Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Autonomous Systems Lab
Prof. Roland Siegwart

Master Thesis

Use of a DVS for High Speed Applications

Autumn Term 2018

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Contents

Preface

Bla bla . . .

Abstract

Hier kommt der Abstact hin ...

Symbols

Symbols

ϕ, θ, ψ	roll, pitch and yaw angle
b	gyroscope bias
Ω_m	3-axis gyroscope measurement

Indices

x	x axis
y	y axis

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
EKF	Extended Kalman Filter
IMU	Inertial Measurement Unit
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter

Chapter 1

Introduction

Hier kommt die Einleitung DVS is

Chapter 2

Einige wichtige Hinweise zum Arbeiten mit LaTeX

Throughout this work the following notation is employed: W denotes the world frame, C_1 or C_2 denotes a camera frame. T_{AB} is the transformation from frame A to frame B, measured in frame A.
$\boldsymbol{X}$ the position of the event with respect to world or camera frame, $\boldsymbol{x}$ the calibrated coordinates of the event.

2.1 From Events to Frame

We group a set of events $\mathscr{E} \doteq \{e_k\}_{k=1}^{N}$ into a temporal window, optimize the motion and scene parameters within this window, then shift the window to the next set of events and repeat this process. The temporal window size is defined by the event numbers N, which should be chosen small enough so that a constant velocity model could be applied within this window. We choose event numbers against a fixed time interval to define the window size, because this corresponds to the data-driven nature of an event-based camera: the more rapid the apparent motion of the scene is, the larger the event rate will be. If the scene stops moving, no events will be generated, the pose will also not be further updated.
An event frame is thus formed by summing up events within this window. If we simply sum along the time axis, the intensity at each pixel will be the sum of the polarities of all the events that are triggered at this pixel location within the window

$$\mathcal{I}(\boldsymbol{x}) = \sum_{1}^{N} \pm_k (\boldsymbol{x} - \boldsymbol{x}_k), \tag{2.1}$$

with $\pm_k$ and $\boldsymbol{x}_k$ denoting the polarity and pixel coordinates of the kth event, respectively. After warping the events with $\boldsymbol{x}'_k = \boldsymbol{W}(\boldsymbol{x}_k, t; \theta)$, we substitute $\boldsymbol{x}_k$ in the above equation to $\boldsymbol{x}'_k$.

2.1.1 Measuring the Sharpness of an Image

$$\mathrm{Var} \doteq \frac{1}{\mid \Omega \mid} \int_{\Omega} \left(\mathcal{I}\left(\boldsymbol{x}\right) - \mu\left(\mathcal{I}\left(\boldsymbol{x}\right)\right)\right)^2 d\boldsymbol{x} \tag{2.2}$$

2.1.2 Planar Homography

The warp function $\boldsymbol{x}' = \boldsymbol{W}(\boldsymbol{x}, t; \theta)$ does not only depend on the motion parameters, but also the scene parameters, which is the unknown depth. In the case of a planar scene the problems simplifies, since a plane $\mathbf{P}$ can be parameterized by two sets of parameters: $\boldsymbol{n} \in \mathbb{S}^2$ the unit surface normal of $\mathbf{P}$ with respect to the current camera frame, and d the distance from the camera center to $\mathbf{P}$. The warp function then becomes

$$\boldsymbol{X}' = \boldsymbol{R}\boldsymbol{X} + \boldsymbol{T} \tag{2.3}$$

$$\boldsymbol{X} = \boldsymbol{R}^\top (\boldsymbol{X}' - \boldsymbol{T}) \tag{2.4}$$

$$\boldsymbol{X} = \boldsymbol{R}^\top \left(\boldsymbol{I} + \boldsymbol{T}\boldsymbol{n}^\top / d\right) \boldsymbol{X}', \tag{2.5}$$

thus $\boldsymbol{x}' \sim \left(\boldsymbol{R}^\top \left(\boldsymbol{I} + \boldsymbol{T}\boldsymbol{n}^\top / d\right)\right)^{-1} \boldsymbol{x}$. Here $(\boldsymbol{R}, \boldsymbol{T}) \in SE(3)$ denotes the relative pose between two cameras at which the current event being warped and the first event within the window happened. Under a constant velocity model with linear velocity $\boldsymbol{v} \in \mathbb{R}^3$ and angular velocity $\boldsymbol{\omega} \in \mathbb{R}^3$, the translation is given by

$$\boldsymbol{T}(t) = \boldsymbol{v}t, \tag{2.6}$$

the rotation matrix is given by the *exponential map* exp: $\mathfrak{so}(3) \to SO(3)$:

$$\boldsymbol{R}(t) = \exp(\boldsymbol{\omega}^\wedge t), \tag{2.7}$$

where $^\wedge$ is the *hat* operator

$$\boldsymbol{\omega}^\wedge = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \in \mathfrak{so}(3), \tag{2.8}$$

