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## Appendix 1: Function atan2

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The ratio of two real numbers defines a single-valued function of two arguments:

$$\text{atan2}(y,x) = \begin{cases} \arctan(y/x), & \text{for } x > 0 \\ \pi + \arctan(y/x), & \text{for } y \geq 0, x < 0 \\ -\pi + \arctan(y/x), & \text{for } y < 0, x < 0 \\ \pi/2, & \text{for } y > 0, x = 0 \\ -\pi/2, & \text{for } y < 0, x = 0 \\ \text{undefined}, & \text{for } y = 0, x = 0 \end{cases}$$

Here, it is applied for calculation of a single value of angle  $\varphi$  given through  $\sin \varphi$  and  $\cos \varphi$ .

*Example A1.1:*

(a) Equation  $\sin \varphi = 1/2$  has two solutions

$$\varphi = \begin{cases} \arcsin(1/2) \\ \pi - \arcsin(1/2) \end{cases} = \begin{cases} \pi/6 \\ 5\pi/6 \end{cases}$$

Equation  $\cos \varphi = \sqrt{3}/2$  also has two solutions

$$\varphi = \begin{cases} \arccos(\sqrt{3}/2) \\ -\arccos(\sqrt{3}/2) \end{cases} = \begin{cases} \pi/6 \\ -\pi/6 \end{cases}$$

(b) Two simultaneous equation  $y \equiv \sin \varphi = 1/2$  and  $x \equiv \cos \varphi = \sqrt{3}/2$  results in a single value. Namely, since  $x = \sqrt{3}/2 > 0$ , the first line in the atan2 definition gives

$$\text{atan2}(y,x) = \arctan(y/x) = \arctan \frac{1/2}{\sqrt{3}/2} = \pi/6.$$

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## Appendix 2: Synthesis of the FSF using Mathematica<sup>®</sup> software system

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### A2.1 Basic HTM matrices of the FSF theory

#### A2.1.1 Matrices of the elementary motions

In the following Mathematica<sup>®</sup> code the  $4 \times 4$  HTM matrices of elementary motions (Table 3.5) are labelled  $m_1, m_2, m_3, m_4, m_5,$  and  $m_6$ ,

$$\begin{aligned}
 m1 &= \{ \{1, 0, 0, \mathbf{xx}\}, \{0, 1, 0, 0\}, \{0, 0, 1, 0\}, \{0, 0, 0, 1\} \} \\
 m2 &= \{ \{1, 0, 0, 0\}, \{0, 1, 0, \mathbf{yy}\}, \{0, 0, 1, 0\}, \{0, 0, 0, 1\} \} \\
 m3 &= \{ \{1, 0, 0, 0\}, \{0, 1, 0, 0\}, \{0, 0, 1, \mathbf{zz}\}, \{0, 0, 0, 1\} \} \\
 m4 &= \{ \{1, 0, 0, 0\}, \{0, \text{Cos}[\text{th}], -\text{Sin}[\text{th}], 0\}, \{0, \text{Sin}[\text{th}], \\
 &\text{Cos}[\text{th}], 0\}, \{0, 0, 0, 1\} \} \\
 m5 &= \{ \{ \text{Cos}[\text{ps}], 0, \text{Sin}[\text{ps}], 0 \}, \{0, 1, 0, 0\}, \{ -\text{Sin}[\text{ps}], 0, \\
 &\text{Cos}[\text{ps}], 0 \}, \{0, 0, 0, 1\} \} \\
 m6 &= \{ \{ \text{Cos}[\text{ph}], -\text{Sin}[\text{ph}], 0, 0 \}, \{ \text{Sin}[\text{ph}], \text{Cos}[\text{ph}], 0, 0 \}, \\
 &\{0, 0, 1, 0\}, \{0, 0, 0, 1\} \}
 \end{aligned} \tag{A2.1}$$

#### A2.1.2 The error matrix

In the following Mathematica<sup>®</sup> code the  $4 \times 4$  HTM error matrix, Eq. (8.9), are labelled **de1**,

$$\begin{aligned}
 \text{de1} &= \{ \{0, -\text{dph}, \text{dps}, \text{dx}\}, \{ \text{dph}, 0, -\text{dth}, \text{dy} \}, \\
 &\{ -\text{dps}, \text{dth}, 0, \text{dz} \}, \{0, 0, 0, 0\} \}
 \end{aligned} \tag{A2.2}$$

For convenience, some error matrices associated with FSS links are prepared. If, for example, the number of the form-shaping system links is less than 11 (including the fixed link No. 0), the following 10 matrices are defined:

