PI-Observer Techniques Applied to Mechanical Systems

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Svenja Kirchenkamp
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Referent:	Univ.-Prof. Dr.-Ing. D. Söffker
Korreferenten:	Univ.-Prof. Dr. rer. nat. P. C. Müller
	Univ.-Prof. Dr. rer. nat. G. Freiling

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Svenja Kirchenkamp

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Svenja Kirchenkamp

Contents

Nomenclature

Abbreviations

LTR	Loop Transfer Recovery
PIO	Proportional Integral Observer
RSS	Reciprocal State-Space
UIO	Unknown Input Observer

Vectors and Matrices

$\boldsymbol{e}$	error vector related to the extended state vector
$\boldsymbol{e}_0$	error vector related to the initial conditions of the state vector
$\boldsymbol{e}_\infty$	remaining error for $t \to \infty$
$\boldsymbol{e}_f$	error vector related to the approximation of the nonlinearities
$\boldsymbol{e}_x$	error vector related to the state vector
$\boldsymbol{e}_z$	error vector related to the state vector $\boldsymbol{z}_\mathrm{n}$
$\boldsymbol{f}$	vector function of nonlinearities
$\boldsymbol{f}_\mathrm{new}$	further vector function of nonlinearities
$\boldsymbol{f}^*$	vector function of nonlinearities, also including known parts
$\tilde{\boldsymbol{f}}$	vector function of nonlinearities at the consideration of model inaccuracies
$\boldsymbol{f}_\mathrm{F}$	vector of forces
$\boldsymbol{h}$	vector which represents the model inaccuracies
$\boldsymbol{i}_\alpha$	α-th unit vector
$\boldsymbol{r}$	residual (of the UIO)
$\boldsymbol{u}$	input vector
$\tilde{\boldsymbol{u}}$	input vector of the dual system
$\boldsymbol{v}$	approximation of the nonlinearities $\boldsymbol{f}$
$\boldsymbol{x}$	state vector
$\boldsymbol{x}_\mathrm{new}$	further state vector
$\tilde{\boldsymbol{x}}$	state vector of the transformed/dual system
$\hat{\boldsymbol{x}}$	observed state vector
$\boldsymbol{x}_0$	initial state vector
$\hat{\boldsymbol{x}}_0$	initial state vector of the observer
$\hat{\boldsymbol{x}}_{0,2}$	initial state vector of a second observer
$\boldsymbol{x}_1$	state vector
$\boldsymbol{x}_\mathrm{e}$	extended state vector for the PIO
$\boldsymbol{x}_\mathrm{new}$	state vector which contains velocities and accelerations

$\boldsymbol{y}$	output vector
$\hat{\boldsymbol{y}}$	output vector of the observer
$\boldsymbol{y}_{\mathrm{new}}$	integrated output vector
$\boldsymbol{z}$	observed transformed state vector
$\boldsymbol{z}_{\mathrm{n}}$	extended state vector for dealing with measurement noise
$\boldsymbol{\delta}_{\mathrm{n}}$	measurement noise vector
$\boldsymbol{\psi}$	LAGRANGE-multiplier
$\tilde{\boldsymbol{\psi}}$	LAGRANGE-multiplier for the dual system

$\boldsymbol{A}$	system matrix
$\boldsymbol{A}_{\mathrm{new}}$	further system matrix
$\boldsymbol{A}_0$	system matrix without model inaccuracies
$\boldsymbol{\Delta A}$	model inaccuracies
$\boldsymbol{A}_{\mathrm{e}}$	extended system matrix for the PIO
$\boldsymbol{A}_{\mathrm{n}}$	system matrix for the system description based on $\boldsymbol{z}_{\mathrm{n}}$
$\boldsymbol{A}_{\mathrm{r}}$	rearranged system matrix of the RSS representation
$\boldsymbol{B}$	input matrix
$\tilde{\boldsymbol{B}}$	input matrix
$\boldsymbol{B}_{\mathrm{e}}$	extended input matrix for the PIO
$\boldsymbol{B}_{\mathrm{n}}$	input matrix for the system description based on $\boldsymbol{z}_{\mathrm{n}}$
$\boldsymbol{B}_{\mathrm{r}}$	rearranged input matrix of the RSS representation
$\boldsymbol{C}$	output matrix
$\boldsymbol{C}^*$	output matrix which describes the available acceleration measurements
$\boldsymbol{C}_{\mathrm{a}}$	output matrix for the consideration of accelerations
$\boldsymbol{C}_{\mathrm{ae}}$	extended output matrix for the PIO for the consideration of accelerations
$\boldsymbol{C}_{\mathrm{e}}$	extended output matrix for the PIO
$\boldsymbol{C}_{\mathrm{n}}$	output matrix for the system description based on $\boldsymbol{z}_{\mathrm{n}}$
$\boldsymbol{D}$	damping matrix
$\boldsymbol{D}_{\mathrm{a}}$	output feed-through matrix for the consideration of accelerations
$\boldsymbol{E}$	input matrix of the RSS representation
$\boldsymbol{F}_{\mathrm{u}}$	system matrix of the UIO
$\boldsymbol{G}$	system matrix of the RSS representation
$\boldsymbol{G}_{\mathrm{u}}$	matrix of the UIO
$\boldsymbol{H}$	matrix for the approximation of the nonlinearities $\boldsymbol{f}$
$\boldsymbol{H}_{\mathrm{m}}$	matrix which allocates the model inaccuracies
$\boldsymbol{I}_n$	identity matrix of dimension n
$\boldsymbol{J}_{\mathrm{u}}$	input matrix of the UIO
$\boldsymbol{K}$	stiffness matrix
$\boldsymbol{K}_{\mathrm{c}_x}$	state feedback matrix
$\boldsymbol{K}_{\mathrm{c}_y}$	output feedback matrix
$\boldsymbol{L}$	observer gain matrix

