A Sherman-Morrison-Woodbury-Formel

Gegeben ist eine Matrix $\mathbf{A}$ der Dimension $n \times n$ sowie zwei Matrizen $\mathbf{B}$ und $\mathbf{C}$ jeweils der Dimension $n \times m$ und eine Matrix $\mathbf{D}$ der Dimension $m \times m$.

Unter der Voraussetzung, dass entsprechende Matrizen invertierbar sind, lautet die Sherman-Morrison-Woodbury-Formel:

$$(\mathbf{A} + \mathbf{B}\mathbf{D}\mathbf{C}^T)^{-1} = \mathbf{A}^{-1} - \mathbf{A}^{-1}\mathbf{B}(\mathbf{D}^{-1} + \mathbf{C}^T\mathbf{A}^{-1}\mathbf{B})^{-1}\mathbf{C}^T\mathbf{A}^{-1} \tag{A.1}$$

Dieser Zusammenhang ist auch als Matrix-Inversions-Lemma bekannt. Häufig findet man auch eine etwas vereinfachte Darstellung, die sich aus Gl. (A.1) durch Einsetzen von $\mathbf{D} = \mathbf{I}$ ergibt.

$$(\mathbf{A} + \mathbf{B}\mathbf{C}^T)^{-1} = \mathbf{A}^{-1} - \mathbf{A}^{-1}\mathbf{B}(I + \mathbf{C}^T\mathbf{A}^{-1}\mathbf{B})^{-1}\mathbf{C}^T\mathbf{A}^{-1} \tag{A.2}$$

Eine weitere nützliche Matrizenidentität ist gegeben durch

$$(\mathbf{A} + \mathbf{B}\mathbf{C}^T)^{-1}\mathbf{B} = \mathbf{A}^{-1}\mathbf{B}(I + \mathbf{C}^T\mathbf{A}^{-1}\mathbf{B})^{-1} . \tag{A.3}$$

Ein Beweis für Gl. (A.2) und Gl. (A.3) ist in [90] zu finden. Mit Hilfe dieser Zusammenhänge kann z.B. die Invers-Kovarianz-Form des Kalman-Filters aus der Standardform hergeleitet werden und umgekehrt.

Invers-Kovarianz-Form des Kalman-Filters

Mit den Substitutionen

$$\begin{aligned} \mathbf{A} &= \mathbf{R}_k \\ \mathbf{B} &= \mathbf{I} \\ \mathbf{C}^T &= \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T \end{aligned}$$

folgt aus Gl. (A.3)

$$\left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} = \mathbf{R}_k^{-1} \left(\mathbf{I} + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1}\right)^{-1} \tag{A.4}$$

■

Setzt man die Kalman-Gain-Matrix

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \tag{A.5}$$

in die Kovarianzmatrix-Update-Gleichung

$$\mathbf{P}_k^+ = \mathbf{P}_k^- - \mathbf{K}_k \mathbf{H}_k \mathbf{P}_k^- \tag{A.6}$$

ein, erhält man

$$\mathbf{P}_k^+ = \mathbf{P}_k^- - \mathbf{P}_k^- \mathbf{H}_k^T \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \mathbf{H}_k \mathbf{P}_k^- \tag{A.7}$$

Mit Gl. (A.4) ergibt sich

$$\mathbf{P}_k^+ = \mathbf{P}_k^- - \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1} \left(\mathbf{I} + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1}\right)^{-1} \mathbf{H}_k \mathbf{P}_k^- \ . \tag{A.8}$$

Mit den Substitutionen

$$\begin{aligned} \mathbf{A}^{-1} &= \mathbf{P}_k^- \\ \mathbf{B} &= \mathbf{H}_k^T \mathbf{R}_k^{-1} \\ \mathbf{C}^T &= \mathbf{H}_k \end{aligned}$$

folgt aus Gl. (A.2) und Gl. (A.8)

$$\begin{aligned} \mathbf{P}_k^+ = \mathbf{P}_k^- - \mathbf{P}_k^- \mathbf{H}_k^T \ \mathbf{R}_k^{-1} \left(\mathbf{I} + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1}\right)^{-1} \mathbf{H}_k \mathbf{P}_k^- \\ = \left((\mathbf{P}_k^-)^{-1} + \mathbf{H}_k^T \mathbf{R}_k^{-1} \mathbf{H}_k\right)^{-1} \ . \end{aligned} \tag{A.9}$$