$$\begin{aligned}
 \text{de10} &= \{ \{0, -\text{dph0}, \text{dps0}, \text{dx0}\}, \{ \text{dph0}, 0, -\text{dth0}, \text{dy0} \}, \\
 &\{ -\text{dps0}, \text{dth0}, 0, \text{dz0} \}, \{0, 0, 0, 0\} \} \\
 \text{de11} &= \{ \{0, -\text{dph1}, \text{dps1}, \text{dx1}\}, \{ \text{dph1}, 0, -\text{dth1}, \text{dy1} \}, \\
 &\{ -\text{dps1}, \text{dth1}, 0, \text{dz1} \}, \{0, 0, 0, 0\} \} \\
 \text{de12} &= \{ \{0, -\text{dph2}, \text{dps2}, \text{dx2}\}, \{ \text{dph2}, 0, -\text{dth2}, \text{dy2} \}, \\
 &\{ -\text{dps2}, \text{dth2}, 0, \text{dz2} \}, \{0, 0, 0, 0\} \} \\
 &\dots \\
 \text{de19} &= \{ \{0, -\text{dph9}, \text{dps9}, \text{dx9}\}, \{ \text{dph9}, 0, -\text{dth9}, \text{dy9} \}, \\
 &\{ -\text{dps9}, \text{dth9}, 0, \text{dz9} \}, \{0, 0, 0, 0\} \}
 \end{aligned} \tag{A2.3}$$

#### A2.1.3 Saving main matrices

To append the listed matrix definitions to any developed file, the entered symbols are saved using the command

```
Save["matr", {m1, m2, m3, m4, m5, m6, del10, del11, del12, del13,
del14, del15, del16, del17, del18, del19}]
```

 (A2.4)

where "matr" and "del" are the filenames.

To manipulate with the matrices using their symbols in any processed file, the name "matr" is entered as follows:

```
<<matr
```

 (A2.5)

where command "<<" allows reading the symbols in Eq. (A4) and evaluation of all read files within the processed file.

#### A2.1.4 Basic HTM matrices for the planar (2-D) case

- Three matrices of the elementary motions associated with symbols  $mx$ ,  $my$ ,  $mz$  are defined:

```
mx={{1, 0, xx}, {0, 1, 0}, {0, 0, 1}}
my={{1, 0, 0}, {0, 1, yy}, {0, 0, 1}}
mph={{Cos[ph], Sin[ph], 0}, {-Sin[ph], Cos[ph], 0}, {0, 0, 1}}
```

 (A2.6)

- The error matrix, Eq. (8.9), is defined:

```
eps ={{0, -dph, dx}, {dph, 0, dy}, {0, 0, 0}}
```

 (A2.7)

For convenience, four error matrices associated with FSS links are prepared,

```
eps0={{0, -dph0, dx0}, {dph0, 0, dy0}, {0, 0, 0}}
eps1={{0, -dph1, dx1}, {dph1, 0, dy1}, {0, 0, 0}}
eps2={{0, -dph2, dx2}, {dph2, 0, dy2}, {0, 0, 0}}
eps3={{0, -dph3, dx3}, {dph3, 0, dy3}, {0, 0, 0}}
```

To append the listed matrix definitions to a developed file, the entered symbols are saved:

```
Save["matr3", {mx, my, mph, eps0, eps1, eps2, eps3}]
```

 (A2.8)

where "matr3" is the filename.

To manipulate with the matrices using only their symbols in any processed file, Eq. (A2.8), is entered as <<matr3.

#### A2.1.5 Transformation of the HTM matrices and vectors to the third order form

The  $4 \times 4$  matrices  $m4$ ,  $m5$ ,  $m6$  (matrices of rotations) and the  $4 \times 1$  vectors can be transformed into the regular matrices and vectors of the third order using the  $3 \times 4$  matrix

$$T_{4to3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

In terms of Mathematica® codes,

$$\mathbf{T4to3} = \{ \{1, 0, 0, 0\}, \{0, 1, 0, 0\}, \{0, 0, 1, 0\} \} \quad (\text{A2.9})$$

*Examples:*

(a) The code for matrix transformation

```
In[1] := m6 = {{Cos[ph], -Sin[ph], 0, 0}, {Sin[ph], Cos
             [ph], 0, 0}, {0, 0, 1, 0}}, {0, 0, 0, 1}};
In[2] := T4to3.m6.Transpose[T4to3]
Out[2] := {{Cos[ph], -Sin[ph], 0}, {Sin[ph], Cos[ph], 0}, {0, 0, 1}}
```

(b) The code for vector transformation

```
In[1] := T4to3.{x,y,z,1}
Out[1] := {x,y,z}
```

where the point “.” stands for matrix multiplication;  $\text{In}[n] :=$  is the input information; and  $\text{Out}[n] :=$  is the  $n$ th output.

## A2.2 Examples: Solutions of problems considered in this book

### A2.2.1 Synthesis of manipulation matrix, Eq. (4.38)

**Given:** Coordinate code of the lathe is  $k = 631$ . **Required:** Synthesis of the manipulation matrix.

**Solution:**

- The code starts from the command `<<matr`, Eq. (A2.5), to add matrices of links motion  $m_6$ ,  $m_3$ , and  $m_1$ , Eq. (A2.1) to the processed file. The identifiers  $A_{01}$ ,  $A_{12}$ ,  $A_{23}$  are assigned to matrices  $m_6$ ,  $m_3$ , and  $m_1$ , respectively;
- Manipulation matrix  $A_{03}$  is obtained by the ordered multiplication  $A_{01}.A_{12}.A_{23}$ ;
- The result is shown in the matrix form.

```
In[1] := <<matr
        "Links motion matrices";
        A01=m6;
        A12=m3;
        A23=m1;
        "Manipulation matrix";
        A03=A01.A12.A23;
        "A03 ="MatrixForm[A03]
```

