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Identification of dynamics of humanoids: systematic exciting motion generation

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***Abstract*— The mass parameters of robots influence performances of model-based control and validation of the simulation results. The mass parameters provided by CAD data are usually rough approximation of the true parameters. Therefore several methods for estimation of those parameters have been proposed. Their precision depends on the used motion, called optimal exciting trajectories.**

This paper describes a new approach to determine humanoid robot exciting trajectories for mass parameters identification. The method was inspired by the studies done in the field of human mass parameters identification, and it is based on observation of condition numbers of sub-regressor matrices created from the columns of the regressor matrix. The method has been experimentally applied to identify mass parameters of HRP-2 and HRP-4 humanoid robots. The proposed method is able to reconstruct ground reaction forces and force moments more accurately than parameters obtained from CAD data.

I. Introduction

Misinterpretation of segment mass parameters (mass, center of mass, and inertia matrix) can influence output of dynamical and kinematic analysis of humanoid motions. Mass parameters of humanoid robots given by the robot designers are often obtained by CAD software. It is common that the data given by CAD are only rough approximation of the true parameters, and they do not take into account possible robot modifications. Moreover, CAD data usually do not includes mass parameters of wiring materials which might affect the performances of model based controllers.

In the field of robotics, a few methods for the identification of mass parameters of human [1]-[3] and humanoid robot [4]-[5] have been developed. It is known that the accuracy of the identified mass parameters depends on the used motions [6]. Those motions are often called optimal exciting trajectories [7]. The optimal exciting trajectories have to be found taking into account the specification and limitations of the robot, and executed by the robot afterward. Joint kinematics and force information recorded during the motion are used to solve the dynamic equation of the motion in its reduced linear form and finally to find mass parameters, using a matrix called regressor, computed from the robot motion. A few methods have been developed for the design of the optimal exciting trajectories of robots manipulators based on non-linear optimization technique [8]-[12]. Nevertheless, those methods can not be used in case of humanoid robots due to the complicated kinematic structure and the lack of fixed base. Recently, Venture et al. proposed methods for choosing optimal exciting motions for identification of human mass parameters [6], [13]. The method described in [6] is based on the decomposition of the regressor matrix into sub-regressors and the computation of the condition number for each of those sub-regressor matrices. The method described in [13] is based on relative standard deviation calculated for each of the base mass parameter. Even though humans and humanoid have similar kinematic structure, the exciting trajectories designed for humans can not always be applied to the humanoid robot since it might imperil the dynamical balance of the system. Indeed human exciting motion usually involve highly dynamic motion that may be difficult for humanoids. For those reasons, there has been no systematic method allowing us to generate exciting trajectories and identify dynamic parameters for humanoid robots.

Therefore, in this paper we present a method for systematic generation of exciting trajectories for humanoid robots inspired by human dynamic parameter identification [6], taking into account the mechanical constraints and stability of humanoid robotic systems, as well as avoiding the possible self-collisions. The proposed method consists of iterative improvements of exciting trajectories based on the condition numbers of sub-regressor matrices, partial extractions of regressor matrix, which give the information about the accuracy of the identified mass parameters. We also demonstrate the generality of the proposed method by applying it to different humanoid robots, HRP-2 and HRP-4.

The rest of the paper is organized as follows. Section II explains the proposed optimization method for identification of mass parameters and the method for systematic choice of exciting trajectories of a humanoid robot. Section III gives specifications of two humanoid robots used in this study. Results are given in Section IV. Concluding remarks and perspectives for future work are given at the end of the article.

II. Method

A. Identification of mass parameters

The dynamic equations of a humanoid robotic system, composed of p rigid body segments, can be expressed as

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[14]:

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_1 \\ \ddot{\mathbf{q}}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{b_1} \\ \mathbf{b_2} \end{bmatrix} = \begin{bmatrix} 0 \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{Nc} \begin{bmatrix} J_{1k}^T \\ J_{2k}^T \end{bmatrix} \mathbf{f_k} \tag{1}$$

The upper part of the equation represents motion of the base link, and the lower part describes the motion of p body segments [15]. Accordingly,

- $\mathbf{q_1}$ represents position and orientation of base link, and $\mathbf{q_2}$ is vector of joint angles of the body segments;
- H_{1j} and H_{2j} $(j = 1, 2)$ are the inertia matrix of the base link and body segments, respectively;
- vectors $\mathbf{b_1}$ and $\mathbf{b_2}$ are the bias force vectors including centrifugal, Coriolis, and gravity forces of the base link and body segments, respectively;
- $\boldsymbol{\tau}$ is the vector of joint torques of the body segments;
- $\mathbf{f_k}$ is the vector of the external forces at contact k. N_c is the number of contact points with the environment;
- J_1 and J_2 are Jacobian matrices at contact k that map external forces to the joint space of the base link and body segments, respectively.