■

Erweitern von Gl. (A.5) mit $\mathbf{I} = \mathbf{P}_k^+ (\mathbf{P}_k^+)^{-1}$ und $\mathbf{I} = (\mathbf{R}_k^{-1} \mathbf{R}_k)$ führt auf

$$\begin{aligned} \mathbf{K}_k &= (\mathbf{P}_k^+ (\mathbf{P}_k^+)^{-1}) \mathbf{P}_k^- \mathbf{H}_k^T (\mathbf{R}_k^{-1} \mathbf{R}_k) \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \\ &= \mathbf{P}_k^+ (\mathbf{P}_k^+)^{-1} \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1} \mathbf{R}_k \mathbf{R}_k^{-1} \left(\mathbf{I} + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1}\right)^{-1} \\ &= \mathbf{P}_k^+ (\mathbf{P}_k^+)^{-1} \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1} \left(\mathbf{I} + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T \mathbf{R}_k^{-1}\right)^{-1} \end{aligned} \tag{A.10}$$

Mit dem Zusammenhang

$$\left(\mathbf{P}_k^+\right)^{-1} = (\mathbf{P}_k^-)^{-1} + \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k \tag{A.11}$$

aus Gl. (A.9) erhält man so

$$\begin{aligned}
\mathbf{K}_k &= \mathbf{P}_k^+ \left((\mathbf{P}_k^-)^{-1} + \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k\right)\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)^{-1} \\
&= \mathbf{P}_k^+ \left(\mathbf{I} + \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{P}_k^-\right)(\mathbf{P}_k^-)^{-1}\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)^{-1} \\
&= \mathbf{P}_k^+ \left(\mathbf{I} + \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{P}_k^-\right)\mathbf{H}_k^T\mathbf{R}_k^{-1}\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)^{-1} \\
&= \mathbf{P}_k^+ \left(\mathbf{H}_k^T\mathbf{R}_k^{-1} + \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)^{-1} \\
&= \mathbf{P}_k^+\mathbf{H}_k^T\mathbf{R}_k^{-1}\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)\left(\mathbf{I} + \mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T\mathbf{R}_k^{-1}\right)^{-1} \\
\mathbf{K}_k &= \mathbf{P}_k^+\mathbf{H}_k^T\mathbf{R}_k^{-1} \qquad (A.12)
\end{aligned}$$

■

Durch Multiplikation der Kalman-Filter-Zustandsvektor-Update-Gleichung

$$\hat{\vec{x}}_k^+ = \hat{\vec{x}}_k^- - \mathbf{K}_k\left(\mathbf{H}_k\hat{\vec{x}}_k^- - \tilde{\vec{y}}_k\right)$$

von links mit $(\mathbf{P}_k^+)^{-1}$ und Einsetzen von Gl. (A.12) erhält man

$$\begin{aligned}
(\mathbf{P}_k^+)^{-1}\hat{\vec{x}}_k^+ &= (\mathbf{P}_k^+)^{-1}\hat{\vec{x}}_k^- - (\mathbf{P}_k^+)^{-1}\mathbf{P}_k^+\mathbf{H}_k^T\mathbf{R}_k^{-1}\left(\mathbf{H}_k\hat{\vec{x}}_k^- - \tilde{\vec{y}}_k\right) \\
(\mathbf{P}_k^+)^{-1}\hat{\vec{x}}_k^+ &= \left((\mathbf{P}_k^+)^{-1} - \mathbf{H}_k^T\mathbf{R}_k^{-1}\mathbf{H}_k\right)\hat{\vec{x}}_k^- + \mathbf{H}_k^T\mathbf{R}_k^{-1}\tilde{\vec{y}}_k
\end{aligned}$$

Mit Gl. (A.11) folgt

$$\begin{aligned}
(\mathbf{P}_k^+)^{-1}\hat{\vec{x}}_k^+ &= (\mathbf{P}_k^-)^{-1}\hat{\vec{x}}_k^- + \mathbf{H}_k^T\mathbf{R}_k^{-1}\tilde{\vec{y}}_k \\
\hat{\vec{x}}_k^+ &= (\mathbf{P}_k^+)^{-1}\left((\mathbf{P}_k^-)^{-1}\hat{\vec{x}}_k^- + \mathbf{H}_k^T\mathbf{R}_k^{-1}\tilde{\vec{y}}_k\right) \qquad (A.13)
\end{aligned}$$

Die Gleichungen (A.11) und (A.13) stellen den Messschritt der Invers-Kovarianz-Form des Kalman-Filters dar.