Out [n] :=

$$\mathbf{A03} = \begin{bmatrix} \cos ph & -\sin ph & 0 & xx \cos ph \\ \sin ph & \cos ph & 0 & -xx \sin ph \\ 0 & 0 & 1 & zz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

### A2.2.2 Synthesis of the form-shaping function, Eq. (4.41)

**Given:** Coordinate code of the lathe is  $k = 631$ . **Required:** Synthesis of the form-shaping function (FSF). **Solution:**

- The code starts from seven commands of the *Example A2.1*;
- The single-point tool vector  $\mathbf{r}_3 = [0, 0, 0, 1]^T$  is entered in the form  $\mathbf{r3} = \{0, 0, 0, 1\}$  and multiplied by the manipulation matrix.
- The Output demonstrates the FSF in the matrix form.

```
In [1] := <<matr;
          "Links motion matrices";
          A01 = m6;
          A12 = m3;
          A23 = m1;
          "Manipulation matrix";
          A03 = A01.A12.A23;
          "Single point-tool vector";
          r3={0,0,0,1};
          r0=A03.r3;
          "r0 ="MatrixForm[r0]
```

$$\text{Out [n] := } \mathbf{r0} = \begin{bmatrix} xx \cos ph \\ -xx \sin ph \\ zz \\ 1 \end{bmatrix} \quad (\text{A2.10})$$

### A2.2.3 Setup (table 6.4)

**Given:** FSF of the lathe from the previous Example. On the lathe, the cylinder of radius  $R$  is machined using longitudinal turning. **Required:** (a) Equation of the machined cylinder; (b) equation of the unit vector of the normal to the machined cylinder; (c) graphical presentation of the cylinder of radius  $R = 50$  mm and length 120 mm, the initial cross section is located on  $z = 20$  mm. **Solution:**

(a) *Input description:*

- The code starts from vector  $\mathbf{r0}$ , Eq. (A2.10);
- The single constraints  $xx = R$  is applied using replacement operator  $/$ .  $xx \rightarrow R$ , and the HTM vector is rearranged to a Cartesian coordinate vector using matrix  $T_{4to3}$ , Eq. (A2.9), with renaming  $\mathbf{r0}$  for  $\mathbf{rcyl}$ ;

- Partial derivatives  $dph$  with respect to  $ph$  and  $dz$  with respect to  $zz$  are defined using operator  $D[rcyl, ph]$  and  $D[rcyl, zz]$ , respectively;
- The normal  $NN$  is defined through vector cross product  $Cross[dph, dz]$ ;
- Unit normal vector  $nn$  is defined and simplified through equation  $nn = NN/(NN.NN)^{1/2}$ ;
- The cylinder  $rcyl50$  of radius 50 is defined using replacement operator  $/.$   $R \rightarrow 50$ ;
- Using commands  $ParametricPlot3D[rcyl50, \{ph, 0, 2 Pi\}, \{zz, 20, 140\}]$ , the cylinder plot is built. The command allows building the surfaces given in the two-parametric form,  $rcyl = rcyl(ph, zz)$ . The parameter limits are  $0 < ph \leq 2\pi$  and  $20 < zz \leq 140$

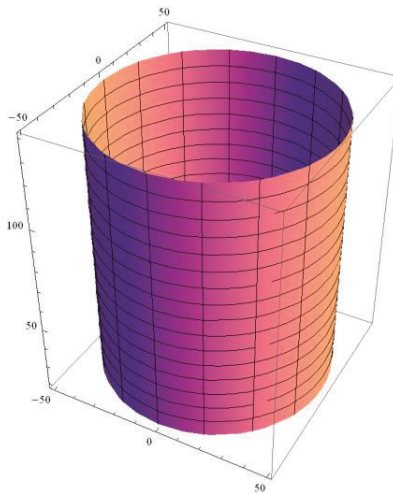
(b) *Output description:*

Formula of the unit vector of the normal gives two possible values,  $nn = \pm[R \cos ph, R \sin ph, 0]^T$ ;

- The plot shows the cylindrical surface between  $z = 20$  and  $z = 140$ .

```
In[n] := <<matr;
r0={xx Cos[ph], xx Sin[ph], zz, 1};
rcyl=Tr4to3.r0 /. xx -> R
dph=D[rcyl, ph];
dz=D[rcyl, zz];
NN=Cross[dph, dz];
nn=Simplify[NN/(NN.NN)^(1/2)]
rcyl50=rcyl /. R->50;
ParametricPlot3D[rcyl50, {ph, 0, 2 Pi}, {zz, 0, 100}]
```

$$\text{Out}[n] := \left\{ -\frac{R \cos ph}{\sqrt{R^2}}, \frac{R \sin ph}{\sqrt{R^2}}, 0 \right\}$$