From (1) the equation of the motion of the base link can be written in the linear form with respect to the set of mass parameters, $\boldsymbol{\phi}$ [15] :

$$Y\boldsymbol{\phi} = \sum_{k=1}^{Nc} J_{1k}^T \mathbf{f_k} \tag{2}$$

Y is the regressor matrix which is a function of joint angles and their derivatives; $\boldsymbol{\phi} = [\boldsymbol{\phi_1^T} \; \boldsymbol{\phi_2^T} \; \dots \; \boldsymbol{\phi_p^T}]^T$ is a vector of mass parameters to estimate. For each body segment i, vector $\boldsymbol{\phi_i}$ is composed of 10 parameters, i.e., $\boldsymbol{\phi_i} = [m_i \; p_{xi} \; p_{yi} \; p_{zi} \; i_{i_{xx}} \; i_{i_{yy}} \; i_{i_{zz}} \; i_{i_{xy}} \; i_{i_{xz}} \; i_{i_{yz}}]^T$, where:

- m_i is the mass of the segment;
- vector $[p_{xi} \; p_{yi} \; p_{zi}]^T = m_i com_i$ is the first moment of inertia of the segment i expressed in the joint frame.
- and the vector $[i_{ixx} \; i_{iyy} \; i_{izz} \; i_{ixy} \; i_{ixz} \; i_{iyz}]^T$ represents the components of inertia matrix I_i expressed in the joint frame;

After sampling the equation (2) along the motion data, for the sake of concision we can write it as:

$$Y_{motion}\boldsymbol{\phi} = \mathbf{f_{motion}} \tag{3}$$

In order to solve the equation (3) the minimum-norm least-square solution can be computed, as done in [2]-[3]. Knowing that for the majority of segments mass parameters should not differ much from the values of mass parameters obtained by CAD software, in this study we used quadratic programming technique to minimize the value of the following optimization function:

$$\begin{aligned} \underset{\boldsymbol{\phi}}{\text{minimize}} \quad & \left\| Y_{motion}\boldsymbol{\phi} - \mathbf{f_{motion}} \right\|^2 + \alpha \left\| \boldsymbol{\phi} - \boldsymbol{\phi_{CAD}} \right\|^2 \\ \text{subject to} \quad & constraints \end{aligned} \tag{4}$$

Vector $\boldsymbol{\phi_{CAD}}$ is a vector of mass parameters obtained using CAD software. The right part of the equation (4) represents damping term used to specify unique solution because matrix $\boldsymbol{Y_{motion}}$ is inherently rank deficient. The influence of the right side term of the equation (4) to optimization results is controlled by choosing the value of the constant α. Equation (4) is subjected to the following linear constraints:

- the mass of each segment i, m_i must be non-negative, and the sum of all segments masses should be equal to the total mass of the robot;
- the CoM position should be inside the segment volume. In this study the robots segment links were modeled as boxes align on the segment frames.
- the inertia matrix of each segment i must be positive definite. This is nonlinear constraint that we approximate by a set of linear inequality constrains.
- masses and center of mass positions of segment links located on the right side of the robot body and masses and center of mass positions of segment links located on the left side of the robot body should have symmetric values. This hypothesis can be omitted when needed, for example in a cases of a robot having different tools at its hands.

The method has been implemented using Matlab Optimization Toolbox Software.

B. Choice of exciting trajectories

In case of humanoid robots, force sensors are located in the robot$'$ feet, therefore, standing position during execution of exiting trajectories is mandatory in order to record ground reaction forces (GRF) needed for the identification process (see equation (4)). Hence, not all exciting trajectories are feasible due to the dynamics balance constraint and possible self-collisions. The method proposed in this study was inspired by the method designed for choosing the motion with optimal excitation properties for identification of human mass parameters [6]. The method is based on the decomposition of the regressor matrix into elementary sub-regressors and on the computation of the condition number for each of these sub-regressors.