$\boldsymbol{L}^*$	observer gain matrix
$\boldsymbol{L}_1$	observer gain matrix belonging to the proportional part of the PIO
$\boldsymbol{L}_2$	observer gain matrix belonging to the integral part of the PIO
$\boldsymbol{L}_{\mathrm{a}}$	observer gain matrix for the consideration of accelerations
$\boldsymbol{L}_{\mathrm{a}_1}$	part of the observer gain matrix $\boldsymbol{L}_{\mathrm{a}}$
$\boldsymbol{L}_{\mathrm{ae}}$	extended observer gain matrix for the PIO for the consideration of accelerations
$\boldsymbol{L}_{\mathrm{e}}$	extended observer gain matrix for the PIO
$\boldsymbol{L}_{\mathrm{n}}$	observer gain matrix for the PIO for the system description based on $\boldsymbol{z}_{\mathrm{n}}$
$\boldsymbol{L}_{\mathrm{r}}$	rearranged observer gain matrix of the RSS representation
$\boldsymbol{L}_{\mathrm{u}}$	observer matrix of the UIO
$\boldsymbol{M}$	mass matrix
$\boldsymbol{N}$	matrix which allocates the nonlinearities to the state space description
$\boldsymbol{N}_{\mathrm{new}}$	further nonlinearities allocating matrix
$\boldsymbol{N}^+$	pseudo inverse matrix of $\boldsymbol{N}$
$\boldsymbol{N}^*$	nonlinearities allocating matrix, also including known parts
$\tilde{\boldsymbol{N}}$	nonlinearities allocating matrix at the consideration of model inaccuracies
$\boldsymbol{N}_{\mathrm{a}}$	nonlinearities allocating matrix at the consideration of accelerations
$\boldsymbol{N}_{\mathrm{n}}$	nonlinearities allocating matrix for the system based on $\boldsymbol{z}_{\mathrm{n}}$
$\boldsymbol{O}$	Kalman observability matrix
$\boldsymbol{P}$	solution of the matrix RICCATI equation or the LYAPUNOV equation
$\tilde{\boldsymbol{P}}$	solution of the matrix RICCATI equation for the dual system
$\boldsymbol{Q}$	weighting matrix
$\tilde{\boldsymbol{Q}}$	weighting matrix for the dual system
$\boldsymbol{R}$	weighting matrix
$\tilde{\boldsymbol{R}}$	weighting matrix for the dual system
$\boldsymbol{S}$	transformation matrix
$\boldsymbol{T}$	transformation matrix
$\boldsymbol{V}$	model of the nonlinearities $\boldsymbol{f}$
$\boldsymbol{V}_{\mathrm{K}}$	correlation matrix of $\boldsymbol{f}$ and $\boldsymbol{v}$
$\boldsymbol{W}_{\mathrm{e}}$	transformation matrix for the extended observer matrix
$\boldsymbol{Z}_{\mathrm{e}}$	transformed extended observer matrix