The conventional coordinate frame used in Mathematica differs from the frame accepted in the lathe (see system  $X_1 Y_1 Z_1$  in Figure 4.7). To transform the coordinate systems, two successive rotations are entered in the previous code: around the  $Y$ -axis at  $90^\circ$  and around the  $Z$ -axis at  $-90^\circ$ . See the following code, where the output is related to the lathe accepted frame:

```

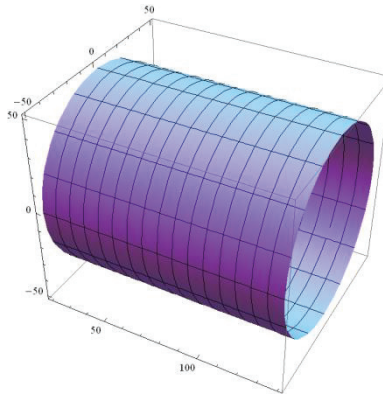
In[n] := <<matr;
r0={xx Cos[ph], -xx Sin[ph], zz, 1};
rL=(m5/.ps->Pi/2). (m6/.ph->-Pi/2). r0
rcyl=Tr4to3.rL/.xx->R;
dph=D[rcyl, ph];
dc=D[rcyl, zz];
NN=Cross[dph, dc];
Nn=Simplify[NN/(NN.NN)^(1/2)]
Rcyl=rcyl/.R->50;
ParametricPlot3D[Rcyl, {ph, 0, 2 Pi}, {zz, 20, 140}]

```

```

Out[n] := {0, - $\frac{R \cos ph}{\sqrt{R^2}}$ ,  $\frac{R \sin ph}{\sqrt{R^2}}$ }

```



#### A2.2.4 Geometrical accuracy of the 2-DOF (RR) manipulator, Eq. (10.1-6)

**Given:** Dimensions of the 2-DOF manipulator (Fig. 10.1): the end-effector (EE) point is given through position vector  $\mathbf{r}_0 = [0, 0, 1]^T$ ;  $a_1 = a_2 = 250$  mm; geometrical errors are  $\delta_{x_0} = \delta_{y_0} = 0$ ;  $\delta_{\varphi_0} = 0$ ;  $\delta_{x_1} = \delta_{y_1} = 0.01$  mm;  $\delta_{\varphi_1} = 0.0005$ ;  $\delta_{x_2} = \delta_{y_2} = 0.1$  mm;  $\delta_{\varphi_2} = 0$ ;  $\delta_{x_3} = \delta_{y_3} = 0.01$  mm;  $\delta_{\varphi_3} = 0.0005$ ;  $\delta_{x_4} = \delta_{y_4} = 0.1$  mm; and  $\delta_{\varphi_4} = 0$ . **Required:** The distance error  $\delta_{AB}$  between the two position of the EE point: configuration A ( $\varphi_{2A} = \pi/12$ ; and  $\varphi_{4A} = \pi/6$ ) and configuration B ( $\varphi_{2B} = \pi/6$ ; and  $\varphi_{4B} = \pi/3$ ).

**Solution:** The In[n] commands are entered in the given order:

- The code fetches file matr3, Eq. (A2.9), with the list of  $3 \times 3$  matrices;

The motion matrices A01 with new parameter pfi1, A12 with new parameter a2, A23 with new parameter pfi2, and A34 with new parameter a4;

- The manipulating matrix  ${}^0A_4$ , Eq. (10.1), called A04;
- The reciprocal matrices A10(-ph1), A21(-a2), A32(-ph3), and A43(-a4);
- The total error matrix E, Eq. (10.3), called "Et";
- The numerical data condA, condB, and condE;
- The position errors  $e_{rA}$  of point A and  $e_{rB}$  of point B;
- The distance error dAB is defined.

The Out[n] consists of a single number for verification of the code.

```
In [n] := <<matr3;
"FSF manipulating matrix";
A01=mph/.ph→phi1;
A12=mx/.xx→a2;
A23=mph/.ph→phi3;
A34=mx/.xx→a4;
A04=Simplify[A01.A12.A23.A34];eps0
A10=mph/.ph→-phi1;
A21=mx/.xx→-a2;
A23=mph/.ph→-phi3;
A34=mx/.xx→-a4;
r4={0,0,1};
r0=A04.r4;
"Error matrix";
Et = Simplify[eps0+A01.eps1.A10+A01.A12.eps2.A21.A10 +
A01.A12.A23.eps3.A32.A21.A10 +
A01.A12.A23.A34.eps4.A43.A32.A21.A10];
"Numerical Example";
condA={phi1→Pi/12, phi3→Pi/6, a2→250, a4→250};
condB={phi1→Pi/6, phi3→Pi/3, a2→250, a4→250};
condE={dx0→0, dy0→0, dph0→0,
dx1→0.01, dy1→0.01, dph1→0.0005,
dx2→0.1, dy2→0.1, dph2→0,
dx3→0.01, dy3→0.01, dph3→0.0005,
dx4→0.1, dy4→0.1, dph4→0};
"Two points";
erA=N[(Et.r0)/.condA/.condE];
erB=N[(Et.r0)/.condB/.condE];
"Distance AB";
dAB=((erA-erB).(erA-erB))^(1/2)
```

```
Out [n] := 0.333215 mm
```

