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Controlling Multi Degree of Freedom Robot Joints Torques Using Genetic Algorithm

O. Shoubaky[1] and T.M. Sharari[2]

[1] *Computer and Intelligent Systems Center, PO.Box. 215, Jo*

[2] *Institue of Eng. and Tech., Cont. Lab& Aut., Po.Box.81. Jo*

***Corresponding Author's E-mail:** o.shoubaky@yahoo.com*

Abstract

Controlling the motions of humanoid robot when interacting in external environment, requires an exact estimation of joint torques. Therefore, this paper suggests a technique to estimate the maximum surplus torque for each joints using a genetic algorithm (GA) when the robot is pushing an object. To demonstrate the effectiveness of the suggested method, a multi degree of freedom humanoid- robot carrying a pushing motion is considered, and a number of simulations are conducted. The results of the simulations show that the suggested technique can be applied to the control of joints' torques for the humanoid robot interacting with external environment.

Keywords: *Humanoid robot, Genetic Algorithm*

1. Introduction

Many people expect that humanoid robots can perform various works in addition to walking motion. In this case, humanoid-robot motion needs to be more complex and sophisticated, and the joints of the robots need to be more precisely controlled for achieving a desirable motion or trajectory. Generally, a humanoid robot consists of many joints, each of which is a combination of an actuator and reducer. So, when a robot performs a cooperative motion with external environment, it is essential to adequately control torques of the joint actuators of the robot. As an example of a cooperative motion, this study considers a robot's action of pushing an object. If a torque required at any joint of a humanoid robot exceeds its maximum capacity for achieving a desirable task, the robot cannot perform a desirable motion or some joints might be damaged. From this point of view, our approach involves finding optimal postures that maximise the working capability of humanoid robots by controlling the joint torques in such a way that the surplus torque for all joints is maximised. Until now, a number of research works showing a growing interest in humanoid-robot motion have been reported. The works [1-2] find optimal configurations in terms of the Cartesian force generation and energy consumption using nonlinear programming technique. However, the works are not directly related to the humanoid-robot research. The work [3] optimises configuration of the posture of humanoid robot by Simulated Annealing Algorithm. However, it is only applicable to the arm part of a humanoid robot. The study for developing a whole body cooperative dynamic walking control method [4] and effective balancing method [5] also reported, but they are restricted to stabilisation of walking mode. Recent successful development can be seen in mobile manipulation of humanoid robots and optimisation of its posture using genetic algorithms[6-9] . However, most of the methods rely on approximate or restricted force information on a humanoid robot instead of precise information. To provide realistic force information with humanoid-robot cooperative motion, this study proposes a

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method to find an optimal posture of a humanoid robot using a genetic algorithm (GA) in such a way that the surplus torque ratio for all joints is maximised when the robot is pushing an object by hands. Also, to assist structure, ANSYS programme is used. The desired joint angle and the generated torque at each arm and leg joint are calculated using forward and inverse kinematics and Jacobian, and the force and moment exerted on the leg part is calculated using ANSYS. The torques thus found are reflected on an objective function which is to be maximised by a GA. As a result of successive maximisation process, an optimised posture having a large surplus joint torque is finally found.

To show the effectiveness of the proposed method, a 24-DOF humanoid-robot's pushing motion is considered, and a number of simulations are carried out. The simulation result shows that the proposed method can be used to the control of torques for humanoid-robot cooperative motion with external environment.

2 Modelling and Analysis of Humanoid Robots

2.1 Degree of Freedom (DOF) and Coordinate System

This study considers a humanoid robot consisting of two arms and two legs. Each arm and leg has 6 DOF of motion, thus the robot has total 24 DOF of motion. Figure 1 shows the kinematic diagram of the robot assumed to be 1.2m in height and 36kg in weight.

