l_2 \sin\theta_4 (\cos\theta_3 \sin\theta_1 \\ &- \cos\theta_1 \sin\theta_2 \sin\theta_3) - l_1 \cos\theta_1 \cos\theta_2 \\ &- l_2 \cos\theta_1 \cos\theta_2 \cos\theta_4 \end{aligned} \tag{5}$$

Where $l_1 = 0.25\ m$, $l_2 = 0.24\ m$.Moreover, position of elbow can be achieved as below:

$$\begin{aligned} X_{el} &= -l_1 \cos\theta_2 \sin\theta_1 \\ Y_{el} &= l_1 \sin\theta_2 + 0.065 \\ Z_{el} &= -l_1 \cos\theta_1 \cos\theta_2 \end{aligned} \tag{6}$$

In order to compare two different approaches for generating trajectory of robot's end effector, the trajectory generation has been done for joints and end effector. In the first method, joint's angles have been considered as quadratic polynomials as below:

$$\theta_1 = a_1 t^4 + a_2 t^3 + a_3 t^2 + a_4 t + a_5 \tag{7}$$

$$\theta_2 = a_6 t^4 + a_7 t^3 + a_8 t^2 + a_9 t + a_{10} \tag{8}$$

$$\theta_3 = a_{11} t^4 + a_{12} t^3 + a_{13} t^2 + a_{14} t + a_{15} \tag{9}$$

$$\theta_4 = a_{16} t^4 + a_{17} t^3 + a_{18} t^2 + a_{19} t + a_{20} \tag{10}$$

In the second method the end effector's trajectory is considered as three time dependent polynomials as below:

$$x = a_1 t^4 + a_2 t^3 + a_3 t^2 + a_4 t + a_5 \tag{11}$$

$$y = a_6 t^4 + a_7 t^3 + a_8 t^2 + a_9 t + a_{10} \tag{12}$$

$$z = a_{11} t^4 + a_{12} t^3 + a_{13} t^2 + a_{14} t + a_{15} \tag{13}$$

In the second method, in order to find joint's angles, inverse kinematics needs to be solved.

3. Inverse Kinematics

In order to solve the inverse kinematics problem of the under-study redundant arm, the redundancy resolution is adopted using all of the joints of the arm. Hence:

$$\dot{q}_{7\times1} = J^{\dagger}_{7\times6}\dot{x}_{6\times1} + \left(I_{7\times7} - J^{\dagger}_{7\times6}J_{6\times7}\right)k_{7\times1} \tag{14}$$

Where $\dot{q}$, $J^{\dagger}_{7\times6}$ and $\dot{x}_{6\times1}$ represent joint space velocity vector, jacobian matrix and task space velocity vector, respectively. Also, $k_{7\times1}$ is a vector of constants that specify the redundancy resolution technique that is adopted. In fact, the second term in right-hand-side of Eq. (14) specifies null space motion (motion in joint space which does not affect task space). In other word, the first term in right-hand-side of Eq. (14) guarantees the first task of the end effector which is moving on a predefined path to be fulfilled, and the second term, without any interference to the first task, exploit the redundant degree(s) of freedom to assure another task implementation. For instance, the redundant degrees of freedom can be exploited to obstacles are avoided or singularities are evaded.

In order to have motion with minimum $\|\dot{q}_{7\times1}\|_2$, the motion in null space should be set to zero. Doing so, the joint space velocities can be calculated:

$$\dot{q}_{7\times1} = J^{\dagger}_{7\times6}\dot{x}_{6\times1} \tag{15}$$

It should be noted that by using Eq. (15) the joint space velocities are calculated and velocity control in joint space should be adopted to realize the desired motion. However, in this approach calculation of pseudo-inverse of a 7×6 matrix is needed and the control of position and orientation of the end-effector are coupled. In this paper, the main focus is on the end effector's positions. Therefore in order to simplify the calculations Eq. (15) can be changed into:

$$\dot{q}_{4\times1} = J^{\dagger}_{4\times3}\dot{x}_{3\times1} \tag{16}$$

In this equation, $\dot{x}_{3\times1}$ is the desired position of the wrist and the desired values for joint space velocities that are calculated to produce minimum $\|\dot{q}_{4\times1}\|_2$. As a result, the shoulder and elbow velocity of the joints should be controlled to realize desired motion for the wrist.