### A2.2.5 Inverse kinematics of the GSP platform, Eq. (5.38-40)

**Given:** The form-shaping system combines the base (coordinate frame  $S_0$ ) and the moving platform (coordinate frame  $S_1$ ); dimensions of the GSP platform (Fig. 5.26):  $r_1 = 700$  mm;  $r_2 = 250$  mm; angles of the limb ends location on the base plane are  $\alpha_i$  ( $i = 1, 2, \dots, 6$ ); angles of the limb ends location on the moving platform plane are  $\beta_i$  ( $i = 1, 2, \dots, 6$ ). **Required:** (a) Lengths of the limbs in the general case; (b) Lengths of the limbs of the 3–3 platform in the configuration  $x = y = 0$ ;  $z = 400$  mm;  $\theta = \psi = \varphi = 0$ , with end limbs location  $\alpha_1 = \alpha_6 = -\pi/3$ ;  $\alpha_2 = \alpha_3 = \pi/3$ ;  $\alpha_4 = \alpha_5 = \pi$ ;  $\beta_1 = \beta_2 = 0$ ;  $\beta_3 = \beta_4 = 2\pi/3$ ;  $\beta_5 = \beta_6 = 4\pi/3$ .



**Solution:**

```

In[n] := <<matr;
  "FSF";
  A01 = m1.m2.m3.m4.m5.m6;
  "Lower ends of limbs in coordinate frame S0";
  rM1={r1 Cos[a11],r1 Sin[a11],0,1};
  rM2={r1 Cos[a12],r1 Sin[a12],0,1};
  rM3={r1 Cos[a13],r1 Sin[a13],0,1};
  rM4={r1 Cos[a14],r1 Sin[a14],0,1};
  rM5={r1 Cos[a15],r1 Sin[a15],0,1};
  rM6={r1 Cos[a16],r1 Sin[a16],0,1};
  "Upper ends of limbs in coordinate frame S1";
  rQ1={r2 Cos[bet1],r2 Sin[bet1],0,1};
  rQ2={r2 Cos[bet2],r2 Sin[bet2],0,1};
  rQ3={r2 Cos[bet3],r2 Sin[bet3],0,1};
  rQ4={r2 Cos[bet4],r2 Sin[bet4],0,1};
  rQ5={r2 Cos[bet5],r2 Sin[bet5],0,1};
  rQ6={r2 Cos[bet6],r2 Sin[bet6],0,1};
  "Upper ends of limbs in coordinate frame S0";
  rU1= A01.rQ1;
  rU2= A01.rQ2;
  rU3= A01.rQ3;
  rU4= A01.rQ4;
  rU5= A01.rQ5;
  rU6= A01.rQ6;
  "Limb lengths in the general case";
  L1=((rU1-rM1).(rU1-rM1))^(1/2);
  L2=((rU2-rM2).(rU2-rM2))^(1/2);
  L3=((rU3-rM3).(rU3-rM3))^(1/2);
  L4=((rU4-rM4).(rU4-rM4))^(1/2);
  L5=((rU5-rM5).(rU5-rM5))^(1/2);
  L6=((rU6-rM6).(rU6-rM6))^(1/2);
  "Numerical example: 3-3 GSP"
  cond={r1→700, r2→250,
    al1→ -Pi/3, al2→ Pi/3, al3→ Pi/3, al4→ Pi, al5→ Pi,
    al6→ -Pi/3,
    bet1→ 0, bet2→ 0, bet3→ 2Pi/3, bet4→ 2Pi/3, bet5→
    4Pi/3, bet6→ 4Pi/3, xx→0,yy→0,zz→400,th→0,ps→0,ph→0};
  "Limb lengths"
  N[L1/.cond]
  N[L2/.cond]
  N[L3/.cond]
  N[L4/.cond]
  N[L5/.cond]
  N[L6/.cond]

```

```

Out[n] := Limb lengths
       733.144
       733.144
       733.144
       733.144
       733.144
       733.144

```

### A2.2.6 Error matrix E and Jacobian $J_c$ for 2RR robot

In the very beginning, the code fetches file “matr3” with the list of  $3 \times 3$  matrices. Then, the following subjects are computed in the given order:

- The manipulating matrix  ${}^0A_4$ , Eq. (10.1), called “A04”;
- The total error matrix E, Eq. (10.149), called “Et”;
- Twist  $\delta$ , Eq. 10.154), called “tw”; and,
- The Jacobian matrix J, Eq. (10.157), called “Jt”.

Remember that the command **Simplify**[*qqq*] simplifies of the bracketed expression *qqq*, the command **Transpose**[*mmm*] transposes the bracketed matrix *mmm*, and the command **Inverse**[*mmm*] carries out inversion of the square matrix *mmm*.

```

In[1] := "3RR robot";
        <<matr3;
        "FSF manipulating matrix";
        A01=mph /. phi->phi1;
        A12=mx/.xx->a2;
        A23=mph /. phi->phi3;
        A34=mx/.xx->a4;
        A04=Simplify[A01.A12.A23.A34];
        "FSF variation";
        Et= Simplify[eps0+A01.eps1.Inverse[A01]+
                A01.A12.eps2.Inverse[A01.A12]+A01.A12.A23.eps3.
                Inverse[A01.A12.A23]+A01.A12.A23.A34.eps4.
                Inverse[A01.A12.A23.A34]];
        "Twist";
        tw={Et[[1,4]],Et[[2,4]],Et[[2,1]]};
        "Jacobian";
        Jt=Transpose[{D[tw,dx0],D[tw,dy0],D[tw,dph0],
                D[tw,dx1],D[tw,dy1],D[tw,dph1],D[tw,dx2],D[tw,dy2],
                D[tw,dph2],D[tw,dx3],D[tw,dy3],D[tw,dph3],
                D[tw,dx4],D[tw,dy4],D[tw,dph4]}}];

