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On the Improvement of Static Force Capacity of Humanoid Robots based on Plants Behavior

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Abstract. Humanoid robots need to interact with the environment and are constantly in rigid contact with objects. When a task must be performed, multiple contact points are responsible to add a degree of complexity to their control and, due to excessive efforts in joints, the durability of the components may be affected. This work presents the use of a recent proposed metaheuristic called Runner-Root Algorithm (RRA) applied on the static force capacity optimization of a humanoid robot. The performance of this algorithm was evaluated and compared to four well stablished methods showing promising results for RRA in this type of application.

1 Introduction

Traditional design of humanoid robots concerns the realization of an anthropomorphic structure with many degrees of freedom. Current researches on humanoid robots are presenting significant improvements on movements in order to reproduce the human body dynamic [1-4]. On this point, the positioning of distinct parts of the robot can significantly affect the force capacity to perform a pre-determinate task [5].

Nevertheless, there are just few studies that deal with the static force capacity of these machines subjected to high loads situations. By considering that the robot can assume different configurations, maintaining the same contact points with the environment, the system can be described as both nonconvex and nonlinear, by increasing its complexity. In this case, the robot force capabilities problem can be treated as a global optimization problem [6], where the main objectives are: *i*) to test metaheuristic optimization techniques applied on the prevention of the robot integrity, those add to the problem by a set of constraints; *ii*) to optimize the horizontal static force capacity of the robot, considering only the sagittal plane.

The next section of this work presents the humanoid model followed by the optimization problem, which is addressed in section 3. Section 4 describes the optimization procedures and, in section 5, the comparison between RRA (Runner-Root Algorithm) [7] and four well stablished metaheuristics is presented. Finally, section 6 concludes this work addressing the future research associated to this paper.

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2 Humanoid Model

This section describes the physical characteristics, the kinematics, and the static balance of the humanoid robot.

2.1 Physical characteristics

The physical model of the robot can be described by twelve revolute joints (from A to L) with one degree of freedom each, and nine links (from 1 to 9), as shown in Fig. 1.

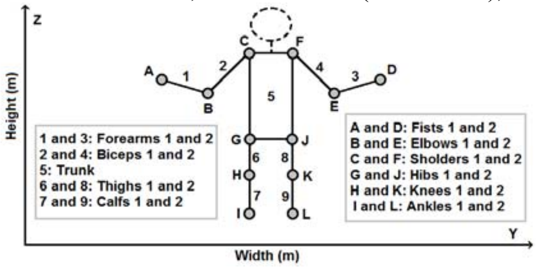

Fig. 1: Humanoid physical model [7].

The maximum torques supported by joints are defined by motors. It is supposed that the links can support any effort. The physical features of joints and links are described in Tab. 1, where the units are written generically as units of mass (u.m.), length (u.l.) and torque (u.t.), respectively. It is also assumed that the joints in contact with the environment (ankles and fists) cannot apply any moment.

Table 1: Humanoid physical features.

Links	Mass (u.m.)	Length (u.l.)	Joints	Maximum torque (u.t.)
Forearms	1,0	1,0	Fists	Absent
Biceps	1,0	1,0	Elbows	10
Trunk	2,0	2,0	Shoulders	20
Thighs	2,0	1,2	Hips	40
Calfs	1,5	1,2	Knees	45
			Ankles	Absent

2.2 Robot kinematic and static balance

By varying both the trunk coordinates and the trunk slant, when the robot adopts any four contact points (hands and feet) as presented in Fig. 2, infinite configurations may be assumed. Taking into account all these humanoid positioning possibilities, the kinematics was calculated according to [1], where the trunk central position and the trunk inclination are defined by the coordinates (x_5, z_5) and the angle θ_5, respectively. The shoulders and hips positions (x_0, z_0) were defined by trigonometric equations. The contact points of each limb (x_2, z_2) are previously configured, and the middle joints positions (x_1, z_1) were calculated using the inverse kinematics.

Environmental influences were considered on the humanoid kinematic. The gravitational force acts on the links as a vertical force concentrated in their center of mass. In the humanoid model, it was assumed that the links have regular geometry and their centers of mass overlaps with the geometry centers.

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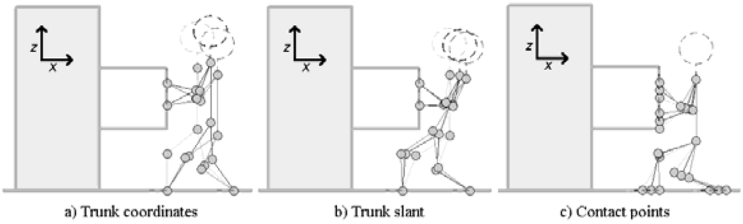

Figure 2: Optimization problem and possible humanoid configurations, when pulling an object.