Exciting the whole system with one motion is hardly achievable, therefore usually the system is excited sequentially by N different motions. Each of the motion excites mass parameters of some specific degrees of freedom (DOF) of the robot. Consequently, equation (3) can be expressed as:

$$\begin{bmatrix} Y_{motion\,1} \\ Y_{motion\,2} \\ \vdots \\ Y_{motion\,N} \end{bmatrix} \boldsymbol{\phi} = \begin{bmatrix} \mathbf{f}_{motion\,1} \\ \mathbf{f}_{motion\,2} \\ \vdots \\ \mathbf{f}_{motion\,N} \end{bmatrix} \tag{5}$$

where $Y_{motion\,i}$ and $\mathbf{f}_{motion\,i}$ for $i = 1, \dots N$ are regressor matrix sampled along an exciting motion i, and ground reaction forces recorded during the exciting motion i, respectively. The columns of the regressor matrix correspond to the mass parameters to be identified (total number of the columns of the regressor matrix is $p \times 10$). Therefore, the regressor matrix can be divided into p sub-regressors, where each of sub-regressor contains the information of the mass parameters of a given DOF.

The algorithm for choosing optimal exciting motions used in this study was as follows:

- First, exciting motions were created. In order to estimate inertia matrix properties motions involving high acceleration of each DOF are needed. The walking type motion was chosen as the initial guess of exciting motion for the identification of the mass parameters of the lower limbs. An established walking pattern generator was used [16] due to its robustness and ease-of-use. For each DOF of the upper-part of the robot, exciting motions were designed using a custom-made motion generator. The motion generator created, for each DOF, at each sample of time a set of random joint positions which are between 10% and 90% of the joint position limitations. The motion velocity of each DOF was chosen to be 80% of the joint velocity limitation. In total between 200 and 300 different exciting trajectories were created, resulting in the total duration of exciting motions of $200s$ in case of HRP-2 humanoid robot and $400s$ in case of HRP-4 humanoid robot. The number of created motions was chosen to be a good tradeoff between covering the entire excitation space and minimizing the computational time.
- Secondly, exciting motions were corrected using a dynamic filter implemented in Choreonoid framework [17]-[18] in order to prevent self-collision and ensure the stability of the robot. Afterward, exciting motions were executed by a humanoid robot and motion and force information were recorded.
- Thirdly, the regressor matrix and its sub-regressor matrices (each of sub-regressor matrices contains the information of the mass parameters of one DOF) were calculated as well as the corresponding condition numbers.
- Finally, the equation (4) was solved using the first three most exciting motions per DOF, with the lowest value of the condition number, for each segment as done in [19]. The other motions were discarded and not used in the identification process, minimizing the required computational time.
- From identified mass parameters the set of base mass parameters was computed. The base mass parameters are defined as a minimum set of mass parameters that can determine the dynamic model uniquely [20]. The relative standard deviation was calculated for each of the base parameter that represents a statistical indicator of the identification results quality, as done in [13]. In case the statistical assumptions upon which the calculation of the standard deviations are based are violated the solution could be biased and not physically consistent. In order to cope with the issue the optimization constraints which deals with physical consistency of the system were added. Other approaches such as the one described in [21] will be investigated in the future.
- Depending on the quality of the mass parameters identification the algorithm was repeated for certain DOFs if necessary.

For easier understanding the schematic representation of the algorithm for generation of exciting trajectories are shown in Fig. 1. In this study the total of two iterations of the described algorithm for choosing optimal exciting motions was needed for obtaining the identified BSIPs.

III. HRP-2 AND HRP-4 HUMANOID ROBOTS USED IN THIS STUDY

The exciting motions created as explained in the previous section were executed into HRP-2 and HRP-4 humanoid robots. Both robots are equipped with sensors measuring the joint angles, force sensors under the feet and hands measuring reaction forces, accelerometer and gyroscope sensors in the trunk segment measuring the acceleration and the posture of the trunk segment.