2.2 From Frames to Map

The contrast maximization procedure in the above section optimizes the relative pose between successive frames. We show in this section that the same idea can be applied to perform global pose tracking in planar scenes. We first explain how the map is defined, and how to track a known map, then we shown how this map is built by selecting a set of keyframes.

2.2.1 Map

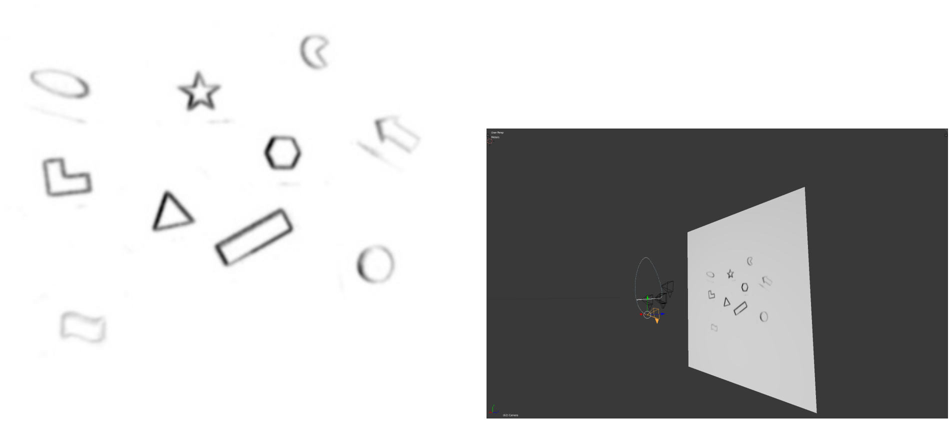
A map is a plane with normal direction $\boldsymbol{n}_w$ and distance d_w to the origin; the texture of a map represents all the edges on the plane. Figure 2.1 shows the an example of such map. Figure 2.1(a) also shows the set of keyframes used to construct the map. We will talk more about keyframes in section 2.2.3. The global coordinate is chosen as the camera coordinate of the first frame.

2.2.2 Tracking

Suppose a map is present, then the normal direction $\boldsymbol{n}_w$ of the plane and the distance d_w to the origin are known. Also the pose of the current frame $(\boldsymbol{R}_{wc}, \boldsymbol{T}_{wc}) \in SE(3)$ is determined by the motion estimation from the last frame (a quick note to the terminology we are using: whenever we say the *pose* of a frame, we always refer to the camera *pose* at which the first event within the frame happens). The parameters left to be estimated for each frame is $\{\boldsymbol{\omega}, \boldsymbol{v}\} \in \mathbb{R}^6$. By substituting $\boldsymbol{n}$ with $\boldsymbol{n}_c = \boldsymbol{R}_{cw}\boldsymbol{n}_w$, and d with $d_c = d_w + \boldsymbol{T}_{wc} \cdot \boldsymbol{n}_w$ in eq. (2.5), we get the homography matrix within each frame as

$$\boldsymbol{H}_1 = \boldsymbol{R}^\top \left(\boldsymbol{I} + \boldsymbol{T}\boldsymbol{n}_c^\top / d_c\right) \tag{2.9}$$

and $\boldsymbol{x}_c' \sim \boldsymbol{H}_1^{-1} x_c$.