4. Dynamic Model of Manipulator

There are different approaches to model dynamic behavior of a robotic manipulator such as Newton-Euler and Lagrange. In this paper, Lagrange approach has been chosen for its simplicity. In this approach, joint's required torque can be achieved using the robots kinetic and potential energy. Main Lagrange equations can be written as :

$$K = \frac{1}{2}m_1 V_1^2 + \frac{1}{2}m_2 V_2^2 \tag{17}$$

$$U = m_1 g(l_1 + Z_{el}) + m_2 g(l_1 + l_2 + Z_{ef}) \tag{18}$$

$$L = K - U \tag{19}$$

$$\tau = \frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} \tag{20}$$

Where $m_1 = 0.43kg$, $m_2 = 0.4kg$, $m_2 = 0.4Kg$ l_1=0.25m $l_1 = 0.25\ m$, $l_2 = 0.24\ m$ Furthermore, in order to calculate V_1, V_2 it can achieved using $X_{el}, Y_{el}, Z_{el}, X_{ef}, Y_{ef}, Z_{ef}$'s derivative with respect to time.

$$V_1 = \sqrt{\dot{X}_{el}^2 + \dot{Y}_{el}^2 + \dot{Z}_{el}^2} \tag{21}$$

$$V_2 = \sqrt{\dot{X}_{ef}^2 + \dot{Y}_{ef}^2 + \dot{Z}_{ef}^2} \tag{22}$$

5. Optimizing Robots Movements

In order to optimize robot's movements, a Genetic Algorithm has been employed. The considered objective function is the consumed energy of the arm which may be specified by the following equation:

$$E = \sum_{i=1}^{4} \tau_i \dot{q}_i = \tau_1\dot{q}_1 + \tau_2\dot{q}_2 + \tau_3\dot{q}_3 + \tau_4\dot{q}_4 \tag{23}$$

In this equation τ represents the joint actuating torque, while $\dot{q}$ denotes the joint velocity. The arbitrary path that is considered for the robot is such that the end-effecter should start from the point [37,-10,-11] with zero velocity, and end its motion at the point [25, 20, 5] with zero velocity. As it has been mentioned earlier, two different approaches are considered to generate trajectory of the robot. For the first method, the optimization constraints may be specified as below. In order to calculate the initial and final joint angles, the inverse kinematics is exploited.

$$
\begin{gathered}
a_5 = -\frac{55\pi}{180}, a_{10} = \frac{1.33\pi}{180} \\
a_{15} = -\frac{54.85\pi}{180}, a_{20} = -\frac{62.11\pi}{180} \\
a_4 = a_9 = a_{14} = a_{19} = 0 \\
16a_1 + 8a_2 + 4a_3 + 2a_4 + a_5 = -\frac{50\pi}{180} \\
16a_6 + 8a_7 + 4a_8 + 2a_9 + a_{10} = \frac{67.51\pi}{180} \\
16a_{11} + 8a_{12} + 4a_{13} + 2a_{14} + a_{15} = -\frac{25.35\pi}{180} \\
16a_{16} + 8a_{17} + 4a_{18} + 2a_{19} + a_{20} = -\frac{106.58\pi}{180} \\
32a_1 + 12a_2 + 4a_3 + a_4 = 0 \\
32a_6 + 12a_7 + 4a_8 + a_9 = 0 \\
32a_{11} + 12a_{12} + 4a_{13} + a_{14} = 0 \\
32a_{16} + 12a_{17} + 4a_{18} + a_{19} = 0
\end{gathered}
\tag{24}
$$

For the second method the constraints can be considered as below:

$$
\begin{gathered}
a_5 = 0.37, a_{10} = -0.1, a_{15} = -0.11 \\
a_4 = a_9 = a_{14} = 0 \\
16a_1 + 8a_2 + 4a_3 + 2a_4 + a_5 = 0.25 \\
16a_6 + 8a_7 + 4a_8 + 2a_9 + a_{10} = 0.2 \\
16a_{11} + 8a_{12} + 4a_{13} + 2a_{14} + a_{15} = 0.05 \\
32a_1 + 12a_2 + 4a_3 + a_4 = 0 \\
32a_6 + 12a_7 + 4a_8 + a_9 = 0 \\
32a_{11} + 12a_{12} + 4a_{13} + a_{14} = 0
\end{gathered}
\tag{25}
$$