HRP-2 robot, presented in Fig. 2a, is $1.54m$ tall, with the CAD mass of $56kg$. It is composed of 31 segment links, and has 30 DOF: 6 at each leg, 7 at each arm, 2 at the waist and 2 at the neck, arranged according to the kinematic structure shown in Fig. 2c [22]. Due to the the maintenance and the improvement modifications of the robot some parts were added or replaced. The CPU board located in trunk segments as well as force sensors located in hands were changed, and one DOF in each wrist was added. The modifications resulted in an increase of the robot total mass of $5kg$, and involving de facto changes of its segment inertial properties.

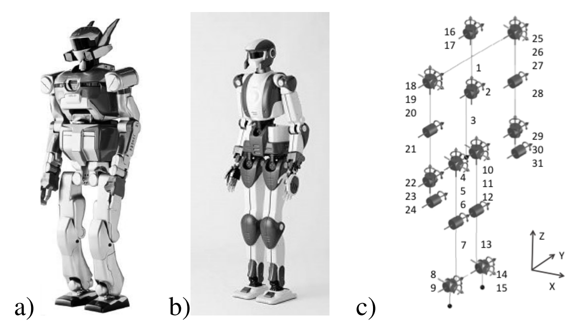

Fig. 2. (a) HRP-2 humanoid robot. (b) HRP-4 humanoid robot. (c) Kinematic structure of HRP-2 and HRP-4 humanoid robots.

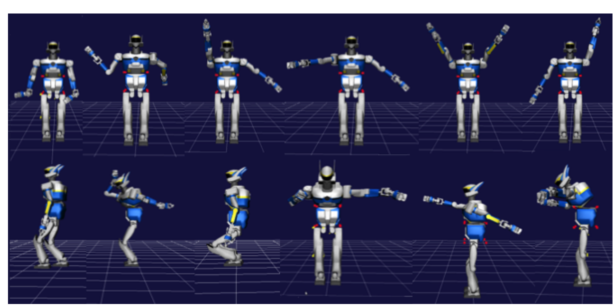

Fig. 3. Examples of a few exciting trajectories executed by HRP-2 humanoid robot in the simulation environment.

HRP-4 humanoid robot [23], presented in Fig. 2b, is $1.58m$ tall, with the CAD mass of $43kg$. It has the same kinematic structure as HRP-2 humanoid robot (Fig 2c).

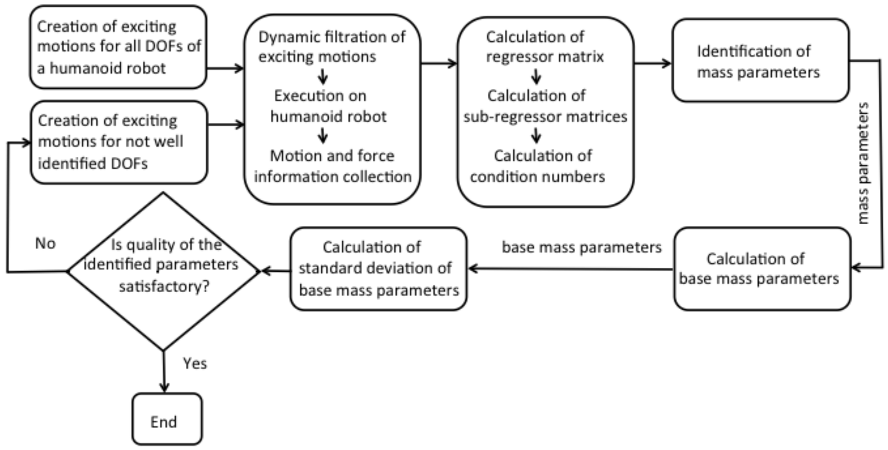

Fig. 1. Algorithm for generation of exciting trajectories.

In case of both humanoid robots the base link was chosen to be at the trunk level due to the location of the accelerometer and gyroscope sensors.

IV. Results

The optimal exciting trajectories have been created, processed by our algorithm and executed by HRP-2 and HRP-4 robots. Examples of a few exciting trajectories are given in Fig. 3. Condition numbers of sub-regressor matrices corresponding to the mass parameter information of each segment link for both humanoid robots are given in Table I.

