List of Symbols

γ	the n-dimensional vector of gravitational accelerations
Π^C	power due to the constraint wrenches, $\mathbf{w}^C$
θ	the n-dimensional vector of generalized coordinates
$\dot{\boldsymbol{\theta}}, \ddot{\boldsymbol{\theta}}$	the n-dimensional vectors of generalized rates and accelerations, respectively
ρ	a Spline function
τ_i	torque at each joint
$\boldsymbol{\tau}$	the n-dimensional vector of generalized forces due to external forces and moments
$\boldsymbol{\Omega}$	the $6n \times 6n$ matrix of angular velocities different than $\mathbf{W}$
$\boldsymbol{\Omega}_i$	the 6×6 angular velocity matrix for the i^{th} body different than $\mathbf{W}_i$
$\boldsymbol{\omega}_e$	the 3-dimensional angular velocity vector of the end-effector
$\boldsymbol{\omega}_i$	the 3-dimensional angular velocity vector of the i^{th} body
$\boldsymbol{\omega}_i, \dot{\boldsymbol{\omega}}_i$	the 3-dimensional vectors of angular velocity and acceleration of link i, respectively
$\mathbf{a}_i$	the 3-dimensional vector denoting point O_{i+1} from O_i
$\mathbf{B}_{ij}$	the 6×6 twist propagation matrix from #i to #j
b	damping coefficient
$b_i, \theta_i, a_i, \alpha_i$	Four DH parameters
$\mathbf{C}$	the $n \times n$ matrix for convective inertia terms (MCI)
c	total number of constraints imposed by p joints
c_i	number of constraints imposed by each joint
$\mathbf{c}_i$	the 3-dimensional vector denoting the mass center C_i from the origin of fixed frame, F
$\dot{\mathbf{c}}, \ddot{\mathbf{c}}_i$	The 3-dimensional vectors of linear velocity and acceleration of the mass center of link i, respectively
$\mathbf{d}_i$	the 3-dimensional vector of the mass center, C_i, from the origin point, O_i
e_{ss}	steady-state error
$\mathbf{e}_i$	the 3-dimensional unit vector along the axis of the i^{th} joint
$\mathbf{f}_{ij}$	the 3-dimensional vector of resulting force exerted on link i by link j at O_i
$\mathbf{g}$	the 3-dimensional vector of acceleration due to gravity
h	the n-dimensional vector of convective inertia terms (VCI)
$\mathbf{I}$	the $n \times n$ Generalized Inertia Matrix (GIM)
$\mathbf{I}_i$	the 3×3 inertia tensor of the i^{th} body or link about its mass center, C_i
$\tilde{\mathbf{I}}_i$	the 3×3 inertia tensor of the i^{th} composite body consisting of rigidly connected links, #i to #n
J	the $6 \times n$ Jacobian matrix for n-DOF robot
k	spring constant

k_p, k_v, k_i	proportional, derivative, and integral gains, respectively
L	Lagrangian
$\mathbf{M}$	the $6n \times 6n$ generalized mass matrix
$\widetilde{\mathbf{M}}$	the $6n \times 6n$ matrix of composite mass matrix
$\mathbf{M}_i$	the 6×6 mass matrix for the i^{th} body
$\widetilde{\mathbf{M}}_i$	the 6×6 mass matrix of the i^{th} 'composite body'
$\widetilde{\mathbf{M}}_\omega$, $\widetilde{\mathbf{M}}_l$, $\widetilde{\mathbf{M}}_e$	the $6n \times 6n$ matrices, which constitute MCI
m_i	mass of i^{th} body
$\mathbf{m}$	linear momentum
$\widetilde{\mathbf{m}}$	angular momentum
$\mathbf{N}$	the $6n \times n$ NOC matrix
$\mathbf{N}_d$	the $6n \times n$ block diagonal matrix of the DeNOC matrices
$\mathbf{N}_l$	the $6n \times 6n$ lower block triangular matrix of the DeNOC matrices
n	degree of freedom of the whole system
n_i	relative degree of freedom of each joint
$\mathbf{n}_{\text{ij}}$	the 3-dimensional vector of resulting moment exerted on link i by link j at O_i.
p	number of kinematic pairs or joints in the system
$\mathbf{p}$	position vector of a point P. Position vector of any other point is similarly represented.
$\mathbf{p}_{\text{i}}$	the 6-dimensional joint-motion propagation vector
$[\mathbf{p}]_{\text{F}}$	representation of vector P in the fixed frame F. Similar representation for other frames.
$\mathbf{Q}$	the 3×3 rotation matrix
$\mathbf{Q}_i$	the 3×3 rotation matrix transforming frame i to frame i+1, i.e., any vector representation in frame i+1 is pre-multiplied by this matrix to find the representation in frame i
r	number of rigid bodies or links in the system
$\mathbf{r}_i$	the 3-dimensional vector of the origin O_{i+1} from the mass center C_i
s	dimension of working space (For planar, $s = 3$; spatial, $s = 6$)
T	kinetic energy
$\mathbf{T}$	the 4×4 homogeneous transformation matrix
$\mathbf{t}$	the $6n$-dimensional vector of generalized twist
$\mathbf{t}_e$	the 6-dimensional twist vector of the end-effector
$\mathbf{t}_i$	the 6-dimensional twist vector associated with the i^{th} body
$\dot{\mathbf{t}}_i$	the 6-dimensional twist-rate vector of the i^{th} body
U	Potential energy
$\mathbf{W}$	the $6n \times 6n$ generalized matrix of the angular velocities
$\mathbf{W}_i$	the 6×6 angular velocity matrix for the i^{th} body
$\mathbf{w}_i$	the 6-dimensional vector of wrench acting on the i^{th} body
$\mathbf{w}$	the $6n$-dimensional vectors of generalized wrench
$\mathbf{w}^E$, $\mathbf{w}^{\text{C}}$	the 6-dimensional vectors of external and constraint wrenches, respectively
$\widetilde{\mathbf{w}}_i^E$	the 6-dimensional vector of external wrench for the i^{th} composite body
$\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$	unit vectors along axes, X, Y and Z, respectively. Similar notations for other unit vectors.
$\mathbf{1}$	the identity matrix of compatible dimension
$\mathbf{O}$	the matrix of compatible dimension whose all elements are zeros
$\mathbf{0}$	the vector of compatible dimension whose all elements are zeros
$[\bullet]^T$	transpose of the argument $[\bullet]$