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Univ Cassino & South Latium Lab of Robotics & Mechatronics
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Vigen Arakelian • Sébastien Briot

Balancing of Linkages and Robot Manipulators

Advanced Methods with Illustrative Examples

Springer

Vigen Arakelian
Institut National des Sciences
Appliquées (INSA), Rennes, France,
and Institut de Recherche en
Communications et Cybernétique
de Nantes (IRCCyN), Nantes, France
Rennes
France

Sébastien Briot
Institut de Recherche en Com.
et Cybernétique de Nantes
CNRS
Nantes
France

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Vigen Arakelian dedicates this work to his charming wife Tatiana and beloved son David.

Sébastien Briot dedicates this work to his beloved wife and sons, Sylvie, Élouan and Guénaël.

Preface

The balancing of linkages is an integral part of the mechanism design. The challenge of reducing vibrations of the frame on which the mechanism is mounted is nothing new. Despite its long history, mechanism balancing theory continues to be developed and new approaches and solutions are constantly being reported. Hence, the balancing problems are of continued interest to researchers. Several laboratories around the world are very active in this area and new results are published regularly. In recent decades, new challenges have presented themselves, particularly, the balancing of robots for fast manipulation.

The authors believe that this is an appropriate moment to present the state of the art of the studies devoted to balancing and to summarize their research results. This monograph is based on the material published by the first author over the last twenty years and the doctoral dissertation of the second author defended in 2007 and rewarded by the Research Group in Robotics of the French National Center for Scientific Research (GDR Robotique, CNRS, 2008), the French Section of the ASME (2011) and the French Région Bretagne in the category "Sciences, Technologies and Interdisciplinarities" (2011).

Some results given in the book were reached in collaboration with Mike Smith, Clément Gosselin, Ilian Bonev, Simon Lessard and Cédric Baradat. The authors acknowledge for their contributions, as well as the "Mechanical Center" of the National Institute of Applied Sciences of Rennes for the development of the prototypes permitting the validation and improvement of the obtained theoretical results.

The authors will be also genuinely grateful to the readers for any critical remarks on the material presented in the book and for any suggestion for its improvement.

Rennes/Nantes, France — Vigen Arakelian
June, 2014 — Sébastien Briot

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List of Symbols and Abbreviations

In the whole book, vectors are represented by bold lowercase symbols and matrices by bold uppercase symbols, except for greek symbols.

List of Symbols

$\alpha, \beta, \gamma, \phi, \varphi, \theta, \psi$	angles used for geometry description of a mechanism
$\mathbf{f}$	a vector of force
$\mathbf{f}^{sh}$	a vector of shaking force
F	a force
F^{sh}	a shaking force
$\mathbf{h}$	an angular momentum
H_x, H_y, H_z	the components of the angular momentum $\mathbf{h}$ around $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{z}$ axes, respectively
$\mathbf{I}j$	the inertia matrix for body j, expressed at the *com* in the local frame attached to this body
I_{cr_j}	the axial moment of inertia of the counter-rotation j
I_{S_j}	the axial moment of inertia of the link j expressed at the *com* when link j is considered to have a planar motion
$I_{xx}^{(j)}, I_{yy}^{(j)}, I_{zz}^{(j)}$	the axial moments of inertia around $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{z}$ axes, respectively, for body j, expressed at the *com* in the local frame attached to this body
$I_{xy}^{(j)}, I_{yz}^{(j)}, I_{yz}^{(j)}$	the inertial cross-moments around $\mathbf{z}$, $\mathbf{y}$ and $\mathbf{x}$ axes, respectively, for body j, expressed at the *com* in the local frame attached to this body
L	the Lagrangian of a system
l_{PQ}	the length of the segment PQ
$\mathbf{m}$	a vector of moment
M	a moment
$\mathbf{m}^{sh}$	a vector of shaking moment
M^{sh}	a shaking moment
m_j	the mass of the body j
m_{cw_j}	the mass of the counterweight j
ω_j	the rotational velocity of body j expressed in the base frame

$\omega_{j_x}, \omega_{j_y}, \omega_{j_z}$	the components of the vector ω_j around **x**, **y** and **z** axes, respectively
$\dot{\omega}_j$	the rotational acceleration of body j expressed in the base frame
$\dot{\omega}_{jx}, \dot{\omega}_{jy}, \dot{\omega}_{jz}$	the components of the vector $\dot{\omega}_j$ around **x**, **y** and **z** axes, respectively
$\mathbf{p}$	a linear momentum
P_x, P_y, P_z	the components of the linear momentum **p** along **x**, **y** and **z** axes, respectively
$\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$	vectors of actuated coordinates, velocities and accelerations, respectively
$q, \dot{q}, \ddot{q}$	some actuated coordinates, velocities and accelerations, respectively
${}^i\mathbf{R}_j$	the rotation matrix from the frame i to the frame j
$\mathbf{r}_P$	the position of point P expressed in the base frame
$\dot{\mathbf{r}}_P$	the velocity of point P expressed in the base frame
$\ddot{\mathbf{r}}_P$	the acceleration of point P expressed in the base frame
S_j	the *com* of the body j
t	the time variable
T	the kinetic ernergy of a system
$\mathbf{x}$	for a manipulator, the Cartesian position of its end-effector
x_P, y_P, z_P	the components of the vector $\mathbf{r}_P$ along **x**, **y** and **z** axes, respectively
$\dot{x}_P, \dot{y}_P, \dot{z}_P$	the components of the vector $\dot{\mathbf{r}}_P$ along **x**, **y** and **z** axes, respectively
$\ddot{x}_P, \ddot{y}_P, \ddot{z}_P$	the components of the vector $\ddot{\mathbf{r}}_P$ along **x**, **y** and **z** axes, respectively
τ	an input torque
V	the potential ernergy of a system
$\mathbf{w}$	a wrench

List of Abbreviations

com	centre of mass
dof	degree of freedom
HOBM	hand-operated balanced manipulators
PAMINSA	parallel manipulator of the INSA
PKM	parallel kinematic machine
PPM	planar parallel mechanism
rms	root mean square
SPM	spatial parallel mechanism