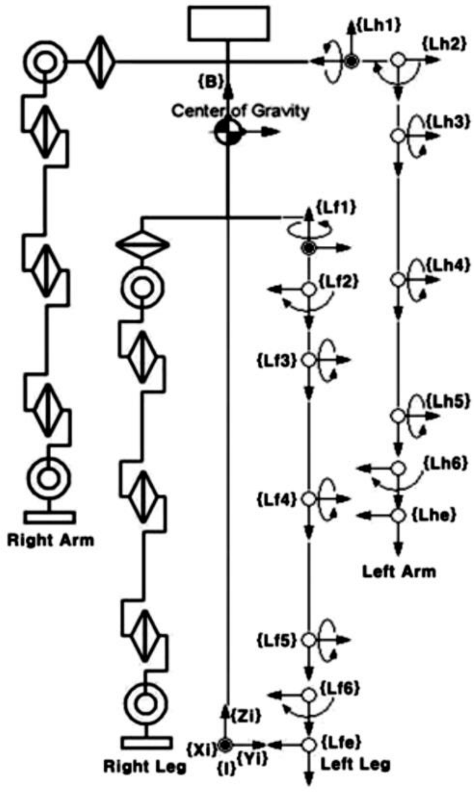

Figure 1: Degree of freedom and the coordinate

As shown in the above figure, the coordinate system is divided into four frames: {Lh} for the left hand, {Rh} for the right hand, {Lf} for the left foot and {Rf} for the right foot.

2.2 Forward and Inverse Kinematics

Forward and inverse kinematics is to be derived with respect to four parts: two arm parts and two leg parts. This study takes the homogeneous transformation consisting of the position vector about the origin of the reference frame, and the rotation matrix described by X-Y-Z Eular Angle. Each joint angle range is assumed to be given as

$$-180 < (\theta_1, \theta_2, \theta_3, \theta_5, \theta_6) < 180, \\ 0 < \theta_4 < 180 \quad or \quad -180 < \theta_4 < 0. \tag{1}$$

Here, the index *i* of each joint angle ϑi follows the same number of each arm and leg part shown in figure 1. Θ_4 corresponds to each knee and elbow of the robot. Frame {B} is attached on the centre of gravity of the robot, so the homogenous transformation ${}_B{}^I T$, {B} with respect to {I}, can be defined. Also, each link transformations, ${}_0{}^B T$, ${}_e{}^6 T$ is defined as the coordinate system. Here, the position

and rotation of frame {0} is coincident with that of frame {1}. Thus, ${}_6{}^0 T$ is given by

$${}_6^0T = {}_0^B T^{-1} \times {}_B^I T^{-1} \times {}_e^I T \times {}_e^6 T^{-1}. \tag{2}$$

For obtaining the close-form solutions to the inverse kinematics, two methods are adopted: algebraic approach and geometric approach. In figure 1, each joint angle with respect to frame {Lh1}, {Lh2} and {Lh3} is obtained by algebraic approach, while each joint angle with respect to frame {Lh4}, {Lh5} and {Lh6} is easily found by geometric approach. The obtained joint angles are verified by the MSC.visualNastran4D, and figure 2 shows the 3D- modelling of an initial posture by the software.

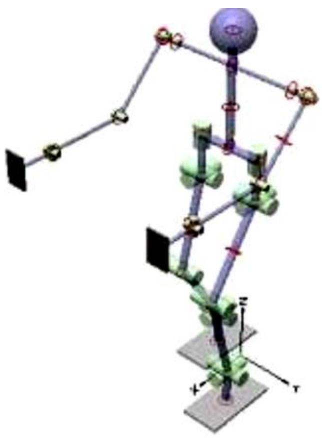

Figure 2: Modelling of the humanoid robot's initial posture using SC.visualNastran4D.

2.3 Force and Torque Analysis for the Arm Part

To find the joint torques, Jacobian J relating joint velocity $\dot{\Theta}$ to Cartesian velocity $\dot{X}$ is used on the basis of calculated angles at the static situation. The Jacobian is defined by

$$\dot{X} = J \times \dot{\theta}. \tag{3}$$

The Jacobian matrix is expressed by a 6× n (n: the number of joints) matrix: the upper three rows for linear velocity and the lower three ones for angular velocity. The Jacobian matrix deriving from the forward kinematics is expressed by the following equation:

Table 1: Parameters for the initial posture.