The mass, center of mass, and inertia matrix of all segment links of HRP-2 and HRP-4 humanoid robots were computed using optimization process described in the previous section. In order to assess the accuracy of the identified parameters, GRF and respective ground reaction force moments (GRFM) were reconstructed using identified mass parameters, and CAD data. The results were compared with GRF and GRFM measured during experiments with force sensors under robots feet. The process was done for excitation like motions used for identification process (direct validation trial), and excitation like motions not used for the identification process (cross-validation trial). The root mean square error (RMSE) and Pearson′s correlation coefficients (CC) between the ground reaction forces and force moments obtained from the force sensors measurements and those reconstructed using identified mass parameters and mass parameters provided by CAD software were computed.

A. *Results for HRP-2 humanoid robot*

Figure 4 shows example of GRF and respective force moments reconstructed using identified mass parameters, CAD data, and measured ones. The RMSE and CC values calculated between the GRF and GRFM obtained from the force sensors measurements and those reconstructed using identified mass parameters and mass parameters provided by CAD software for one direct and one cross validation trial are given in Table II. From the results presented in the Table II it can be noticed that our method led to a more accurate reconstruction of GRF and GRFM comparing with those reconstructed using CAD data in case of both direct and cross validation trial. The mass of each segment link obtained using our method and the ones given by CAD software are presented in Fig. 5. The dotted lines in Fig. 5 show expected segment masses for the modified segment links of the robot. The estimation is done based on the knowledge of the mass parameters of replaced components. Observing Fig. 5 it can be noticed that the identification method was able to estimate the mass changes in the hands and torso segments of the robot that could not be assessed using CAD data. Examples of 3D CoM positions and elements of inertia matrix expressed in segment frame for trunk and leg segments are given in Table III. From results presented in Table III and Fig. 5 it can be noticed that identified BSIPs respect physical consistency.

B. *Results for HRP-4 humanoid robot*

The RMSE and CC values calculated between GRF and GRFM reconstructed using identified mass parameters, CAD data, and measured ones using the force sensors under the robot feet for one direct validation trial and one cross validation trial are given in Table IV. Similarly in case of identification of mass parameters of HRP-4 humanoid robot, our method led to a more accurate reconstruction of the GRF and GRFM compared to those reconstructed using CAD data in case of both direct and cross validation trial. Even though masses of the segment links of the HRP- 4 robot have not been changed, and consequently the mass parameters should be similar with the ones given by CAD software, we believe that the more accurate reconstruction of the GRF and GRFM in case of the identified mass parameters is due to the fact that CAD data do not take into account wiring materials.

TABLE I

CONDITION NUMBERS OF SUB-REGRESSOR MATRICES CORRESPONDING TO THE MASS PARAMETER INFORMATION OF EACH SEGMENT LINK CALCULATED FOR OPTIMAL EXITING MOTIONS FOR HRP-2 AND HRP-4 HUMANOID ROBOTS. FOR THE EXTRA INFORMATION ABOUT SEGMENT LINKS LOCATIONS SEE FIG. 2C.

	Trunk			Left and Right Leg											
Segment number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
HRP-2	463	598	98	79	33	7	7	9	12	80	33	7	7	9	11
HRP-4	11475	9211	114	26	27	28	33	8011	233	35	31	34	35	10610	182

	Head		Left and Right Arm													
Segment number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
HRP-2	432	68	344	11	9	7	7	7	7	331	11	8	8	7	6	6
HRP-4	181	181	45	14	10	9	6	7	6	6	7	4	16	9	9	7

TABLE II

RMSE AND CC VALUES BETWEEN THE GRF AND GRFM MEASURED USING FORCE SENSORS AND THOSE RECONSTRUCTED USING IDENTIFIED AND CAD DATA FOR HRP-2 HUMANOID ROBOT.

			GRF		GRFM	
			Identified parameters	CAD parameters	Identified parameters	CAD parameters
Direct validation	X-axis	RMSE	7.3 [N]	7.4 [N]	4.8 [Nm]	6.5[Nm]
		CC	0.65	0.58	0.92	0.90
	Y-axis	RMSE	7.4 [N]	7.9 [N]	6.2 [Nm]	7.4 [Nm]
		CC	0.32	0.30	0.96	0.96
	Z-axis	RMSE	6.8 [N]	45.6 [N]	2.7 [Nm]	2.7[Nm]
		CC	0.95	0.94	0.81	0.80
			Identified parameters	CAD parameters	Identified parameters	CAD parameters
Cross validation	X-axis	RMSE	8.0 [N]	9.3 [N]	5.0[Nm]	6.3 [Nm]
		CC	1.00	1.00	0.93	0.87
	Y-axis	RMSE	12.4 [N]	13.8 [N]	6.7 [Nm]	12.4 [Nm]
		CC	0.14	0.14	0.92	0.92
	Z-axis	RMSE	9.8 [N]	32.8 [N]	5.3 [Nm]	5.5 [Nm]
		CC	0.98	0.98	0.31	0.28