(a) The texture of a map (b) A map in the global frame

Figure 2.1: Map

A nonlinear optimizing problem naturally suffers from local optima. Without a good initialization, the motion computed with the method in section 2.1 could sometimes be a local optimum delivering an image that appears sharp, despite being wrongly estimated (see fig. 2.2). In order to make sure that the estimated motion from the per frame contrast maximization also conform to the global map. Thus we perform another optimization, where we project the events of the current frame to the global map. The parameter set is still $\{\boldsymbol{\omega}, \boldsymbol{v}\}$, and we use the output from last procedure as an initial guess.
The procedure described in the first paragraph of this section can be understood as projecting the events on a *blank canvas*. Similarly, in the projecting-to-map procedure we project the events on the *texture* of the map, and measure the strength of the synthesized image with the same variance function as in eq. (2.2), thus finding the set of the parameters that best align the events in the current frame to their correspondences in the texture.
The projection from an event to the map is $\boldsymbol{x}_w \sim \boldsymbol{R}_n \boldsymbol{H}_2^{-1} \boldsymbol{H}_1^{-1} \boldsymbol{x}_c$, with $\boldsymbol{R}_n$ the transformation from the orientation of the global frame to the orientation of the map, computed by

$$\boldsymbol{K} = (\boldsymbol{n}_w \times \boldsymbol{z})^{\wedge} \tag{2.10}$$

$$\boldsymbol{R}_n = \boldsymbol{I} + \boldsymbol{K} + \boldsymbol{K}^2/(1 + \boldsymbol{n}_{\boldsymbol{w}} \cdot \boldsymbol{z}), \tag{2.11}$$

where $\boldsymbol{z} = (0, 0, -1)$ denotes the plane fronto-parallel to the camera, and

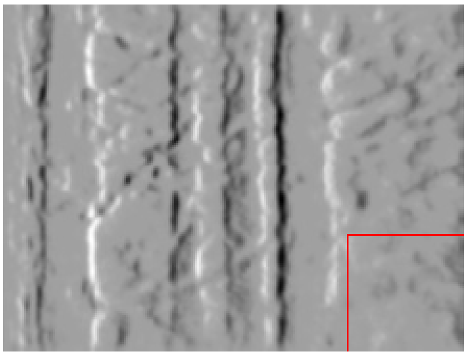
$$\boldsymbol{H}_2 = \boldsymbol{R}_{cw} \left(\boldsymbol{I} + \boldsymbol{T}_{wc} \boldsymbol{n}^\top / d_w \right), \tag{2.12}$$

the projection from the current frame to the global frame, with $\boldsymbol{R}_{wc}, \boldsymbol{T}_{wc}$ being the pose of the current frame. $\boldsymbol{H}_1$ is the planar homography for each frame as in eq. (2.9). But the $\boldsymbol{R}$ and $\boldsymbol{T}$ might be different since we are refining these parameters.

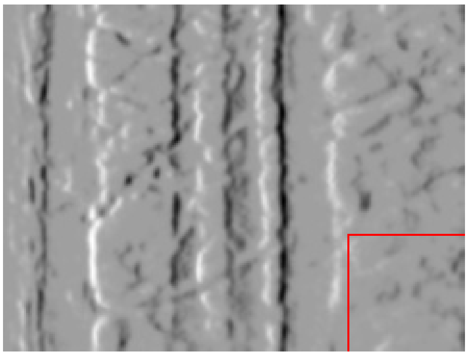
2.2.3 Mapping

2.2.4 note

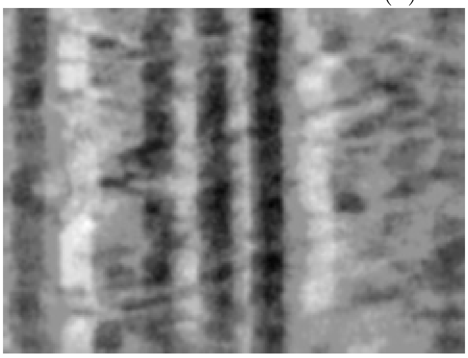
tried initialize with multiple frames, didn't work very well. similarly sliding window didn't work; too many events didn't work



(a) Estimation



(b) Groundtruth



(c) Without motion compensation

Figure 2.2: An example of local optima. This is the dataset *slider_hdr_close* with a window size of 50000 events. (a) shows the optimized image with *linear velocity* $(0.231, 0.109, 0.256)$, *angular velocity* $(0.405, -0.130, -2.278)$ and *plane normal* $(-0.579, 0.282, -0.765)$. (b) shows the result using groundtruth parameters with *linear velocity* $(0.163, 0, 0)$, *angular velocity* $(0, 0, 0)$ and *plane normal* $(0, 0, -1)$. Both images appear mostly identical, though at the lower right corner, for example, one can still recognize the difference. Also both images look much sharper than the image without motion compensation in (c). It is worth mentioning that the contrast of the estimation is actually slightly larger than that of the groundtruth

Chapter 3

Discussion

3.1 Gliederungen

Ein Text kann mit den Befehlen `\chapter{.}`, `\section{.}`, `\subsection{.}` und `\subsubsection{.}` gegliedert werden.