$\Theta_{ij,leg}$[°] If i=1, for right. If i=2, for left. J=joint number.	θ_{11}, θ_{21} θ_{12}, θ_{22} θ_{13}, θ_{23} θ_{14}, θ_{24} θ_{15}, θ_{25} θ_{16}, θ_{26}	0.0000 0.0000 14.6965 -48.3177 33.6212 0.0000	0.0000 0.0000 -33.6212 48.3177 -14.6965 0.0000	$\Theta_{ij,arm}$ [°] If i=3, for right. If i=4, for left. J=joint number.	θ_{31}, θ_{41} θ_{32}, θ_{42} θ_{33}, θ_{43} θ_{34}, θ_{44} θ_{35}, θ_{45} θ_{36}, θ_{46}	0.0000 0.0000 45.0000 45.0000 0.0000 0.0000	0.0000 0.0000 -45.0000 -45.0000 0.0000 0.0000
Θ_B [°] For frame {B} about {I}	α_B β_B γ_B	0.0000 0.0000 0.0000		P_B [m] For frame {B} about {I}	P_{Bx} P_{By} P_{Bz}	0.0750 0.0000 0.7500	
$\Theta_{e1,2}$ [°] For frame {e} about {I} at leg	α_{e1}, α_{e2} β_{e1}, β_{e2} γ_{e1}, γ_{e2}	180.0000 -90.0000 0.0000	180.0000 -90.0000 0.0000	$P_{e1,2}$ [m] For frame {e} about {I} at leg	P_{e1x}, P_{e2x} P_{e1y}, P_{e2y} P_{e1z}, P_{e2z}	0.0000 -0.0800 0.0000	0.1500 0.0800 0.0000
$\Theta_{e3,4}$ [°] For frame {e} about {I} at arm	α_{e3}, α_{e4} β_{e3}, β_{e4} γ_{e3}, γ_{e4}	90.0000 0.0000 0.0000	90.0000 0.0000 0.0000	$P_{e3,4}$ [m] For frame {e} about {I} at arm	P_{e3x}, P_{e4x} P_{e3y}, P_{e4y} P_{e3z}, P_{e4z}	0.5164 -0.2000 0.7086	0.5164 0.2000 0.7086
$F_{f1,2}$ [N] $M_{f1,2}$ [Nm] at leg	F_{f1x}, F_{f2x} / M_{f1x}, M_{f2x} F_{f1y}, F_{f2y} / M_{f1y}, M_{f2y} F_{f1z}, F_{f2z} / M_{f1z}, M_{f2z}	-80 -80 0 0 -180 -180	-7.2 7.2 3.312 3.312 3.2 -3.2	$F_{h3,4}$ [N] at arm	F_{h3x}, F_{h4x} F_{h3y}, F_{h4y} F_{hz3}, F_{h4z}	-80 0 0	-80 0 0
$\tau_{ij,leg}$ [Nm] i and j imply the same at θ.	τ_{11}, τ_{21} τ_{12}, τ_{22} τ_{13}, τ_{23} τ_{14}, τ_{24} τ_{15}, τ_{25} τ_{16}, τ_{26}	3.2000 7.2000 -12.6880 -43.4501 -35.1880 7.2000	-3.2000 -7.2000 12.6880 54.2588 62.1880 -7.2000	$\tau_{ij,arm}$ [Nm] i and j imply the same at θ.	τ_{31}, τ_{41} τ_{32}, τ_{42} τ_{33}, τ_{43} τ_{34}, τ_{44} τ_{35}, τ_{45} τ_{36}, τ_{46}	11.3137 0.0000 -11.3140 0.0000 0.0000 0.0000	-11.3137 0.0000 11.3140 0.0000 0.0000 0.0000

$$
{}^0_6J = \begin{bmatrix} {}^0_6J_{v,leg-arm} \\ {}^0_6J_{\omega,leg-arm} \end{bmatrix} = \begin{bmatrix} {}^0_1Rk \times ({}^0_ed - {}^0_1d) & \cdots & {}^0_6Rk \times ({}^0_ed - {}^0_6d) \\ {}^0_1Rk & \cdots & {}^0_6Rk \end{bmatrix}. \quad (4)
$$