B Differentiation von Spuren von Matrizen

Bei der Minimierung von Kostenfunktionen im Rahmen der Herleitung von Minimum-Varianzschätzern ist es häufig notwendig, die Ableitung der Spur einer Matrix nach einer Matrix zu berechnen.

Die wichtigsten Zusammenhänge sind dabei gegeben durch

$$\frac{d\,Spur(\mathbf{B})}{d\,\mathbf{B}} = \mathbf{I} \tag{B.1}$$

$$\frac{d\,Spur(\mathbf{B}^i)}{d\,\mathbf{B}} = i \cdot \mathbf{B}^{i-1,T} \tag{B.2}$$

$$\frac{d\,Spur(\mathbf{A}\mathbf{B}^{-1}\mathbf{C})}{d\,\mathbf{B}} = -(\mathbf{B}^{-1}\mathbf{C}\mathbf{A}\mathbf{B}^{-1})^T \tag{B.3}$$

$$\frac{d\,Spur(\mathbf{A}^T\mathbf{B}\mathbf{C}^T)}{d\,\mathbf{B}} = \frac{d\,Spur(\mathbf{C}\mathbf{B}^T\mathbf{A})}{d\,\mathbf{B}} = \mathbf{A}\mathbf{C} \tag{B.4}$$

$$\frac{d\,Spur(\mathbf{A}\mathbf{B}\mathbf{C}\mathbf{B}^T)}{d\,\mathbf{B}} = \mathbf{A}^T\mathbf{B}\mathbf{C}^T + \mathbf{A}\mathbf{B}\mathbf{C} \tag{B.5}$$

$$\frac{d\,Spur(\mathbf{A}\mathbf{B}\mathbf{C}\mathbf{B})}{d\,\mathbf{B}} = \mathbf{A}^T\mathbf{B}^T\mathbf{C}^T + \mathbf{C}^T\mathbf{B}^T\mathbf{A}^T\,. \tag{B.6}$$

Ferner gilt

$$Spur(\mathbf{B}) = Spur(\mathbf{B}^T) \tag{B.7}$$

$$Spur(\mathbf{A}\mathbf{B}) = Spur(\mathbf{B}\mathbf{A})\,. \tag{B.8}$$

C MATLAB-Code zum Beispiel Abschnitt 7.3.5

Im Folgenden ist der MATLAB-Code der Filter, die zum Schätzen der Schwingung eines Pendels verwendet wurden, angegeben. Die Filter verfügen jeweils über eine Initialisierungsfunktion, die einmal zu Beginn aufgerufen werden muss. Der Propagationsschritt und der Messschritt sind ebenfalls in separaten Funktionen realisiert. Diese Funktionen können von einem Scheduler entsprechend aufgerufen werden.

Initialisierungsschritt des Partikelfilters

```
function pf = pf_filter_init(init_angle)
    pf.num = 300;                           % Anzahl der Partikel
    pf.X = zeros(2,pf.num);                 % Partikel anlegen
    pf.w = 1/pf.num*ones(1,pf.num);         % Gewichte
    pf.Q = [(1/180*pi)^2, 0;                % Systemrauschen definieren
                  0,    (1e-4)^2];
    pf.cholQ = chol(pf.Q);
    pf.R = 0.1^2;                           % Varianz der Messungen
    pf.Xs = [init_angle/180*pi;0];          % Initialer Zustand
    pf.Ps = [(init_angle/180*pi)^2,0;       % Initiale Unsicherheit
                    0,    (10/180*pi)^2];

    % Ziehen der Partikel entsprechend initialem Zustand/Unsicherheit
    cholP = chol(pf.Ps);
    for k=1:pf.num
        pf.X(:,k) = cholP*randn(2,1) + pf.Xs;
    end
end
```

Propagationsschritt des Partikelfilters

```
function pf = pf_filter_propagation(pf,pend,dt)
    % Propagation der Partikel entsprechend dem Systemmodell
    % und dem Systemrauschen
    for k=1:pf.num
       tmp = pf.X(1,k);
       pf.X(1,k) = pf.X(1,k) + pf.X(2,k)*dt ...
                                    + randn(1)*pf.cholQ(1,1);
       pf.X(2,k) = pf.X(2,k) - pend.g/pend.length*sin(tmp)*dt ...
```

```
                                    + randn(1)*pf.cholQ(2,2);

       if (pf.X(1,k) > pi) % Winkelbereich auf +/- 180° beschränken
           pf.X(1,k) = pf.X(1,k) - 2*pi;
       end
       if (pf.X(1,k) < -pi)
           pf.X(1,k) = pf.X(1,k) + 2*pi;
       end

    end
end
```

Bei der Eingangsvariable `dt` handelt es sich um die Zeitschrittweite, `pend.g` ist die Schwerebeschleunigung und `pend.length` ist die Länge des Pendels.