The tumbling and the sliding effects were also considered and the concept of the Zero Moment Point (ZMP), which represents the projection of the robot's gravity center (GC) on the ground, was adopted to avoid tumbling [8]. The ZMP should be inside the stability polygon, which is the region on the ground between the feet. To avoid the sliding effect, it is assumed that the friction coefficients are known and a specific task can just be performed if a required roughness is available.

To obtain the static balance of the robot, *i.e.* the definition of both internal forces and moments, the Davies' Method was adopted [9]. This method provides a matrix framework to solve the static analysis. More information about the application of Davies' Method in the humanoid static balance can be found in [6].

3 Optimization Problem

The optimization problem is a task where the humanoid should pull an object through a handle (a rigid cable fixed on the object), which consists in maximizing the horizontal static force capacity by fulfilling physical constraints. The cost function can be specified as the inverse of the horizontal forces:

$$f(\vec{x}) = \frac{1}{|Fx_A|+|Fx_D|}, \tag{1}$$

where the components Fx_A and Fx_D are the horizontal forces in the upper contacts with the environment. The strategy adopted in this work is to use 5 joints' torques as primary variables and Fx_A and Fx_D become secondary variables defined by the static balance. Further, the contact points (4 coordinates) and the trunk positioning (3 variables) are required to define the kinematics. The dimension of the optimization problem is equal to 12 (Tab. 2). Physical constraints related to physical limitations of the human body, to the humanoid and to the surroundings were also considered.

Table 2: Decision variables.

Var.	Specification (unit)	Search Space	Var.	Specification (unit)	Search Space
$\boldsymbol{x_5}$	Trunk center in *x* (m)	[6.50, 9.5]	$\boldsymbol{x_L}$	Contact *z* of ankle 2 (m)	[4.5, 8.0]
$\boldsymbol{z_5}$	Trunk center in *z* (m)	[1.00, 3.4]	$\boldsymbol{\tau_C}$	Shoulder 1 torque (Nm)	[-20, 20]
$\boldsymbol{\theta}$	Trunk angle (rad)	$[\pi/6, \pi/2]$	$\boldsymbol{\tau_F}$	Shoulder 2 torque (Nm)	[-20 ,20]
$\boldsymbol{z_A}$	Contact *z* of fist 1 (m)	[2.0, 4.0]	$\boldsymbol{\tau_G}$	Hip 1 torque (Nm)	[-40, 40]
$\boldsymbol{z_D}$	Contact *z* of fist 2 (m)	[2.0, 4.0]	$\boldsymbol{\tau_J}$	Hip 2 torque (Nm)	[-40, 40]
$\boldsymbol{x_I}$	Contact *z* of ankle 1 (m)	[4.5, 8.0]	$\boldsymbol{\tau_K}$	Knee 2 torque (Nm)	[-45, 45]

The limbs have a known reachable space and the following geometric inequality must be fulfilled to each limb in order to guarantee that the surroundings are contained within the reachable space:

$$g_1(\vec{x}): \sqrt{(x_2 - x_0)^2 + (z_2 - z_0)^2} - \mathrm{d}_1 - \mathrm{d}_2 \leq 0, \quad (2)$$

where d_1 and d_2 are the lengths of the links, x_2 e z_2 are the coordenates for the contact joints with the surroundings and x_0 e z_0 with the trunk. Torque constraints must be respected in order to allow the humanoid to perform a particular task:

$$g_2(\vec{x}): T_j - T_j^{max} \leq 0, \forall\, j\ \in \{B, C, E, F, G, H, J, K\}. \quad (3)$$

In equation 3, T_j^{max} is the upper bound for joint torque T_j. When the torques are considered null at contact joints, these constraints are neglected. Moreover, the following constraint is imposed to avoid the sliding factor:

$$g_3(\vec{x}): \mu - \mu_{max} \leq 0 \quad (4)$$

where μ_{max} is the friction coefficient and μ the calculated friction. This condition need to be fulfilled by all the contact points, where $\mu_{\mathrm{max}} = 0.5$ was adopted.

In order to avoid that a given joint is positioned inside the object or below the ground, the following constraints are considered:

$$g_4(\vec{x}): x_j - x_o \leq 0, \quad (5)$$

$$g_5(\vec{x}): z_s - z_j \leq 0, \forall\, j\ \in \{B, C, E, F, G, H, J, K\}, \quad (6)$$

where x_j and z_j are the coordinates of join j, x_o the object's coordinate along the x-axis and z_s the coordinate along z-axis. Furthermore, it is necessary that the ZMP be inside the stability polygon:

$$g_6(\vec{x}): ZMP - x_{zmp}^{max} \leq 0, \quad (7)$$

$$g_7(\vec{x}): x_{zmp}^{min} - \mathrm{ZMP} \leq 0, \quad (8)$$

where $\mathrm{x}_{\mathrm{zmp}}^{\mathrm{min}}$ and $\mathrm{x}_{\mathrm{zmp}}^{\mathrm{max}}$ are the joints' coordinates in contact with the ground (rear and front contact, respectively). To guarantee that the resultant forces are in the right direction, the following constraint is stated to each one of the upper contact joints:

$$g_8(\vec{x}): -F_{x,j} \leq 0\ \forall\, j\ \in \{A, D\} \quad (9)$$

Finally, elbows and hips cannot be attached in the handle/fixed cable:

$$g_9(\vec{x}): \begin{cases} 1, (x_j < x_h) \wedge (z_j > z_h^{min}) \wedge (z_j < z_h^{max}) \\ -1, \qquad otherwise \end{cases}, \forall\, j\ \in \{B, C, E, F, G, H, J, K\} \quad (10)$$

where x_h is the coordinate of the handle contact at the *x*-axis and $[z_h^{min}, z_h^{max}]$ is the handle range in the *z*-axis. Aiming to incorporate the above listed constraints into the optimization problem, a penalty function is defined, such that:

$$p(\vec{x}) = w * \sum_{k=1}^{9} g_k(\vec{x}) > 0 \quad (11)$$

where, w is a constant used to weight the penalization of the undesired solutions. In this paper, this value has been defined as 10000 based on previous tests. To conclude the optimization problem, the final cost function is the sum of equations (1) and (11).

4 Optimization Procedures

In order to evaluate the performance of RRA [7] the optimization problem described in section 3 was adopted. The results provided by RRA were compared with four well

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stablished algorithms: Self-adaptive Differential Evolution (SaDE) [10], Adaptive Differential Evolution with Optional External Archive (JADE) [11], Symbiotic Organisms Search (SOS) [12], and Particle Swarm Optimization (PSO) [13].

The number of mother plants for the RRA, the populations sizes of SaDE and JADE, the SOS's number of organisms, and the PSO's swarm size have been defined as 120 (10 times the problem dimension) [16]. The parameters for all the algorithms were obtained from specialized literature and are illustrated on Tab. 3.

Table 3: Algorithms' parameters.

RRA [11]	SaDE [12]	JADE [13]	SOS [14]	PSO [15]
$d_{runner} = 10^{10}$ $d_{root} = 10^{8}$ $toll = 10^{-3}$ $stall_{max} = 2\times10^{3}$	$LP = 50$ $CRm_k = 0.05$	$c = 0.1$ $p = 0.05$ $CRm = 0.5$ $Fm = 0.5$ $Archive = 120$	$initial\_ecosystem = 50$	$c_1 = 2$ $c_2 = 1.3$ $w = 0.7$ $v = 0.2$

5 Results

In order to properly evaluate the performance of the algorithms, 30 runs of each algorithm have been executed. The stop criterion has been defined as 10,000 times the problem dimension, as suggested in [16]. The results were presented in terms of minimum, average, and maximum costs and also by the standard deviation, as presented in Tab. 4. As it can be seen by the emphasized results, RRA did not present the best result, which means the minimum value for the cost function. However, in terms of 30 runs (mean), maximum and standard deviation, the RRA has overcome the other ones. Figure 3 shows the robot position found by RRA Algorithm, where it can be noticed that the hibs are near but not in contact with the object.

Table 4: Comparison among RRA, SaDE, JADE, SOS and PSO algorithms.

Algorithm	Minimum	Mean	Maximum	Standard deviation
RRA	0.0117766	**0.0117821**	**0.0117959**	**5.34E-06**
SaDE	0.0117740	0.0117850	0.0118446	1.73E-05
JADE	0.0119194	0.0134109	0.0159493	1.11E-03
SOS	0.0117757	0.0118038	0.0122513	8.74E-05
PSO	**0.0117739**	0.0125039	0.017092	1.16E-03

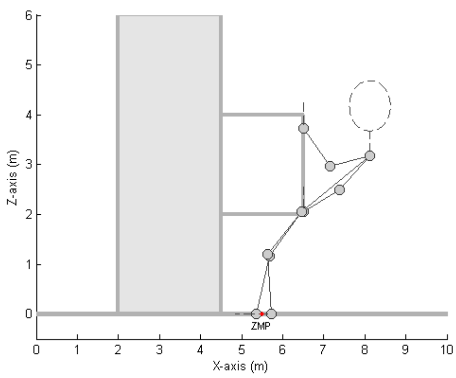

Figure 3: Best position for the humanoid found by RRA algorithm.

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6 Conclusion

This work proposed an investigation of a recent introduced metaheuristic method submitted to a humanoid robot static force capacity optimization problem. The Runner-Root Algorithm (RRA) was tested and compared to four well-stablished optimization methods: SaDE, JADE, SOS, and PSO. The RRA found a maximum horizontal force of 84.92N without any significant variation when compared to the best result found by the PSO method. Future research will be related to test distinct optimization methods and to create a three-dimensional model for the humanoid.

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