Moreover, a spherical obstacle with 3 cm diameter from arbitrary point of [42, 12, 0] with a known straight path with equation (18) is considered.

$$
\begin{gathered}
X_{obs} = -0.0218\,t + 0.42 \\
Y_{obs} = -0.0218\,t + 0.12 \\
Z_{obs} = -0.0218\,t
\end{gathered}
\tag{26}
$$

In order to avoid the obstacle, a penalty function is added to the goal function. Hence, the normal distance between the center of spherical obstacle and the end-effecter would be calculated in each iteration, and if this distance is less than sum of sphere and manipulator arm's radius penalty function amount would be added as below:

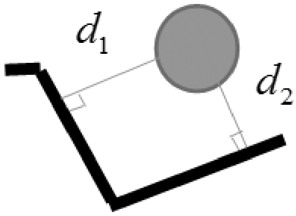

Figure 5. Distance between obstacle and robot arm

$$
If \begin{cases} d_1 < 0.05 & m = 100 \\ d_1 \geq 0.05 & m = 0 \end{cases};\quad If \begin{cases} d_2 < 0.05 & k = 100 \\ d_2 \geq 0.05 & k = 0 \end{cases} \tag{27}
$$

$$
E = \tau_1 \dot{q}_1 + \tau_2 \dot{q}_2 + \tau_3 \dot{q}_3 + \tau_4 \dot{q}_4 + m + k \tag{28}
$$

This problem should be solved, once the obstacle and its motion are recognized. So, in this case, we need to make a compromise between the required time for optimization and the accuracy of the calculated goal function. To be more specific, in order to reduce the required time of optimization, the initial population of GA should be reduced. Meanwhile, to have a motion with the lowest energy consumption, the initial population should be increased to yield the optimal motion. So, the problem is solved, using various initial populations to find the motion with minimum time of optimization, as well as the minimum energy consumption. In order to solve the problem by second method, the inverse kinematic should be solved in each iteration. Due to the massive amount of calculation, extreme time is necessary to solve the optimization problem. Therefore, this method is disqualified. But in the first method, the necessary time for optimization is more reasonable. As it is specified in table 3, the problem is solved for four different initial populations.

Table 3. First method Optimization Results

	N_{pop}=20		N_{pop}=50		N_{pop}=75		N_{pop}=100	
	Obj Value	Time	Obj Value	Time	Obj Value	Time	Obj Value	Time
1	7.66	12.3	8.31	61	4.98	92	6.4	77
2	7.19	20.6	8.33	52	8.73	80	7.02	79
3	19.16	24.9	6.51	60	9.67	69.8	7.45	78.9
4	5.57	29.2	8.48	47	5.94	76	7.07	72.5
5	13.83	26	5.87	38	5.95	74.5	5.96	75
6	11.35	22.8	6.54	34	6.03	71.1	5.96	75
7	5.68	17.6	5.69	69	4.75	73	4.82	82
8	9.55	24.6	7.18	58	6.57	81.7	6.36	66
9	10.63	19.8	8.06	48.2	7.86	83.9	6.67	126.6
10	16.42	18.7	8.07	61.2	5.7	45	5.49	110
Ave	10.71	21.65	7.30	52.84	6.62	74.7	6.22	87.1
SD	4.58	4.87	1.08	11.09	1.61	12.4	0.9	19.53

As it may be seen in this table, increasing initial population results less objective function value in average. Moreover, the amount of standard deviation (SD) is reduced that shows the accuracy of solving the problem. Although increasing the initial population causes more mathematical calculation that needs more time to solve the problem. Figures 3 and 4 show objective function and time of solving the problem with respect to the amount of initial population, respectively.