Messwertverarbeitung und Resampling beim Partikelfilter

```
function pf = pf_filter_estimation(pf,pend,y)
    for k=1:pf.num
        pf.w(k) = exp(-1/2*(y - pend.length*sin(pf.X(1,k)))^2/pf.R);
    end
    pf.w = pf.w/sum(pf.w);

    peff = 1/sum(pf.w.^2); % Anzahl der effektiven Partikel bestimmen
    if (peff<0.7*pf.num)   % Resampling notwendig ?
        top(1) = pf.w(1);
        for k=1:pf.num-1   % Intervallgrenzen festlegen
            top(k+1) = top(k) + pf.w(k+1);
        end

        pf.resampled = zeros(2,pf.num);
        for k=1:pf.num
            zf = rand(1);  % gleichverteilte Zufallszahl ziehen
            for j=1:pf.num % zugehöriges Intervall suchen
                if (top(j)>zf)
                    pf.resampled(:,k) = pf.X(:,j); % Partikel
                    break;                         % reproduzieren
                end
            end
        end
        pf.X = pf.resampled;
    end
end
```

Bei der Eingangsvariable `y` handelt es sich um den Messwert.

Initialisierungsschritt des Kalman-Filters

```
function kf = kf_filter_init(init_angle)
    kf.Q = [(1/180*pi)^2, 0;            % Systemrauschen definieren
                  0,    (1e-4)^2];
    kf.R = 0.1^2;                       % Varianz der Messwerte
    kf.X = [init_angle/180*pi;0];       % Initialer Zustand
    kf.P = [(init_angle/180*pi)^2,0;    % Initiale Unsicherheit
                 0,    (10/180*pi)^2];
end
```

Propagationsschritt des Kalman-Filters

```
function kf = kf_filter_propagation(kf,pend,dt)
   % Zustandsschätzung propagieren
   tmp = kf.X(1);
   kf.X(1) = kf.X(1) + kf.X(2)*dt;
   kf.X(2) = kf.X(2) - pend.g/pend.length*sin(tmp)*dt;

   % Jacobi-Matrix der Systemmodell-DGL berechnen
   Phi = [1                              , dt;
          -pend.g/pend.length*cos(tmp)*dt,  1];

   % Kovarianzmatrix des Schätzfehlers propagieren
   kf.P = Phi*kf.P*Phi' + kf.Q;
end
```

Messwertverarbeitung des Kalman-Filters

```
function kf = kf_filter_estimation(kf,pend,y)
    y_pred = pend.length*sin(kf.X(1));  % Messwert-Vorhersage
    H = [pend.length*cos(kf.X(1)), 0];  % Messmatrix

    K = kf.P*H'*inv(H*kf.P*H' + kf.R);  % Kalman Gain Matrix
    kf.X = kf.X - K*(y_pred - y);       % Zustandsschätzung updaten
    % Update der Kovarianzmatrix des Schätzfehlers (Joseph's Form)
    kf.P = (eye(2) - K*H)*kf.P*(eye(2) - K*H)' + K*kf.R*K';
end
```