```

### A2.2.7 Diagnostic procedure: Computation of Eq. (10.174)

```

In[1] := "Structural matrix";
        js={{Cos[0], Sin[0],0,0,0,1},

```

```

{Cos[Pi/3], Sin[Pi/3], 0, 0, 0, 1},
{Cos[2Pi/3], Sin[2Pi/3], 0, 0, 0, 1},
{Cos[3Pi/3], Sin[3Pi/3], 0, 0, 0, 1},
{Cos[4Pi/3], Sin[4Pi/3], 0, 0, 0, 1},
{Cos[5Pi/3], Sin[5Pi/3], 0, 0, 0, 1},
{Cos[0], Sin[0], -100 Sin[0], 100 Cos[0], 100, 1},
{Cos[Pi/3], Sin[Pi/3], 100 Sin[Pi/3], 100
  Cos[Pi/3], 100, 1},
{Cos[2Pi/3], Sin[2Pi/3], -100 Sin[2Pi/3], 100
  Sin[2Pi/3], 100, 1},
{Cos[3Pi/3], Sin[3Pi/3], -100 Sin[3Pi/3], 100
  Cos[3Pi/3], 100, 1},
{Cos[4Pi/3], Sin[4Pi/3], -100 Sin[4Pi/3], 100
  Cos[4Pi/3], 100, 1},
{Cos[5Pi/3], Sin[5Pi/3], -100 Sin[5Pi/3], 100
  Sin[5Pi/3], 100, 1}};

"Results of measurements, Eq. (10.172)";
meas={0.01, 0.02, 0.02, 0.03, 0.02, 0.01, 0.02, 0.03, 0.03,
0.03, 0.02, 0.02};

"Estimates Eq. (10.174)"
Inverse[N[Transpose[js]].js].N[Transpose[js]].meas

```

```

Out[n] := {-0.0057578, .00288675, -0.0000310551, -0.000002773,
0.00006667, 0.0183333}

```

### A2.2.8 The Fichter's singular configuration of the 3-3 GSP matrix (Fig. 11.13)

The Jacobian matrix for Fichter's singular configuration is built. A part of the code is identical to that in Appendix A.2.2.5. The demonstrated results are the determinant graph of the Jacobian matrix vs. angle  $\varphi$  (see Out[65]) and zero value of the determinant for  $\varphi = \pi/2$  (see Out[66]).

```

In[1] := "Fichter singularity of the 3-3 GPS";

```

```

<<matr;
  A01=m1.m2.m3.m4.m5.m6;

"Lower ends of limbs";

rM1={r1 Cos[a11], r1 Sin[a11], 0, 1};
rM2={r1 Cos[a12], r1 Sin[a12], 0, 1};
rM3={r1 Cos[a13], r1 Sin[a13], 0, 1};
rM4={r1 Cos[a14], r1 Sin[a14], 0, 1};
rM5={r1 Cos[a15], r1 Sin[a15], 0, 1};

```

```

rM6={r1 Cos[a16],r1 Sin[a16],0,1};

"Upper ends of limbs in S1";
rQ1={r2 Cos[bet1],r2 Sin[bet1],0,1};
rQ2={r2 Cos[bet2],r2 Sin[bet2],0,1};
rQ3={r2 Cos[bet3],r2 Sin[bet3],0,1};
rQ4={r2 Cos[bet4],r2 Sin[bet4],0,1};
rQ5={r2 Cos[bet5],r2 Sin[bet5],0,1};
rQ6={r2 Cos[bet6],r2 Sin[bet6],0,1};

"Upper ends of limbs in S0";
rU1=A01.rQ1;
rU2=A01.rQ2;
rU3=A01.rQ3;
rU4=A01.rQ4;
rU5=A01.rQ5;
rU6=A01.rQ6;

"Limb vectors";
l1=rU1-rM1;
l2=rU2-rM2;
l3=rU3-rM3;
l4=rU4-rM4;
l5=rU5-rM5;
l6=rU6-rM6;

"Limb lengths";
L1=(l1.l1)^(1/2);
L2=(l2.l2)^(1/2);
L3=(l3.l3)^(1/2);
L4=(l4.l4)^(1/2);
L5=(l5.l5)^(1/2);
L6=(l6.l6)^(1/2);

"Limb orts";
e1=l1/L1;
e2=l2/L2;
e3=l3/L3;
e4=l4/L4;
e5=l5/L5;
e6=l6/L6;

"Limb arms";
arm1=A01.rQ1/.zz-> 0;
arm2=A01.rQ2/.zz-> 0;