TABLE III

EXAMPLES OF IDENTIFIED COM POSITION AND INERTIA MATRIX ELEMENTS OF HRP-2 HUMANOID ROBOTS. FOR THE EXTRA INFORMATION ABOUT SEGMENT LINKS LOCATIONS SEE FIG. 2C.

Segment	Trunk			Right Leg					
number	1	2	3	4	5	6	7	8	9
CoM_X [m]	-0.095	0.007	0.187	-0.010	0	0.013	-0.014	0.013	0
CoM_Y [m]	0.013	0.005	-0.015	0.003	-0.027	-0.078	-0.058	0.006	-0.006
CoM_Z [m]	0.108	-0.016	0.500	0.074	0.057	-0.123	-0.083	0.114	-0.07
$I_{xx}[kgm^2]$	0.1910	0.0050	5.5495	0.0083	0.0050	0.0594	0.0369	0.0050	0.0155
$I_{yy}[kgm^2]$	0.0068	0.0050	5.3242	0.0089	0.0050	0.0561	0.0292	0.0087	0.0207
$I_{zz}[kgm^2]$	0.1054	0.0050	0.0050	0.0050	0.0050	0.0164	0.0103	0.0050	0.0051
$I_{xy}[kgm^2]$	-0.0133	0	0.0271	0.0002	0	0.0124	0.0124	0.0004	-0.0006
$I_{xz}[kgm^2]$	0.0181	0	-0.0775	0	0	0.0130	0.0062	0	0.0010
$I_{yz}[kgm^2]$	-0.0133	0	-0.0775	-0.0002	0	-0.0171	-0.0059	-0.0001	0

	Left Leg					
Segment number	10	11	12	13	14	15
CoM_X [m]	-0.010	0	0.013	-0.014	0.013	0
CoM_Y [m]	-0.003	0.027	0.078	0.058	-0.006	0.006
CoM_Z [m]	0.074	0.057	-0.123	-0.083	0.114	-0.07
$I_{xx}[kgm^2]$	0.0081	0.0050	0.0593	0.0365	0.0050	0.0163
$I_{yy}[kgm^2]$	0.0090	0.0050	0.0589	0.0291	0.0076	0.0200
$I_{zz}[kgm^2]$	0.0050	0.0050	0.0138	0.0119	0.0050	0.0053
$I_{xy}[kgm^2]$	0.0003	0	0.0018	0.0019	0.0003	-0.0009
$I_{xz}[kgm^2]$	0.0001	0	0.0179	-0.0120	0	0.0019
$I_{yz}[kgm^2]$	-0.0001	0	0.0132	0.0067	0	0.0004

V. CONCLUSION

In this study we presented a method for systematic determination of the exciting motions useful for the identification of the mass parameters of humanoid robots. The method was inspired by the work done in the field of identification of human mass parameters, and it is based on decomposition of the regressor matrix into elementary sub-regressors and

TABLE IV

RMSE AND CC VALUES BETWEEN THE GRF AND GRFM MEASURED USING FORCE SENSORS AND THOSE RECONSTRUCTED USING IDENTIFIED AND CAD DATA FOR HRP-4 HUMANOID ROBOT.