Using the principle of virtual work W, each joint torque is derived by the following equations:

$$
\dot{W} = \tau^T \times \dot{\theta}, \;\; F^T \times \dot{X} = \tau^T \times \dot{\theta}, \;\; \tau = J^T \times F. \quad (5)
$$

Here, F is the 6×1 force and moment vector applied at the robot with respect to frame {I}.

2.4 Force and Torque Analysis for the Leg Part

In general, the reaction force and moment applied at the leg part of a humanoid robot cannot be simply calculated when frame {B} is varied. So this study uses a structure analysis programme ANSYS. As the first step, the position of each joint angle with respect to frame {I} is determined from forward and inverse kinematics and is to be used for modelling by ANSYS. In the process of modelling, the acting force F=[-80 0 0] is applied on each palm and F=[0 0 - 360] is applied on frame {B}, where two kinds of the force are presented with respect to frame {I}. As a result of structure analysis, the reaction force and moment at frame {0} located on the robot's waist of leg-part is found. In the same way as the arm part, joint torques at the leg part are computed by such obtained force and moment. Figure 3 shows the modelling of ANSYS for the initial posture, while table 1 shows joint angles, joint torques, input force for each part and the position and rotation of frame {B} at the initial posture.

Figure 3: Modelling of the humanoid robot's initial posture using ANSYS.

3. Optimisation using a Genetic Algorithm (GA)

3.1 Parameters and Objective Functions

GA has been known to perform generally well when searching large spaces with many local optima, and formulates evolution process of survival by the fitness. This paper adopts a simple genetic algorithm (SGA) with roulette wheel selection, simple crossover and mutation. In addition, elitist strategy in which individual with the strongest fitness would be survived in the next generation is used for enhancing performance of the algorithm. Table 2 shows parameters used in this algorithm.

Table 2: Parameters of a genetic algorithm.

Parameters	Value
Maximum generation	300
Population size	100
Number of variables	6
Probability of crossover, Pc	0.8
Probability of mutation, Pm	0.01

To increase overall acting force through maximising the overall surplus joint torque ratio, the objective function F(x) is defined by

$$F(x) = \sum_{i=1}^{n} \left(1 - \left| \frac{\tau_i}{\tau_{\max_i}} \right|^2 \right). \qquad (i=1,\dots,6) \qquad (6)$$

Here, τ_i is each joint torque and τ_{max} is maximum allowable torque of each joint.

3.2 Constraints in a GA

The following shows the constraints for achieving optimisation by the GA.

1. Each position and rotation of the palm and the sole is fixed at the initial posture.
2. The force acting on the palm and on the centre of gravity of the robot keeps constant.
3. The torque at each joint should be lower than its allowable maximum torque shown in table 3.
4. The rotation and position of frame {B} should follow the allowable range shown in table 4.

Table 3: Maximum allowable torques at joints.

Joint No.	T_{max} [Nm]	**Joint No.**	T_{max} [Nm]
Joint11(θ_{11}), Joint21(θ_{21})	57.8	Joint31(θ_{31}), Joint41(θ_{41})	57.8
Joint12(θ_{12}), Joint22(θ_{22})	189.8	Joint32(θ_{32}), Joint42(θ_{42})	57.8
Joint13(θ_{13}), Joint23(θ_{23})	189.8	Joint33(θ_{33}), Joint43(θ_{43})	57.8
Joint14(θ_{14}), Joint24(θ_{24})	227.8	Joint34(θ_{34}), Joint44(θ_{44})	57.8
Joint15(θ_{15}), Joint25(θ_{25})	227.8	Joint35(θ_{35}), Joint45(θ_{45})	57.8
Joint16(θ_{16}), Joint26(θ_{26})	189.8	Joint36(θ_{36}), Joint46(θ_{46})	57.8

Table 4: Allowable range of {B}.