Symbolverzeichnis

Abkürzungen

AAIM	Aircraft Autonomous Integrity Monitoring
ADR	Accumulated deltarange
BOC	Binary offset carrier
BPSK	Binary phase-shift keying
C/A	Coarse/Acquisition
CDMA	Code division multiple access
CS	Galileo Commercial Service
DCM	Direction cosine matrix, Richtungskosinusmatrix
DGPS	Differential-GPS
DOP	Dilution of precision
ECEF	Earth-centered Earth fixed
EGNOS	European geostationary navigation overlay service
EKF	Erweitertes Kalman-Filter (extended Kalman filter)
E5, E6	Galileo Frequenzen
FOG	Fiber optic gyroscope
GCC	Galileo Control Center
GDOP	Geometric dilution of precision
GJU	Galileo Joint Undertaking
GPS	Global positioning system
GSS	Galileo Sensor Station
GSSS	GPS space segment simulator
HDOP	Horizontal dilution of precision
HIL	Hardware-in-the-loop
ICD	Interface control document
IEKF	Iterated extended Kalman filter
IMM	Interacting Multiple Model
IMU	Inertial measurement unit
INS	Inertial navigation system
IOC	Integrated optics circuit
IOV	In-orbit validation
L1,L2,L5	GPS-Trägerfrequenzen
MAV	Mini / Micro aerial vehicle
MEMS	Micro electro-mechanical system
MMAE	Multiple Model Adaptive Estimator
OS	Galileo Open Service
OOSM	Out-Of-Sequence Measurement
P-Code	Precise Code

PDOP	Position dilution of precision
PLL	Phase lock loop
PRN	Pseudorandom noise
PRS	Galileo Public Regulated Service
PSR	Pseudorange
RAIM	Receiver Autonomous Integrity Monitoring
RLG	Ring laser gyroscope
RMS	Root-mean-square
SA	Selective availability
SBAS	Satellite-based augmentation system
SAASM	Selective availability anti-spoofing module
SAR	Galileo Search- and Rescue Service, synthetic aperture radar
SDA	Strapdown-Algorithmus
SIS	Signal in space
SoL	Galileo Savety-of-Life Service
SPKF	Sigma-Point-Kalman-Filter
TCC	Galileo telemetry, tracking and command station
TEC	Total electron count
UAV	Unmanned aerial vehicle
ULS	Galileo uplink station
VDOP	Vertical dilution of precision
VSIMM	Variable Structure Interacting Multiple Model
VTOL	Vertical take-off and landing
WAAS	Wide area augmentation system
WGN	White gaussian noise

Indizes

A	GPS-Antenne
b	Körperfestes Koordinatensystem
e	Erdfestes Koordinatensystem
h	Horizontales Koordinatensystem
i	Inertialkoordinatensystem
n	Navigationskoordinatensystem
S	Satellit
$(...)_k$	Zeitpunkt t_k
$(\vec{...})^n$	Vektor in Koordinaten des n-KS.
$(\vec{...})^n_{eb}$	b-KS. bezüglich e-KS., gegeben in Koordinaten des n-KS.
$(\tilde{...})$	Gemessene Größe
$(\hat{...})$	Geschätzte Größe
$(\bar{...})$	Gemittelte Größe
$(...)_n$	Komponente in Nordrichtung
$(...)_e$	Komponente in Ostrichtung
$(...)_d$	Komponente in Richtung der Vertikalen

$(...)_x$	Komponente in Richtung der x-Achse
$(...)_y$	Komponente in Richtung der y-Achse
$(...)_z$	Komponente in Richtung der z-Achse
$[(...)\times]$	kreuzproduktbildende Matrix von (...)

Lateinische Buchstaben

$\vec{a}$	Beschleunigung
a	Quaternionenkomponente, große Halbachse des Erdellipsoids
$\mathbf{A}$	Gewichtungsmatrix oder Änderung einer DCM
$\vec{b}$	Bias
b	Quaternionenkomponente, kleine Halbachse des Erdellipsoids
$\mathbf{B}_k$	Steuermatrix
$\mathbf{B}$	Steuermatrix, kontinuierlich
C	Kapazität
$\mathbf{C}$	Richtungskosinusmatrix, Kovarianzmatrix oder Gewichtungsmatrix
c	Lichtgeschwindigkeit oder Quaternionenkomponente
c_{ii}	Koeffizient der Richtungskosinusmatrix
c_g	Gruppengeschwindigkeit
c_p	Phasengeschwindigkeit
d	Quaternionenkomponente
$\mathbf{D}$	Gewichtungsmatrix
e	Exzentrizität des Erdellipsoids
ϵ_0	Dielektrizitätskonstante
$E[...]$	Erwartungswert
f	Frequenz, Abflachung des Erdellipsoids, specific force
F	Kummulative Wahrscheinlichkeit oder Kraft
$\mathbf{F}$	Systemmatrix
$G(s)$	Übertragungsfunktion im Laplace-Bereich
G_a	Antennengewinn
$\mathbf{G}_k$	Einflussmatrix
$\mathbf{G}$	Einflussmatrix, kontinuierlich
g , $\vec{g}_l$	Schwerebeschleunigung
h	Höhe über dem WGS84-Erdellipsoid
$\vec{h}$	Erdmagnetfeld
$\mathbf{H}$	Messmatrix
$\mathbf{I}$	Einheitsmatrix
I	Intensität, Strom oder Inphasen-Komponente
j	Imaginäre Einheit
$\mathbf{J}$	Trägheitsmoment
$\mathbf{K}$	Kalman-Gain-Matrix
K	Kostenfunktion
$\vec{l}$	Hebelarm zwischen GPS-Antenne und IMU