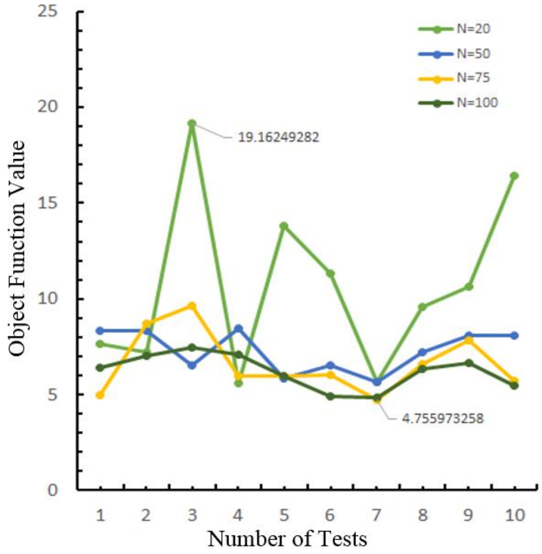

Figure 6. Resulted Objective value in different tests with different population numbers

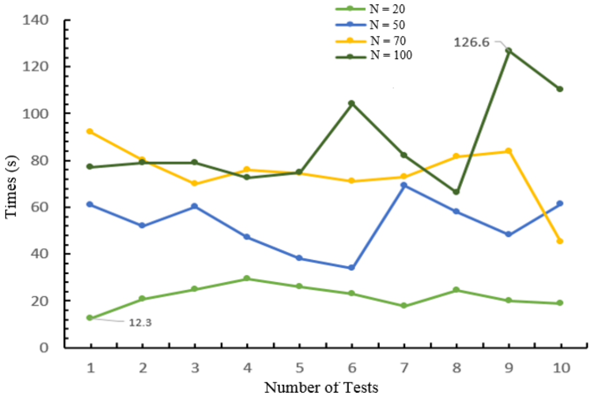

Figure 7. Solving time in different tests with different population numbers

According to Table 3, high amount of objective values averages and variances with initial population of 20 makes it a wrong decision. Also, high amount of necessary time for solving with initial population of 100 and almost same results between 75 and 100 population made 100 as an unsuitable choice for number of population. Moreover, the objective value and variance of two different optimization problems with 50 and 75 have small difference. Therefore 50 would be better population number in order to minimize solving time and also have appropriate and accurate answer at the same time. After implementing the best optimized answer with least objective value (4.75), joint angles and afterward by solving forward kinematic, the answers can be seen in Figure 8.

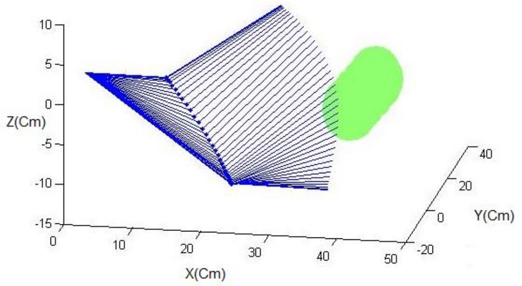

Figure 8. Robot and obstacle motion

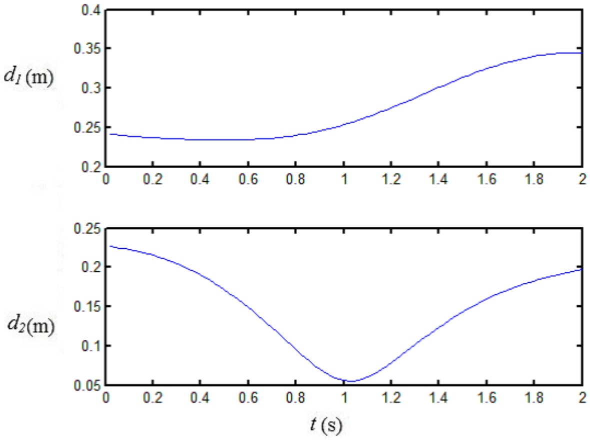

Figure 9. Distance between moving obstacle and each arm part

The Figure 9 shows the minimum distance between moving obstacle and each arm part. As it can be seen, obstacle is avoided by the robot arm and the minimum amount of difference between robot arm and obstacle is 0.05 which is obstacle's ratio. Figure 10 shows the applied torque by the robot actuators and each motor and robot consumed energy can be seen in Figure 11 and 12 respectively.