Range of Px [m] ({B} of robot)	$0 \leq Px \leq 0.15$
Range of Py [m] ({B} of robot)	$-0.1 \leq Py \leq 0.1$
Range of Pz [m] ({B} of robot)	$0.5 \leq Pz \leq 0.8$
Range of Rx [°] ({B} of robot)	$-10 \leq Rx \leq 10$
Range of Ry [°] ({B} of robot)	$-10 \leq Ry \leq 10$
Range of Rz [°] ({B} of robot)	$-10 \leq Rz \leq 10$

3.3. Optimisation Algorithm

Figure 4 shows the flow chart of the proposed optimisation algorithm.

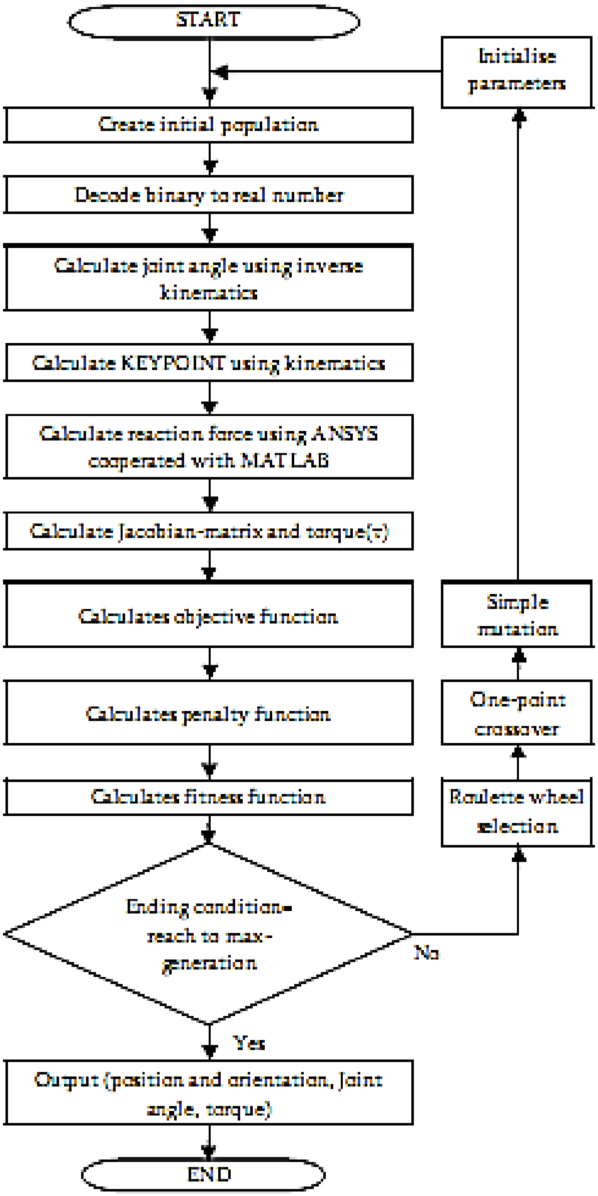

Figure 4: Flowchart of the proposed optimisation algorithm.

4 Simulation Results

Using the proposed approach, a number of simulations are carried out to show the effectiveness of the algorithm. Figure 5 shows the change of the average fitness function and the maximum value of the objective function. The figure show that values tend to increase through the simulation.

