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Andreas Pott

Cable-Driven Parallel Robots

Theory and Application

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"Theoria cum praxi"
(Unity of theory and application)
Maxim of Gottfried W. Leibniz

Dedicated to

Eva and Jana.

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Sindelfingen, Germany Andreas Pott
September 2017

Contents

Symbols

$\mathbf{A}^{\mathbf{T}}$	Pose-dependent structure (wrench) matrix $\in \mathbb{R}^{m \times n}$
$\widehat{\mathbf{A}}^{\mathrm{T}}$	Non-normalized structure matrix $\in \mathbb{R}^{m \times n}$
$\mathbf{A}^{+\mathbf{T}}$	Moore–Penrose pseudo-inverse of $\mathbf{A}^{\mathrm{T}}$
A_{C}	Cross section of the cable
$\mathbf{a}_i$	Position vector $\in \mathbb{R}^3$ of i-th proximal anchor point of the machine frame
$\mathbf{b}_i$	Position vector $\in \mathbb{R}^3$ of i-th distal anchor point of the mobile platform
β_{R}	Wrapping angle of the cable on the pulley
$\mathbf{c}$	Vector of calculation variables in the constraint satisfaction problem
$\mathbf{C}$	Compliance matrix $\in \mathbb{R}^{6 \times 6}$ of the cable robot in operational space
$\mathcal{C}$	Set $\subset \mathbb{R}^m$ of the m-dimensional hypercube of feasible forces in the cables
γ_{R}	Rotation of the panning pulley about the z-axis
d_{D}	Diameter of the drum
E_{C}	Young's modulus of the cable
$\mathbf{f}$	vector $\in \mathbb{R}^m$ collecting all cable forces as generalized forces
$\mathcal{F}$	Set $\subset \mathbb{R}^m$ with feasible solutions for the force distribution problem
$f_{\min}$	Required pretension in the cable
$f_{\max}$	Feasible maximum tension in the cable
f_{H}	Horizontal part of the cable force $\mathbf{f}_i$ when considering cable sagging
$\mathbf{f}_{\mathrm{P}}$	Force applied to the platform
$\boldsymbol{\varphi}^{\mathrm{IK}}$	$\mathbb{R}^n \rightarrow \mathbb{R}^m$ the mapping defining the inverse kinematics transformation
$\boldsymbol{\varphi}^{\mathrm{DK}}$	$\mathbb{R}^m \rightarrow \mathbb{R}^n$ the mapping defining the forward kinematics transformation
$\boldsymbol{\Phi}^{\mathrm{C}}$	$\mathbb{R}^2 \rightarrow \mathbb{R}^2$ the mapping of the sagging cable model
$\boldsymbol{\Phi}^{\mathrm{G}}$	$\mathbb{R}^{n_{\mathrm{D}}} \rightarrow \mathbb{R}^{6m}$ mapping for parameterization for robot geometry
$\boldsymbol{\Phi}$	Mapping of inequality constraints in the constraint satisfaction problem
g	Gravity acceleration
g_{C}	Specific gravity force of the cable per length
$\mathbf{g}^{\mathrm{C}}$	Vector $\in \mathbb{R}^n$ of generalized centripetal and Coriolis forces
h_{D}	Pitch of the groove of the drum
$\mathbf{H}$	Matrix $\in \mathbb{R}^{m \times r}$ with a spanning base of the kernel of $\mathbf{A}^{\mathrm{T}}$
$\mathbf{h}_i$	Spanning base vector $\in \mathbb{R}^m$ of the kernel $\mathbf{H}$ of $\mathbf{A}^{\mathrm{T}}$

$\mathbf{I}$	Square identify matrix
I_D	Moment of inertia of the drum
I_M	Moment of inertia of the servo motor
$\mathbf{I}_P$	Inertia tensor $\in \mathbb{R}^{3\times3}$ of the mobile platform
I_{PG}	Moment of inertia of the planetary gearbox
I_R	Moment of inertia of the pulley
I_S	Moment of inertia of the spooling unit
I_W	Effective overall moment of inertia of the winch
$\mathbf{i}_{dq}$	Current of the servo motor
$\mathbf{J}$	Kinematic Jacobian $\in \mathbb{R}^{n\times m}$ of the robot
$\mathbf{J}_A$	Jacobian of the closure constraints v w.r.t. changes in the pose
$\mathbf{J}_B$	Jacobian of the closure constraints v w.r.t. changes in the cable length
$\mathbf{J}_v$	Jacobian of forward kinematics constraints v w.r.t. changes in the pose
$\mathbf{K}_C$	Stiffness matrix $\in \mathbb{R}^{m\times m}$ of the robot in configuration space
$\mathbf{K}_G$	Geometric stiffness matrix $\in \mathbb{R}^{6\times6}$ of the robot in operational space
$\mathbf{K}_O$	Linear elastic stiffness matrix $\in \mathbb{R}^{6\times6}$ of the robot in operational space
$\mathbf{K}_{OS}$	Stiffness matrix $\in \mathbb{R}^{6\times6}$ of the robot in operational space
$\mathcal{K}_0$	Fixed world coordinate system
$\mathcal{K}_i$	Coordinate system associated with point i
$\mathcal{K}_P$	Reference coordinate system attached to the mobile platform
$\mathcal{K}_{A,i}$	Local coordinate system of the i-th proximal anchor point A_i
$\mathcal{K}_{B,i}$	Local coordinate system of the i-th distal anchor point B_i
k_i	Stiffness coefficient of the i-th cable
k'_C	Specific stiffness of the cable
k_A	Stiffness of the winch drivetrain
$\mathbf{l}_i$	Vector $\in \mathbb{R}^3$ of the i-th cable
l_i	Length of the i-th cable
$\mathbf{l}$	Vector $\in \mathbb{R}^m$ collecting all cable lengths as generalized coordinates
$\mathbf{L}$	Diagonal matrix $\in \mathbb{R}^{m\times m}$ with the cable lengths as elements
L	Lagrangian function
$\mathbf{L}_{12}$	Winding induction of the servo motor
m	Number of cables of the robot
$\mathbf{m}$	Vector $\in \mathbb{R}^3$ of the center of the workspace used for hull projection
m_G	Mass of linear traveling carriage (spooling unit) of the winch
m_P	Mass of the mobile platform
n	Degrees-of-freedom of the mobile platform
n_R	Number of pulleys in the drivetrain
n_W	Number of windings on the drum
n_D	Number of design parameters
$\boldsymbol{v}$	$\mathbb{R}^m \rightarrow \mathbb{R}^n$ mapping defining the robot's kinematic closure constraints
v_C	Effective density of a cable cross section
v_{PG}	Gear ratio of the winch's planetary gearbox
v_W	Overall transmission ratio of the winch
$\mathbf{P}$	Transformation matrix $\in \mathbb{R}^{3\times4}$ for quaternion in dynamics