L	Länge des Lichtweges oder Anzahl der Komponenten eines erweiterten Zustandsvektors
$\vec{L}$	Drehimpuls
m	Koeffizient der Misalignment-Matrix, Mittelwert oder Masse
$\vec{M}$	Drehmoment
$\mathbf{M}$	Misalignment-Matrix
$\mathbf{M}_b$	Beobachtbarkeitsmatrix
$\vec{n}, n$	Stochastische Störung
N	Trägerphasenmehrdeutigkeit oder Rauschleistung
p	Wahrscheinlichkeitsdichte
P	Leistung oder Wahrscheinlichkeit
$\mathbf{P}$	Kovarianzmatrix der Zustandsschätzung
$\mathbf{q}$	Quaternion
Δq	Ladungsänderung
Q	Ladung oder Quadraturkomponente
$\mathbf{Q}_k$	Kovarianzmatrix des Systemrauschens
$\mathbf{Q}$	Spektrale Leistungsdichte des Systemrauschens
$\vec{r}$	Ortsvektor oder Quaternion
$\vec{r}_A$	Position der GPS-Antenne
$\vec{r}_S$	Satellitenposition
$\vec{r}_{SA}$	Vektor von der GPS-Antenne zum Satellit
r	Spektrale Leistungsdichte oder Korrelationsfunktion
R_n , R_e	Krümmungsradien in Nord- und Ostrichtung
R_0	Durchschnittlicher Krümmungsradius
R	Widerstand
$\mathbf{R}$	Kovarianzmatrix des Messrauschens
$\mathbf{R}_t$	Spektrale Leistungsdichte des Messrauschens
s	Komplexe Variable, Motorstellgröße oder Skalenfaktor
S	Spektrale Leistungsdichte
t	Zeit
$T, \delta T, \delta t$	Zeitliche Verschiebung oder Abtastzeit
u	Eingangsgrößen oder Inertialsensordatendifferenzen
$U(s)$	Laplace-Transformierte von $u(t)$ oder Spannung
$\vec{v}$	Geschwindigkeit oder Messrauschen
$\vec{w}$	Systemrauschen
x, y, z	Koordinatenachsen oder Ausgangsgrößen
$\vec{x}, \Delta\vec{x}$	Zustandsvektor
$X(s)$	Laplace-Transformierte von $x(t)$
$\vec{y}$	Vektor der Messwerte
$\vec{z}$	Eigenvektor

Griechische Buchstaben

α, β, γ	Lagefehler
$\vec{\chi}$	Sigma Punkt
Δ, δ	Fehler, Änderung, Intervall oder Fehlausrichtung
δt_U	Uhrenfehler des GPS-Empfängers
$\vec{\eta}$	Weißes Rauschen
λ	Geographische Länge, Wellenlänge oder Eigenwert
$\vec{\mu}$	Weißes Rauschen
∇	Nabla-Operator
$\vec{\omega}$	Drehrate
ω	Kreisfrequenz
Ω	Erddrehrate
$\boldsymbol{\Omega}$	Kreuzproduktbildende Matrix eines Drehrate
ψ	Yaw-Winkel
$\vec{\psi}$	Vektor der Lagefehler α, β, γ
$\boldsymbol{\Psi}$	Kreuzproduktbildende Matrix der Lagefehler
$\Delta\phi$	Phasenverschiebung
$\boldsymbol{\Phi}$	Transitionsmatrix
Φ	Trägerphase
ϕ	Rollwinkel
τ	Zeitdifferenz, zeitliche Verschiebung
φ	Geographische Breite oder Phase
ρ	Pseudorange
$\vec{\sigma}$	Orientierungsvektor
$\Delta\vec{\sigma}_c$	Coning-Term
σ	Standardabweichung oder Betrag des Orientierungsvektors
θ	Pitchwinkel
$\Delta\theta$	Winkelinkrement

Literaturverzeichnis

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