Scalars and Functions

a	constant
$\tilde{a}_{\mu\nu}$	μ,ν-th element of the inverse system matrix $\boldsymbol{A}^{-1}$
b	degree of stability

c	constant
f	scalar function of nonlinearities (i.e., $\boldsymbol{f}$ of dimension 1)
i	index
k	index
J	performance index of the feedback control
$\tilde{J}$	performance index of the observer
l_s	s-th element of the observer gain matrix
m	dimension of the input vector $\boldsymbol{u}$
m_{add}	additional mass
n	dimension of the state vector $\boldsymbol{x}$
n_1	dimension of the state vector $\boldsymbol{x}_1$
p	index
q	observer gain included in the set-up of $\boldsymbol{Q}$
r_1	dimension of the output vector $\boldsymbol{y}$
r_2	dimension of the vector function $\boldsymbol{f}$
r_3	dimension of $\boldsymbol{v}$
s	index
t	time
t_0	initial time
T	time, integration limit
u	scalar input (i.e., $\boldsymbol{u}$ of dimension 1)
w_i	deflection
x_{mass}	displacement at the node of an additional mass
y	scalar output (i.e., $\boldsymbol{y}$ of dimension 1)
z	number of the first derivation of the disturbance $\boldsymbol{f}$ which is equal zero
α	index of the measured state
β	index of the state influenced by the nonlinearity f
γ	grade of the differentiation
δ	KRONECKER symbol
ε	one-dimensional model of the nonlinearities f
λ	eigenvalue
μ	index
ν	index
ν_{B}	observability index
φ_i	inclination angle
E	expectation value
H	HAMILTON function

Section 2.3

a	semimajor axis
b	semiminor axis
c_{MW}	spring between drive and wheelset
c_{W_x}	longitudinal wheelset spring
c_{W_z}	vertical wheelset spring
d_{MW}	damper between drive and wheelset
d_{W_x}	longitudinal wheelset damper
d_{W_z}	vertical wheelset damper
e	eccentricity coefficient
g	gravitational constant
m_{W}	mass of the wheelset
r	radius of the wheel
$r_{\mathrm{l}}, r_{\mathrm{r}}$	radii of the wheels (left and right side)
$u_{\mathrm{R1}},\ u_{\mathrm{R2}}$	vertical displacements at the contact
u_{W_x}	longitudinal displacement of the wheelset
u_{W_z}	vertical displacement of the wheelset
v_0	translational velocity
$B(e)$	elliptic integral
C_{11}	KALKER coefficient
$D(e)$	elliptic integral
$D_{\mathrm{R1}}, D_{\mathrm{R2}}$	damping portions of the track oscillations
$E(e)$	elliptic integral
$F_{x\mathrm{l}}, F_{x\mathrm{r}}$	forces of the springs in longitudinal direction (left and right side)
$F_{z\mathrm{l}}, F_{z\mathrm{r}}$	forces of the springs in vertical direction (left and right side)
G	shear modulus
$K(e)$	elliptic integral
M	magnitude of the input step function
M_{Ml}	torque of the power train
M_{M}	torque of the motor
N	normal force
$N_{\mathrm{l}}, N_{\mathrm{r}}$	normal forces (left and right side)
R_{10}, R_{20}	flexibilities of the track for the track oscillations
$R_{\mathrm{a}}, R_{\mathrm{b}}$	main radii of curvature
R_{x1}, R_{x2}	main radii of the two contact bodies in longitudinal direction
R_{y1}, R_{y2}	main radii of the two contact bodies in horizontal direction
T_ξ	tangential contact force
$T_{\xi\mathrm{l}}, T_{\xi\mathrm{r}}$	tangential contact forces (left and right side)
$T_{\xi,\mathrm{lin}}$	linear part of the tangential contact force T_ξ

α	coefficient at the calculation of the tangential contact force T_ξ
α_a	abbreviation at the calculation of the semimajor axis a
α_δ	abbreviation for the calculation of the penetration δ
$\alpha_{\mathrm{R1}}, \alpha_{\mathrm{R2}}$	normal force damping portions of the track oscillations
Δz	stochastic value for the longitudinal track displacement
δ	penetration
μ	friction coefficient
$\mu_{\max}$	maximum friction coefficient
μ_∞	friction coefficient for $\lvert\nu_\xi\rvert \to \infty$
ν_Q	Poisson's ratio
ν_ξ	longitudinal slip
$\omega_{\mathrm{R1}}, \omega_{\mathrm{R2}}$	angular frequencies of the track oscillations
θ_{M}	motor inertia
θ_{W_y}	rotational inertia of the wheelset versus the wheel angle
φ_{M}	motor angle
φ_{W_y}	wheel angle

with the indices

l	left side
r	right side
x	longitudinal direction
y	lateral direction
z	vertical direction
ξ	tangential
M	motor, i.e., electric drive
Ml	power train
R	rail
W	wheel(set)