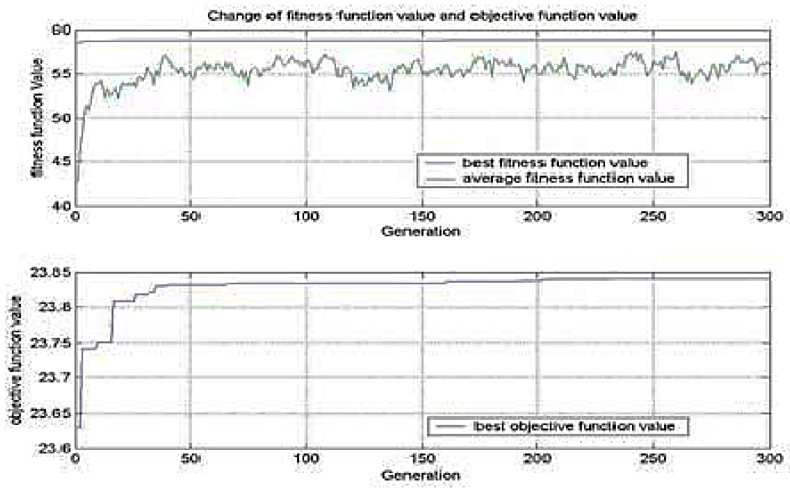

Figure 5: Change of the fitness function and the objective function.

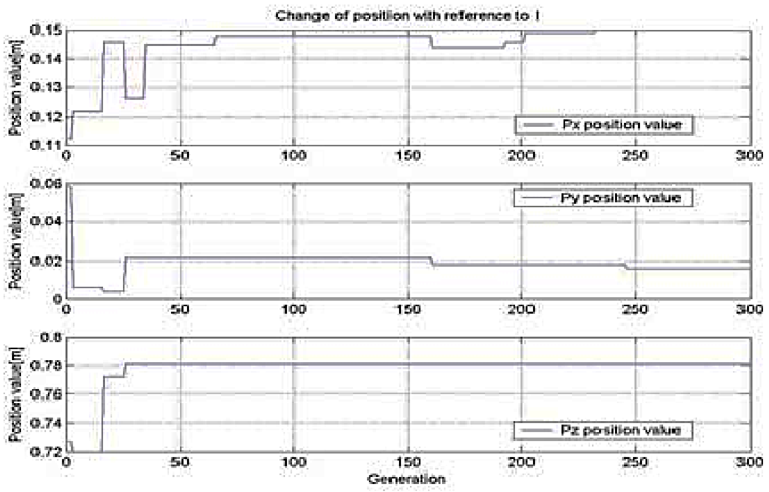

Figure 6: Change of position with reference to {I}.

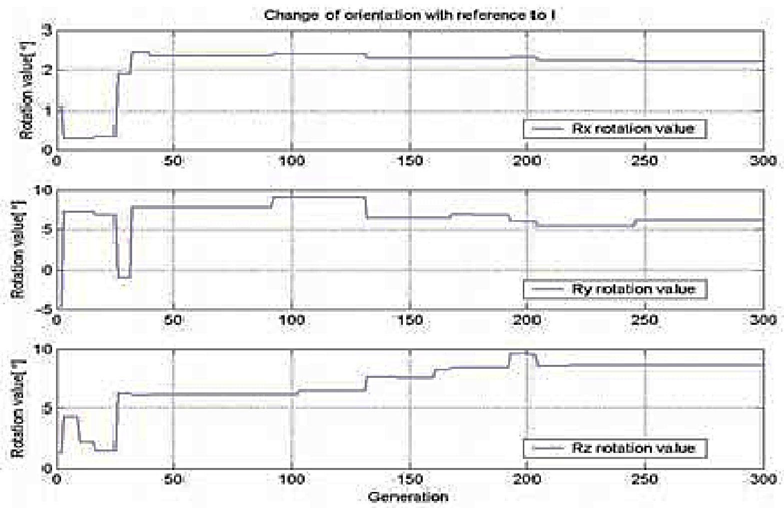

Figure 7: Change of rotation with reference to {I}.

Figures 6 and 7 show the position (Px, Py, Pz) and rotation (Rx, Ry, Rz) of frame {B} is varying in progress of generation with respect to frame {I}. The figure shows that values (Px, Py, Pz, Rx, Ry, Rz) tend to converge into a single value through the simulation. Figures 8 and 9 show the comparisons between the initial joint torque ratio and the final joint torque ratio. Each joint torque ratio at the final posture is less than that at the initial posture, as shown in figure 8 and figure 9. This means that surplus joint torque at final posture is larger than that at the initial posture.

