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Software for global dynamics evaluation of mechanisms

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ABSTRACT

The paper deals with the multibody system software which implements the solution of the global dynamic problem for multibody systems described by redundant coordinates (DAE equations) and with a possibility of redundant number of actuators. The aim of the global dynamics evaluation is mainly the machine synthesis. The necessity of such formulation arises especially in robotics where the accessible velocities and accelerations on the given trajectory are important for the motion planning and for the design optimization of robots and manipulators. The analogical problem can be very important also for the design of any other machine type. The developed software is therefore one of the important tools for the multiobjective machine synthesis.

1. Introduction

The design and synthesis of machines with complex kinematic structures like robots is a difficult problem [1,2]. The design parameters are mutually dependent which leads to significantly increased computational complexity. A lot of special problems have been addressed like special synthesis algorithms [3–5], problems of sensitivity analysis [6], problems of overdetermined kinematics [7], usage of neural-genetic approaches [8], structural synthesis [9] or software implementations suitable for mechanism synthesis [10]. There has been developed a special design methodology for complex kinematics [11–14]. This methodology has succeeded to decreasing the computational complexity of the design by decomposition of design process into several hierarchical levels and by the usage of computational tools capable to compute the mechanical properties globally (for whole workspace instead just for one position in it). Specifically the design has been decomposed into three hierarchical levels of design conflicts and related structural and parametric optimizations. Firstly the geometric design including especially workspace, dexterity and other kinematical requirements, secondly the structural and mass design including stiffness, modal and global dynamics requirements and finally the complex testing including the actuator and feedback design. The applied design methodology is heavily based on the efficient computational tools for mapping design parameters into design criteria (requirements and constraints) and following multiobjective optimization. The parameters of machine are selected on the Pareto set of design criteria, i.e. it is a design-by optimization method. One of the important parts of the multiobjective machine evaluation is the so called global dynamics. The problem is, that the solution of the global dynamics problem is not the part of standard commercial MBS softwares. The need of such automated tool for the machine optimization problems induced the building of the bellow described program. The paper is organized as follows. The chapter 2 describes the basics of the global dynamics method. The used multibody formalism is described within the chapter 3. The chapter 4 explains the structure of the implementation, the chapter 5 shows the example of program usage and chapter 6 is the short conclusion.

2. Global dynamics method

Within the dynamics of multibody systems two main types of problems are well known: the solution of direct dynamics and the solution of inverse dynamics. The solutions of both these problems enable to determine in each time instant the relation between motion described by positions, velocities, accelerations and the acting forces and couples. From the point of view of machine synthesis the problem emerges, that such solutions do not provide with the global overview about the dynamic capabilities of a mechanical. Thus besides the two basic dynamical problems there is a third one: the global dynamic problem. The necessity of such formulation arise especially in robotics where the accessible velocities and accelerations on the given trajectory are important for the motion planning (e.g. [15,16]) and for the design optimization of robots. Nevertheless the analogical problem can be very important also for the design of any other machine type. This problem has been solved firstly for the rigid robots described as multibody systems with independent coordinates and with the same number of

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drives and degrees of freedoms (DOF) [16]. The generalization of the global dynamic problem for multibody systems described by redundant coordinates and overactuated systems (the number of drives is higher than the number of DOF) has been done in [17,18]. Let investigate the dynamics of a mechanical system (e.g. machine, robot, manipulator) modeled as multibody system. Its dynamics is generally described by Lagrange equations of mixed type (e.g. [19])

$$\mathbf{M}\ddot{\mathbf{z}} - \Phi^{\mathbf{T}}\lambda = \mathbf{g} + \mathbf{T}\mathbf{n} \tag{1}$$

where $\mathbf{z}$ is the vector of coordinates, $\mathbf{M}$ is the mass matrix, $\mathbf{g}$ is the vector of dynamical and applied forces, $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers, $\boldsymbol{\Phi}$ is the Jacobian matrix of kinematical constraint equations $\mathbf{F}(\mathbf{z}) = \mathbf{0}$, $\mathbf{n}$ is the vector of drive forces and couples and $\mathbf{T}$ is their influence matrix with respect to coordinates. Let a desired generalized robot/machine end-effector trajectory be given as $\mathbf{R} = \mathbf{R}(p)$, where p is a geometric parameter $0 < p < p_{max}$. Starting from the generalized trajectory description $\mathbf{R} = \mathbf{R}(p)$ it was obtained the trajectory plan $\mathbf{z} = \mathbf{z}(p)$. After time differentiation it follows

$$\begin{aligned} \dot{\mathbf{z}} &= \frac{d\mathbf{z}}{dp} d_1 \\ \ddot{\mathbf{z}} &= \frac{d\mathbf{z}}{dp} d_2 + \frac{d^2\mathbf{z}}{dp^2} d_1^2 \end{aligned} \tag{2}$$

Symbol d_1 denotes the first time differentiation of p and d_2 its second time differentiation. These values can be understood as the generalized velocity and generalized acceleration on the given trajectory. The accessible dynamics can be described in the plane $d_1 - d_2$ (Fig. 1) as a function of the geometrical parameter p. Eq. (1) can be rewritten to

$$\begin{bmatrix} \Phi^T & \mathbf{T} \end{bmatrix} \begin{bmatrix} -\lambda \\ -\mathbf{n} \end{bmatrix} = \mathbf{g} - \mathbf{M}\ddot{\mathbf{z}} \tag{3}$$