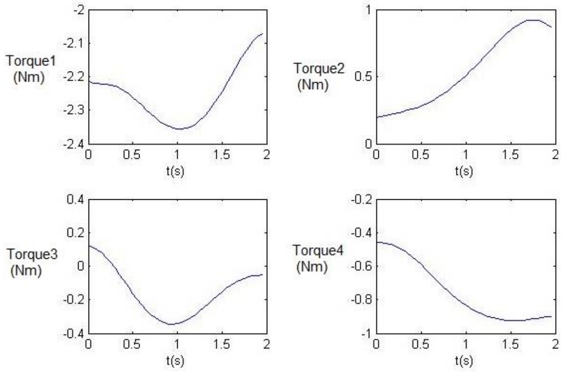

Figure 10. Applied torque by the robot actuators

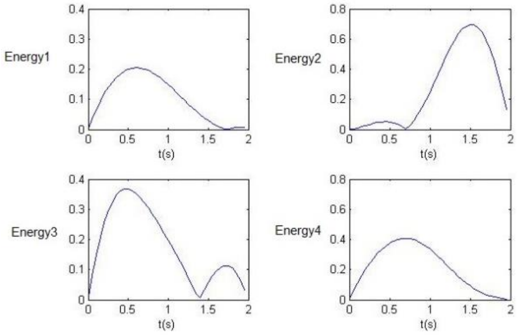

Figure 11. Robot actuators consumed energy

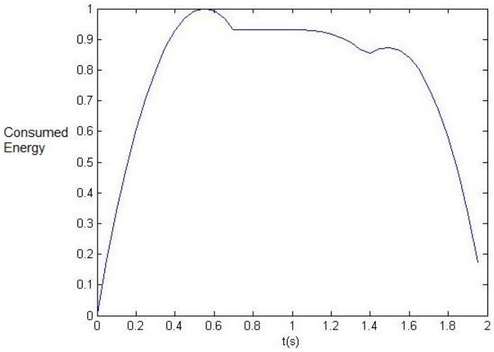

Figure 12. Total robot consumed energy

In order to compare and evaluate optimized problem, each motors consumed energy is separated for straight line and optimized movements between specified points in Figure 13.

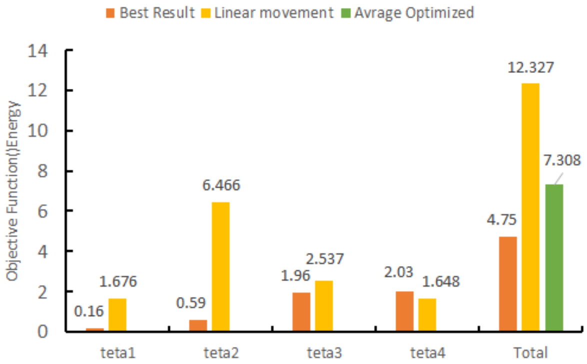

Figure 13. Each motor consumed energy for straight and optimized motion

As it can be seen in Figure 13 robot consumed energy is highly reduced. The avrage of optimization results show that this method reduces the consumed energy by 40 percents. Also as can be seen it reduced upto 60 percents.

6. Conclusion

In this paper, trajectory of a 4 DOF robotic arm has been generated by optimizing robot consumed energy and avoiding a moving obstacle. To do so, each joint trajectory has been defined as a fourth order polynomial. Afterward, using a genetic algorithm, consumed energy has been optimized by the assumption of known initial and final position and zero velocity. In order to reduce the delay between the detecting the object and moving toward the goal position, it is desired to solve the optimization problem in minimum time. Therefore, the optimization problem was solved with different population number and each time it has been solved ten times in order to have an accurate response. The obtained results showed that the best number for the initial population in this problem is 50. Finally, the optimal trajectory in terms of energy consumption was proposed.

7. Acknowledgements

The authors would like to express deep gratitude to the Industrial Development and Renovation Organization of Iran (IDRO) for financial supports to develop the SURENA III humanoid robot. We further thank to the members of the Center of Advanced Systems and Technologies (CAST) for their valuable participation in design and fabrication of SURENA III humanoid robot.