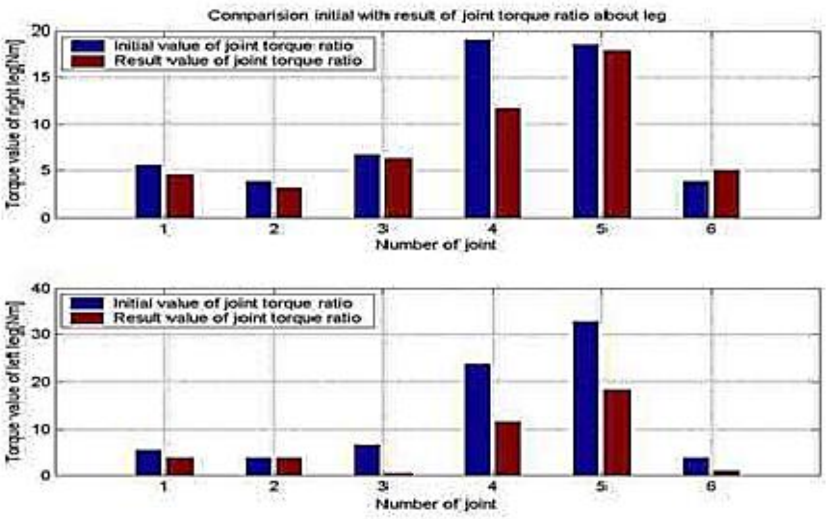

Figure 8: Comparison of the joint torque ratio between the initial and the final posture at the leg part.

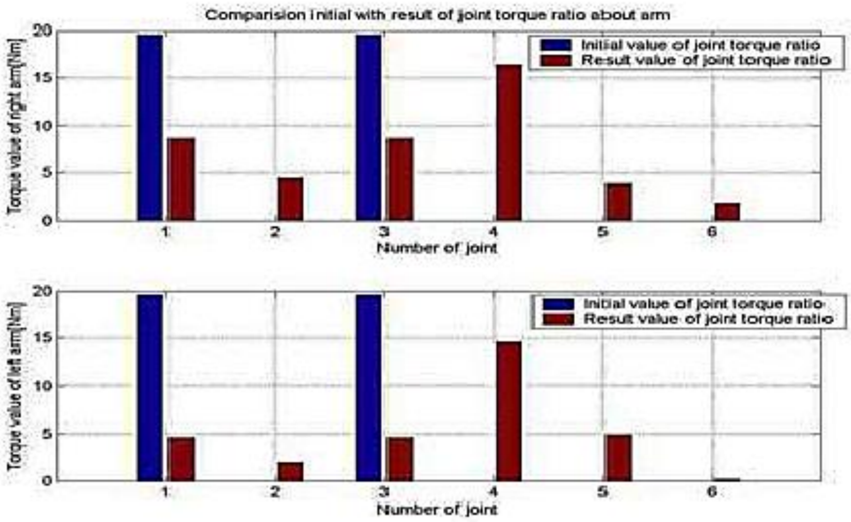

Figure 9: Comparison of the joint torque ratio between the initial and final posture at the arm part.

It can be seen that sum of the each joint torque is 300.9Nm at the initial posture while 207.5Nm at the final posture. This means the humanoid robot has more surplus torque by 93.3Nm than it of initial posture. Table 5 shows the simulation results at the

Table 5: Simulation results of optimal posture.