The system of equations can be solved by the singular decomposition method (SVD). Concerning the case of the redundantly actuated system the number of unknowns is higher than the number of equations and the vector $\mathbf{y}_{red}$ means the solution parameterization. Substituting the lower drive limits $\mathbf{n}^-$ and the upper drive limits $\mathbf{n}^+$ the following system of inequalities is determined

$$\mathbf{n}^- \leqslant \mathbf{A}_n d_1^2 + \mathbf{B}_n d_1 + \mathbf{C}_n + \mathbf{D}_n d_2 + \mathbf{V}_{red,n}\mathbf{y}_{red} \leqslant \mathbf{n}^+ \tag{4}$$

The dimension of the vector $\mathbf{y}_{red}$ corresponds to the degree of redundancy $r = \dim(\mathbf{n}) - n_{DOF}$, where n_{DOF} is the number of degrees of freedom. Consequently, there are r equations necessary for the determination of the parameter the vector $\mathbf{y}_{red}$. The substitution of limit states of r + 1 drives is the necessary condition for the point on the limit curves. The solution of free parameters $\mathbf{y}_{red}$ needs r limit equations from (4). $\mathbf{A}_n$, $\mathbf{B}_n$, $\mathbf{C}_n$, $\mathbf{D}_n$ are the column vectors of size (n_{DOF}+r, 1) generated by the substitution of relations (1), (2) to Eqs. (3). The column vectors contain coefficients.

$$\mathbf{y}_{red,j} = \mathbf{V}_{red,nj}^{-1}(\mathbf{n}_j^{lim} - \mathbf{A}_{nj} d_1^2 - \mathbf{B}_{nj} d_1 - \mathbf{C}_{nj} - \mathbf{D}_{nj} d_2) \tag{5}$$

The parameter vectors $\mathbf{y}_{red,j}$ are computed in the cycle through the possible 'r-tuples' of drives by the substitution of limits of these drives. The vector $\mathbf{n}_j^{lim}$ represents $\mathbf{n}_j^+$ or $\mathbf{n}_j^-$, j is the index of cycle. In details, among the inequalities (4) r of them are selected and they become Eqs. (5). From them r parameters $\mathbf{y}_{red}$ are determined and substituted into the rest inequalities (4).

The accessible subregions $d_1 - d_2$ for points on the characteristic curves within the workspace (circles, lines etc.) can be used as the criterions of the machine synthesis. The form of these regions is illustrated for two different circles within the workspace of the machine Sliding Star (Fig. 1).

3. Automation of global dynamics computations

The process of automation of global dynamics computations needs a suitable unique description of the system. The description of position by physical coordinates has been chosen. The basic input information necessary for the equations set up are as follows:

- structure of mechanism,
- mass, centroid position and matrix of inertia of each body,
- drives,
- external loads.

3.1. Multibody formalism

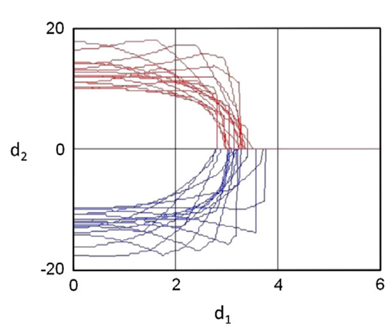
As mentioned above the physical coordinates have been used for the description of position of each body. Physical coordinates have six components. First three components (x_{1Si}, y_{1Si}, z_{1Si}) are the Cartesian coordinates of center of gravity of each body. Components are in global coordinate system (6). The second triple of components (φ_x, φ_y, φ_z) are the Cardan's angles of the body.

To sequence of rotations is as follows: first rotation around x-axis by the angle φ_x, second rotation around u_y-axis by the angle φ_y and finally rotation around ζ-axis by the angle φ_z. Cardan angles are shown in Fig. 2. The used coordinates can be written in the compact vector form

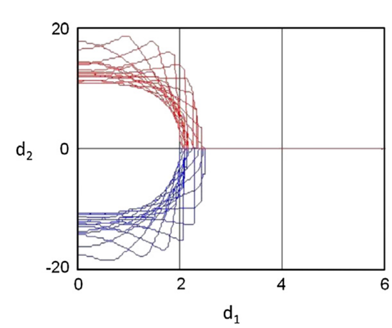
$$\boldsymbol{\Theta}_i = [x_{1S_i}\ y_{1S_i}\ z_{1S_i}\ \varphi_{x_i}\ \varphi_{y_i}\ \varphi_{z_i}]^{\mathrm{T}} \tag{6}$$

Its first time derivative $\dot{\boldsymbol{\Theta}}_i = [\dot{x}_{1S_i}\ \dot{y}_{1S_i}\ \dot{z}_{1S_i}\ \dot{\varphi}_x\ \dot{\varphi}_y\ \dot{\varphi}_z]^T$ and second time derivative $\ddot{\boldsymbol{\Theta}}_i = [\ddot{x}_{1S_i}\ \ddot{y}_{1S_i}\ \ddot{z}_{1S_i}\ \ddot{\varphi}_x\ \ddot{\varphi}_y\ \ddot{\varphi}_z]^T$ are used in the equations below. The complete vector of coordinates $\mathbf{z}$ which is used in general global dynamics formulation (paragraph 2) is composed from the particular vectors $\mathbf{z} = [\boldsymbol{\Theta}_1, \boldsymbol{\Theta}_2, \ldots, \boldsymbol{\Theta}_{ns}]^T$, where n_s is the number of bodies.

Kinematic constraints are defined between the couple of adjacent bodies (ith and the jth) connected by corresponding joint.



(a) for circle with radius 0.35 m



(b) for circle with radius 0.15 m

Fig. 1. The accessible subregions $d_1 - d_2$ for two circular trajectories of the machine SlidingStar [14].