V. FD ALGORITHM RELATIVE TO MANIPULATOR ACTUATORS

Similar to Eq. (1), the motion equations for the manipulator relative to the torques/forces of the robot actuators can be written as

$$\mathbf{H}_{\mathrm{a}}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{u}'_{\mathrm{a}}(\mathbf{q},\dot{\mathbf{q}},\mathbf{k}_{\mathrm{ea}}) = \mathbf{u}_{\mathrm{a}}\,, \tag{42}$$

$$\mathbf{u}'_{\mathrm{a}}(\mathbf{q},\dot{\mathbf{q}},\mathbf{k}_{\mathrm{ea}}) = \mathbf{C}_{\mathrm{a}}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}_{\mathrm{a}}(\mathbf{q}) + \mathbf{J}(\mathbf{q})^{\mathbf{T}}\mathbf{k}_{\mathrm{ea}} + \mathbf{F}_{v}\dot{\mathbf{q}} + \mathbf{F}_{s}\,\mathrm{sign}(\dot{\mathbf{q}})\,. \tag{43}$$

Herein, $\mathbf{H}_{\mathrm{a}}(\mathbf{q})$, $\mathbf{u}'_{\mathrm{a}}(\mathbf{q},\dot{\mathbf{q}},\mathbf{k}_{\mathrm{ea}})$, and $\mathbf{u}_{\mathrm{a}}$ relate to the actuator rotors. $\mathbf{F}_{\mathrm{v}}$ denotes an $n \times n$ diagonal matrix of viscous friction coefficients $f_{\mathrm{v}i}$. The static friction torques are considered as Coulomb friction torques; $\mathbf{F}_{\mathrm{s}}$ is an $n \times n$ diagonal matrix of the Coulomb friction constants. Herein, $\mathrm{sign}(\dot{\mathbf{q}})$ denotes an $n \times 1$ vector whose components are given by the sign functions of single joint velocities.

If certain absolute value of $u_{\mathrm{a}i}$ exceeds its limit, it is reduced to the maximum possible. These achievable values of $u_{\mathrm{a}i}$ are then used in the following linear system of n equations to calculate the achievable (realistic) joint accelerations $\ddot{q}_i$:

$$\sum_{j=1}^{n} h_{\mathrm{a}ij}\ddot{q}_j = u_{\mathrm{a}i} - u'_{\mathrm{a}i}\,,\ i = 1 \text{ to } n. \tag{44}$$

VI. CONCLUSIONS

An algorithm which calculates the achievable joint accelerations in each interpolation cycle based on the FD model and actuators' capabilities was given in this paper. Presented algorithm enables the setting of only attainable joint velocities within each interpolation cycle as determined from the joint acceleration by taking into account the achievable actuator torques. As a result, a precise simulation of the robot movements is provided. This algorithm can indicate to the operator that the programmed parameters of the movements are not achievable. Furthermore, calculation of the realistic forces and moments of the robot joints can be achieved when the simulation system is used in the design phase.

In presented simulation, the mRNEA that gives the mass matrix $\mathbf{H}$ and the bias vector $\mathbf{u}'$ of a dynamic model was used. Consequently, mRNEA allows for solving FD by calculating ID only once. It was shown that proposed FD algorithm does not need to calculate the input vector $\mathbf{u}$ of the FD algorithm, which additionally increases the computational efficiency of the presented method. Compared with the other methods given in the literature, the algorithm presented herein is one of the most efficient ones. Apart from that, it is very simple to develop and implement.

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