$\Theta_{ij,leg}$ [°] If i=1, for right. If i=2, for left. J=joint number.	Θ_{11}, Θ_{21}	9.2083	9.1767	$\Theta_{ij,arm}$ [°] If i=3, for right. If i=4, for left. J=joint number.	Θ_{31}, Θ_{41}	81.7883	-79.4531
	θ_{12}, θ_{22}	-5.1509	-4.8602		θ_{32}, θ_{42}	-12.7198	-10.9853
	θ_{13}, θ_{23}	-6.1560	-22.5192		θ_{33}, θ_{43}	-67.1485	48.0091
	θ_{14}, θ_{24}	-8.0116	24.7964		θ_{34}, θ_{44}	92.0997	-64.0467
	θ_{15}, θ_{25}	20.3628	-8.4696		θ_{35}, θ_{45}	-10.6342	-0.5651
	θ_{16}, θ_{26}	2.9610	2.6686		θ_{36}, θ_{46}	3.7247	1.9254
Θ_B [°] For frame {B} about {I}	α_B	2.22		P_B [m] For frame {B} about {I}	P_{Bx}	0.150	
	β_B	6.17			P_{By}	0.016	
	γ_B	8.65			P_{Bz}	0.781	
$\tau_{ij,leg}$ [Nm] i and j imply the same at θ.	τ_{11}, τ_{21}	2.6156	-2.2315	$\tau_{ij,arm}$ Nm] i and j imply the same at θ.	τ_{31}, τ_{41}	-5.0062	2.6511
	τ_{12}, τ_{22}	6.2494	-7.2037		τ_{32}, τ_{42}	2.5589	1.1189
	τ_{13}, τ_{23}	-12.0265	0.9187		τ_{33}, τ_{43}	5.0338	-2.6631
	τ_{14}, τ_{24}	-26.7286	26.5393		τ_{34}, τ_{44}	-9.4526	8.3913
	τ_{15}, τ_{25}	-33.9862	34.6487		τ_{35}, τ_{45}	-2.2310	2.8452
	τ_{16}, τ_{26}	9.5074	-1.7913		τ_{36}, τ_{46}	-1.0702	0.0776

optimised posture. Figure 10 shows the humanoid robot's final posture from the simulation results in table 5. This result means that surplus torque can be enlarged as much as reduced. Thus, it is concluded that proposed method can be efficiently used to the control of torques for humanoid robots cooperative with external environment.

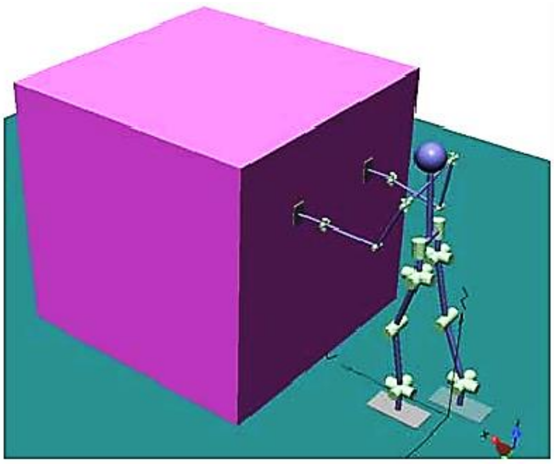

Figure 10: Optimised configuration as a result of the simulation posture.

Conclusion

Controlling the motions of humanoid robot when interacting in external environment requires an exact estimation of joint torques. Therefore, this paper suggests a technique to estimate the maximum surplus torque for each joints using a genetic algorithm (GA) when the robot is pushing an object. The robot with 24 degree of freedom is considered, and forward and inverse kinematics is derived on the basis of modelling. Then, the torque of all joints is calculated from the relation of forward and inverse kinematics and Jacobian. Then ANSYS programme is used to find the acting force and moment at the leg part. Such obtained torques are reflected to an objective function which is to be minimised by a genetic algorithm (GA). Here, the position and the rotation angle of the centre of gravity of the robot are considered as the design variables. As a result of successive maximisation of the objective function by the GA, an optimised posture having a maximum surplus torque for the cooperative motion is finally found. And to show the effectiveness of the proposed method, a number of simulations are carried out. The simulation result shows that the proposed method can be adopted to the control of torques for humanoid robot cooperative motion with external environment.

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