References

[1] G. Field, Y. Stepanenko. “Iterative Dynamic Programming: An Approach to Minimum Energy Trajectory Planning for Robotic Manipulators”, Intemational Conference on Robotics and Automation, Minneapolis, Minnesota, April, (1996).

[2] A. R. Hirakawa, A. Kawamura, “Trajectory Planning of Redundant Manipulators for Minimum Energy Consumption without Matrix Iniversion” International Conference on Robotics and Automation. Albuquerque, New Mexico, April (1997).

[3] S. F. P. Saramago, V. Steffen Jr., “Optimization Of The Trajectory Planning Of Robot Manipulators Taking Into Account The Dynamics Of The System”, *Mechanism and Machine Theory*, (1998).

[4] Y. F. Li Ding, S. K. Tso, “Dynamic optimization of redundant manipulators in worst”, *Mechanism and Machine Theory*, (2000).

[5] Y. G. Zhang, L. M. X. H. Shen, L. Jin, “Dynamic Optimization Of A Robot Manipulator Based On Ga”, International Conference On Machine Learning And Cybernetics. Baoding, (2009).

[6] Y. Zhang, S. S. Ge and T. H. Lee, “A Unified Quadratic-Programming-Based Dynamical System Approach to Joint Torque Optimization of Physically Constrained Redundant Manipulators”, *IEEE Transactions On Systems, Man, and Cybernetics*, (2004).

[7] S. Ma, “A New Formulation Technique for Local Torque Optimization of Redundant Manipulators”, *IEEE Transactions On Industrial Electronics*, (1996).

[8] Z. Y. Guo, T. C. Hsia, “Joint Trajectory Generation For Redundant Robots In An Environment With Obstacles”, *Journal of Robotic Systems*, (1990).

[9] N. Baba, N. Kubota, “Collision Avoidance Planning of a Robot Manipulator by Using Genetic Algorithm-A Consideration for the Problem in Which Moving Obstacles and/or Several Robots Are Included in the Workspace”, IEEE World Congress on Computational Intelligence, (1994).

[10] Y. Zhang, J. Wang, “Obstacle Avoidance for Kinematically Redundant Manipulators Using a Dual Neural Network”, *IEEE Transactions On Systems, Man, And Cybernetics–Part B: Cybernetics*, (2004).

[11] M. Kawato, Y. Maeda, Y. Uno , and R. Suzuki, “Trajectory Formation of Arm Movement by Cascade Neural Network Model Based on Minimum Torque-Change Criterion”, *Biological Cybernetics*, (1990).

[12] A. S. Deo, I. D. Walker, “Minimum Effort Inverse Kinematics for Redundant Manipulators”, *IEEE Transactions On Robotics And Automation*, (1997).

[13] S. F. P. Saramago, V. Steffen Jr, “Dynamic Optimization for the Trajectory Planning of Robot Manipulators in the Presence of Obstacles” *Journal of the Brazilian Society of Mechanical Sciences*, (1999).

[14] Z. H. Zhu , R. V. Mayorga and A. K. C. Wong, “Dynamic Robot Manipulator Trajectory Planning For Obstacle Avoidance”, *Mechanics Research Communication*s, (1999).

[15] Y .Zhang, S. Ma. “Minimum-Energy Redundancy Resolution of Robot Manipulators Unified by Quadratic Programming and its Online Solution”, International Conference on Mechatronics and Automation, (2007).

[16] G. S. Sharma, A. kaur, “Optimization of Energy in Robotic arm using Genetic Algorithm”, *International Journal of Computer Science and Technology*, (2011).

[17] S. F. P. Saramagoa,V. Stefen Jr. “Optimal trajectory planning of robot manipulators in the presence of moving obstacles”, *Mechanism and Machine Theory*, (2000).

[18] S. Kucuk, “Energy minimization for 3-RRR fully planar parallel manipulator using particle swarm optimization”, *Mechanism and Machine Theory*, (2012).

[19] D. Hui, D. Zhijiang, “Obstacle Avoidance Path Planning of Planar Redundant Manipulators using Workspace Density”, *International Journal of Advanced Robotic Systems*, (2015).

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