$\mathcal{P}$	Set of measurement poses for calibration
ψ_{dq}	Flux linkage of the servo motor
$\mathcal{Q}$	Set $\subset \mathbb{R}^n$ of wrenches to be generated by the robot
$\mathbf{Q}$	Quaternion for parameterization of SO_3
$\mathbf{q}$	Vector of the generalized coordinates in dynamics
r	Degree-of-redundancy of a robot
$\mathbf{r}$	Position of the platform where $\mathbf{r} \in \mathbb{R}^3$
$\mathbf{r}_{\mathrm{M}}$	Mobile platform's center of gravity $\in \mathbb{R}^3$
r_{C}	Radius of the cable
r_{D}	Radius of the drum of the winch
r_{R}	Radius of the pulley
$\mathbf{R}$	Orientation of the platform where $\mathbf{R} \in SO_3$
$\mathcal{R}_0$	Set $\subset SO_3$ of orientation matrices
R_{12}	Ohmic resistance of the servo motor windings
ϱ_{C}	Density of the cable
ϱ'_{C}	Linear density of the cable per length
s	Sagging of the cable
$\mathcal{S}$	Set $\subset \mathbb{R}^m$ of the solution space of feasible force distributions
SO_3	Set of the special orthogonal group with all spatial rotations
SE_3	Euclidian displacement group with all spatial rigid body transformations
T	Kinematic energy of the cable robot
T_{P}	Kinematic energy of the mobile platform
T_{W}	Torque in the winch
T_{M}	Servo motor torque
T_{F}	Friction torque in the winch
$\mathbf{T}$	Transformation matrix $\in \mathbb{R}^{6\times 6}$
$\Theta_{\mathrm{eff},i}$	Shaft/drum angle of the *i*-th motor/winch
Θ_{D}	Rotation angle of the winch drum
$\mathbf{\Theta}_{\mathrm{D}}$	Vector $\in \mathbb{R}^m$ collecting the rotation angles of all winch drums
Θ_{M}	Rotation angle of the servo motor
$\boldsymbol{\tau}_{\mathrm{P}}$	Torque vector $\in \mathbb{R}^3$ applied to the mobile platform
U	Potential energy of the robot
U_{P}	Potential energy of the mobile platform
U_i	Potential energy of the *i*-th cable
$\mathbf{u}_i$	Unit vector $\in \mathbb{R}^3$ of the *i*-th cable
$\widehat{\mathbf{u}}_i$	Unit vector $\in \mathbb{R}^3$ of the effective direction of *i*-th cable under sagging
$\mathbf{u}_{\mathrm{dq}}$	Input voltage of the servo motor
$\mathbf{v}$	Vector of verification variables in the constraint satisfaction problem
$\mathbf{w}_{\mathrm{P}}$	Vector $\in \mathbb{R}^n$ of the applied wrench of the platform
$\mathcal{W}$	Set of poses in the respective motion group representing the workspace
$\mathcal{X}_c$	Solution set of the constraint satisfaction problem
$\mathcal{X}_s$	Search space is a set used with constraint satisfaction problem

$\mathcal{X}_v$	Verification domain is a set for the constraint satisfaction problem
$\mathbf{y}$	Pose as generalized coordinate vector $\in \mathbb{R}^n$ of the platform
Z_{P}	Pole pair number of the servo motor

Subscripts

A	Proximal anchor point on the machine frame
B	Distal anchor point on the mobile platform
C	Cable
D	Drum
M	Motor
P	Platform
R	Pulley (roller), not to be confused with platform
W	Winch
DK	Direct kinematics/forward kinematics
IK	Inverse kinematics
FD	Forward dynamics
ID	Inverse dynamics
OS	Operational space
CO	Constant orientation (workspace)
TO	Total orientation (workspace)