			GRF		GRFM	
			Identified parameters	CAD parameters	Identified parameters	CAD parameters
Direct validation	X-axis	RMSE	1.0 [N]	17.2 [N]	2.3 [Nm]	3.9 [Nm]
		CC	0.96	0.09	0.98	0.96
	Y-axis	RMSE	2.9 [N]	3.4 [N]	1.7 [Nm]	5.0 [Nm]
		CC	0.99	0.99	0.58	-0.50
	Z-axis	RMSE	12.6 [N]	13.0 [N]	0.4 [Nm]	0.5 [Nm]
		CC	0.96	0.96	0.99	0.92
			Identified parameters	CAD parameters	Identified parameters	CAD parameters
Cross validation	X-axis	RMSE	1.5[N]	3.0 [N]	2.6 [Nm]	4.9 [Nm]
		CC	0.71	0.38	-0.66	-0.89
	Y-axis	RMSE	1.5 [N]	1.6 [N]	2.8 [Nm]	4.7 [Nm]
		CC	0.14	0.05	0.26	-0.17
	Z-axis	RMSE	9.8 [N]	10.1 [N]	0.5 [Nm]	0.7 [Nm]
		CC	0.60	0.41	0.92	0.61

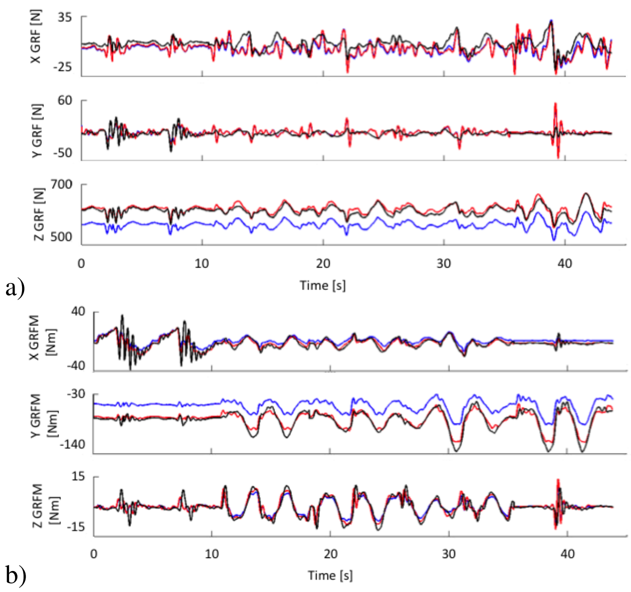

Fig. 4. Example of GRF (a) and GRFM (b) reconstructed using identified mass parameters (red line), CAD data (blue line), and obtained using force sensors measurements (black line) for HRP-2 humanoid robot for the cross validation trail.

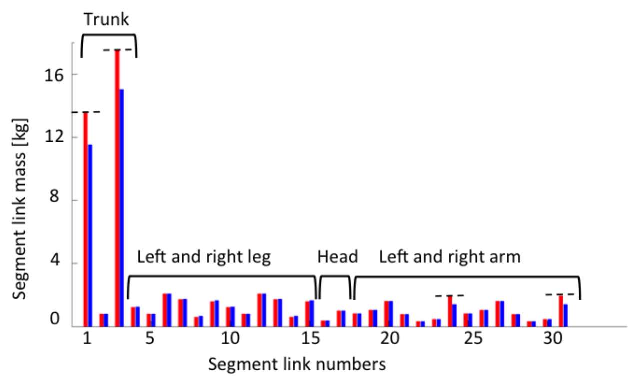

Fig. 5. Segment link masses distribution for HRP-2 humanoid robot. X-axis shows segment segment link numbers, for the extra information see Fig. 2c. Red bars represent segment masses obtained using identification method, the blue ones segment masses obtained from the CAD data. Dotted lines show expected segment masses based on the knowledge of the replaced components.

computation of their condition numbers that represent the precision of the identified mass parameters. The method described in this study takes into account mechanical constraints and dynamic stability of humanoid robotic structure and ensures self-collision free motions.

We have tested the algorithm on HRP-2 and HRP-4 humanoid robots. The results obtained using the proposed method were compared with the results obtained using CAD data. Our method was able to reconstruct the ground reaction forces and respective force moments more accurately compared to the method based on the use of CAD software. In addition, the proposed method was able to estimate correctly mass parameters of the modified segment links of the HRP-2 robot.

In the future, the accuracy of the algorithm will be assessed by attaching a known mass to HRP-2 and HRP-4 humanoid robots limbs and performing the identification experiments as done in [24]. In addition the generation of the exciting trajectories will be done in the task space respecting the robot specifications rather than the joint space in order to generalize the method for all types of humanoid robots. We plan to use dynamic optimization approach which would allow automatic generation of exiting trajectories that handle balance and self-collisions issues without manual intervention.

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