```

```

arm3=A01.rQ3/.zz-> 0;
arm4=A01.rQ4/.zz-> 0;
arm5=A01.rQ5/.zz-> 0;
arm6=A01.rQ6/.zz-> 0;

```

```

"Ort moments";
n1=Cross[T4to3.arm1, T4to3.e1];
n2=Cross[T4to3.arm2, T4to3.e2];
n3=Cross[T4to3.arm3, T4to3.e3];
n4=Cross[T4to3.arm4, T4to3.e4];
n5=Cross[T4to3.arm5, T4to3.e5];
n6=Cross[T4to3.arm6, T4to3.e6];

```

```

"Jacobian matrix synthesis"

```

```

JJ={ {e1[[1]],e1[[2]],e1[[3]],n1[[1]],n1[[2]],n1[[3]]},
      {e2[[1]],e2[[2]],e2[[3]],n2[[1]],n2[[2]],n2[[3]]},
      {e3[[1]],e3[[2]],e3[[3]],n3[[1]],n3[[2]],n3[[3]]},
      {e4[[1]],e4[[2]],e4[[3]],n4[[1]],n4[[2]],n4[[3]]},
      {e5[[1]],e5[[2]],e5[[3]],n5[[1]],n5[[2]],n5[[3]]},
      {e6[[1]],e6[[2]],e6[[3]],n6[[1]],n6[[2]],n6[[3]]} };

```

```

cond = {r1-> 0.7, r2-> 0.25, a11-> -Pi/3, a12-> Pi/3, a13->
Pi/3, a14-> Pi, a15-> Pi, a16-> -Pi/3, bet1-> 0, bet2-> 0,
bet3-> 2Pi/3, bet4-> 2Pi/3, bet5-> 4Pi/3, bet6-> 4Pi/3, xx->
0, yy-> 0, zz-> 0.4, th-> 0, ps-> 0};

```

```

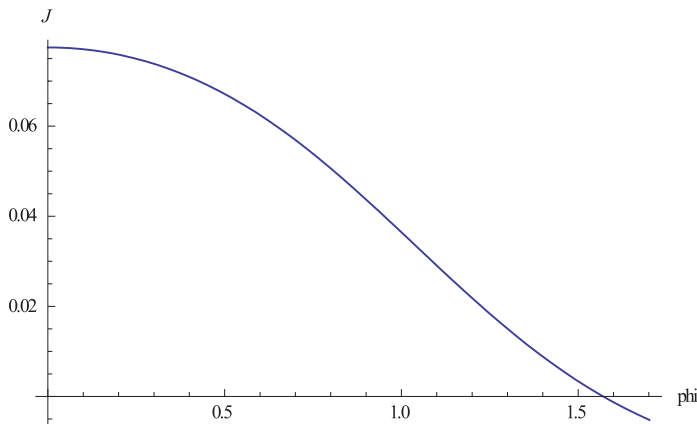
JJphi=JJ/.cond;
detJ=Det[JJphi];
Plot[detJ, {ph, 0, Pi/2+Pi/24}, AxesLabel->{phi, J}]

```

```

Out[65] :=

```



```

In[66] := Chop[N[detJ/.ph-> Pi/2]]

```

```

Out[66] := 0

```

---

## Appendix 3: Some symbols and operations from the Mathematica® software system

---

### A3.1 Global objects

#### A3.1.1 Input and output

`In[n]` is the  $n$ th input information entered by the user;

`Out[n]` is an output resulting from code processing generated by the software system.

#### A3.1.2 Algebraic symbols

Regular symbols “+”, “-”, “×”, “/”, and “()” are used for algebraic operations on scalar values and functions; “=” is the assignment symbol;

The power symbol is “^”, i.e.,  $x^y$  means  $x^y$ ;

Dot “.” is the symbol of product of matrices, matrices by vectors, and the dot-product (scalar product) of two vectors.

*Attention:*

- instead of product symbol “×”, the blank is regularly used for multiplication of scalars, i.e.,  $a \times b \equiv a b$ ;
- square brackets are used for giving parameter/s of commands and functions;
- braces are used a list of elements, vectors and matrices.

### A3.2 Matrix and Vector Synthesis

- *Vectors of the third order*

```
In[n] := r = {x, y, z}
```

```
Out[n] := {x, y, z}
```

where “=” is the assignment symbol.

- *Position vector of the fourth order*

```
In[n] := r = {x, y, z, 1}
```

```
Out[n] := {x, y, z, 1}
```

- *Non-position vector of the forth order*

```
In[n] := r = {x, y, z, 0}
```

```
Out[n] := {x, y, z, 0}
```

- *Matrix of the 4×4 order (an expression in the braces is the matrix row)*

```
In[n] := A = {{a11, a12, a13, a14}, {a11, a12, a13, a14},  
             {a11, a12, a13, a14}, {a11, a12, a13, a14}}
```

```
Out[n] := {{a11, a12, a13, a14}, {a11, a12, a13, a14}, {a11,  
           a12, a13, a14}, {a11, a12, a13, a14}}
```

### A3.3 Operations on Vectors and Matrices

- *Sum of the third order vectors*

```
In[n] :=      r1 = {x1, y1, z1};
              r2 = {x2, y2, z2};
              rs = r1 + r2
Out[n] :=     {x1 + x2, y1 + y2, z1 + z2}
```

- *Sum of position and non-position vectors*

```
In[n] :=      r1 = {x1, y1, z1, 1}
              r2 = {x2, y2, z2, 0}
              rs = r1 + r2
Out[n] :=     {x1 + x2, y1 + y2, z1 + z2, 1}
```

- *Sum of two non-position vectors*

```
In[n] :=      r1 = {x1, y1, z1, 0}
              r2 = {x2, y2, z2, 0}
              rs = r1 + r2
Out[n] :=     {x1 + x2, y1 + y2, z1 + z2, 0}
```

- *Sum of the matrices (e.g., of the 4×4 order)*

```
In[n] :=      A = {{a11, a12, a13, a14}, {a21, a22, a23, a24},
                  {a31, a32, a33, a34}, {a41, a42, a43, a44}};
              B = {{b11, b12, b13, b14}, {b21, b22, b23, b24},
                  {b31, b32, b33, b34}, {b41, b42, b43, b44}};
              AS = A + B
Out[n] :=     {{a11 + b11, a12 + b12, a13 + b13, a14 + b14}, {a21
+ b21, a22 + b22, a23 + b23, a24 + b24}, {a31 +
b31, a32 + b32, a33 + b33, a34 + b34}, {a41 + b41,
a42 + b42, a43 + b43, a44 + b44}}
```

- *Product of two real or numbers*

```
In[n] :=      x = a;
              y = b;
              x y
Out[n] :=     a b
```

- *Dot product of vectors*

```
In[n] :=      r1 = {x1, y1, z1};
              r2 = {x2, y2, z2};
              rp = r1.r2
Out[n] :=     x1 x2 + y1 y2 + z1 z2
```

- *Vector (cross) product of two vectors of the third order*

```
In[n]:=      r1 = {x1, y1, z1};
              r2 = {x2, y2, z2};
              rp = Cross[r1,r2]
Out[n]:=     {-y2 z1 + y1 z2, x2 z1 - x1 z2, - x2 y1 + x1 y2}
```

- *Product of the matrix and vector*

```
In[n]:=      A = {{a11, a12, a13, a14}, {a21, a22, a23, a24},
                  {a31, a32, a33, a34}, {a41, a42, a43, a44}};
              r1 = {x, y, z, v};
              r = A.r1
Out[n]:=     {a14 v + a11 x + a12 y + a13 z, a24 v + a21 x + a22
              y + a23 z, a34 v + a31 x + a32 y + a33 z, a44 v + a4
              1x + a42 y + a43 z}
```

- *Product of two matrices (e.g., the 3×4 matrix by 4×2 matrix)*

```
In[n]:=      A={{a11,a12,a13,a14},{a21,a22,a23,a24},{a31,a32,a33,
                  a34}};
              B={{b11,b12},{b21,b22},{b31,b32},{b41,b42}};
              A.B
Out[n]:=     {{a11 b11 + a12 b21 + a13 b31 + a14 b41,
              a11 b12 + a12 b22 + a13 b32 + a14 b42},
              {a21 b11 + a22 b21 + a23 b31 + a24 b41,
              a21 b12 + a12 b22 + a23 b32 + a24 b42},
              {a31 b11 + a32 b21 + a33 b31 + a34 b41,
              a31 b12 + a32 b22 + a33 b32 + a34 b42}}
```

- *Demonstration*

- Symbol *expr*; evaluates *expr*, but ignores demonstration of the result in the Output.
- Symbol “text” ignores evaluation of the text and demonstrates it as is.
- Command `MatrixForm[matr]` demonstrates matrix *matr* in the regular matrix form:

```
In[n]:=      matr={{a11, a12}, {a21, a22}};
              MatrixForm[matr]
Out[n]:=     
$$\begin{bmatrix} a11 & a12 \\ a21 & a22 \end{bmatrix}.$$

```



## Abbreviations

AE – active element of the FSS

CMM – coordinate measuring machine

CNC – computer numerical control

DC – dimensional chain

DOF – degree of freedom

EE – end-effector

FSF – form-shaping function

FSS – form-shaping system

GSP – Gough-Stewart platform

HTM – homogeneous transformation matrix

IR – industrial robot

IT – international tolerance

LMS – least-mean square

LVDT – linear variable differential transformer

MinZ – minimum zone

MT – machine tool

NC – numerical control

PWM – precision working machine

PKM – parallel-kinematics machine

SKM – serial-kinematics machine

TE – target element of the FSS

WM – working machine



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## Z

Zero error, 12-411



## About the Author

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After repatriation in Israel in 1990, he has been served as Professor of Machine Design and Mechanism and Machine Theory at BGU.

Professor Portman published over 200 papers, books, patents, and other academic works in the field of parallel kinematic machines, accuracy of machine tools and robots, precision machining, dimensional metrology, and FMS simulation. The most important work is the authored book in common with Prof. D. N. Reshetov – monograph *Accuracy of Machine Tools*, issued in 1986 in Russian by Mashinostorenie, Moscow, former USSR, and translated in English in 1988 (additional issues 1989, 1991, 1992) by ASME Press, New York, NY.