3.2 Referenzen und Verweise

Literaturreferenzen werden mit dem Befehl `\citep{.}` und `\citet{.}` erzeugt. Beispiele: ein Buch [1], ein Buch und ein Journal Paper [1, 2], ein Konferenz Paper mit Erwähnung des Autors: Pratt and Williamson [3].
Zur Erzeugung von Fussnoten wird der Befehl `\footnote{.}` verwendet. Auch hier ein Beispiel[1].
Querverweise im Text werden mit `\label{.}` verankert und mit `\cref{.}` erzeugt. Beispiel einer Referenz auf das zweite Kapitel: chapter 2.

3.3 Aufzählungen

Folgendes Beispiel einer Aufzählung ohne Numerierung,

- Punkt 1
- Punkt 2

wurde erzeugt mit:

```
\begin{itemize}
\item Punkt 1
\item Punkt 2
\end{itemize}
```

Folgendes Beispiel einer Aufzählung mit Numerierung,

1. Punkt 1
2. Punkt 2

wurde erzeugt mit:

[1] Bla bla.

```
\begin{enumerate}
\item Punkt 1
\item Punkt 2
\end{enumerate}
```

Folgendes Beispiel einer Auflistung,

P1 Punkt 1

P2 Punkt 2

wurde erzeugt mit:

```
\begin{description}
\item[P1] Punkt 1
\item[P2] Punkt 2
\end{description}
```

3.4 Erstellen einer Tabelle

Ein Beispiel einer Tabelle:

Table 3.1: Daten der Fahrzyklen ECE, EUDC, NEFZ.

Kennzahl	Einheit	ECE	EUDC	NEFZ
Dauer	s	780	400	1180
Distanz	km	4.052	6.955	11.007
Durchschnittsgeschwindigkeit	km/h	18.7	62.6	33.6
Leerlaufanteil	%	36	10	27

Die Tabelle wurde erzeugt mit:

```
\begin{table}[h]
  \begin{center}
    \caption{Daten der Fahrzyklen ECE, EUDC, NEFZ.}\vspace{1ex}
    \label{tab:tabnefz}
    \begin{tabular}{ll|ccc}
      \hline
      Kennzahl & Einheit & ECE & EUDC & NEFZ \\ \hline \hline
      Dauer & s & 780 & 400 & 1180 \\
      Distanz & km & 4.052 & 6.955 & 11.007 \\
      Durchschnittsgeschwindigkeit & km/h & 18.7 &  62.6 & 33.6 \\
      Leerlaufanteil & \% & 36 & 10 & 27 \\
      \hline
    \end{tabular}
  \end{center}
\end{table}
```

3.5 Einbinden einer Grafik

Das Einbinden von Graphiken kann wie folgt bewerkstelligt werden:

```
\begin{figure}
  \centering \includegraphics[width=0.75\textwidth]{images/k_surf.pdf}
```

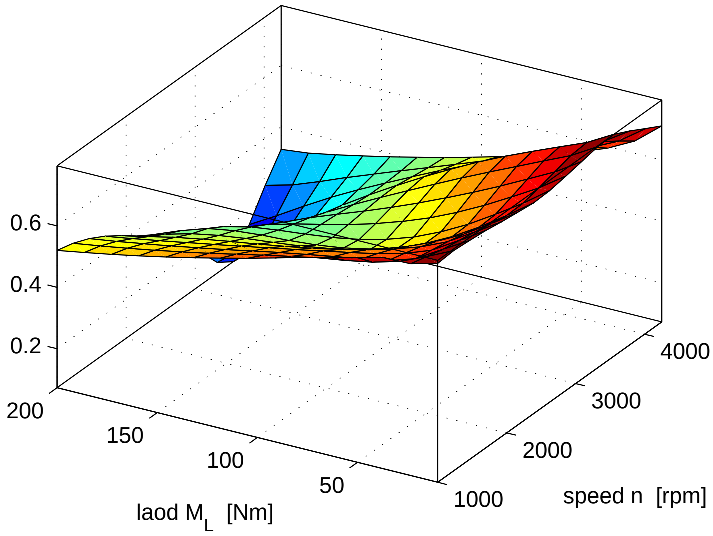


Figure 3.1: Ein Bild

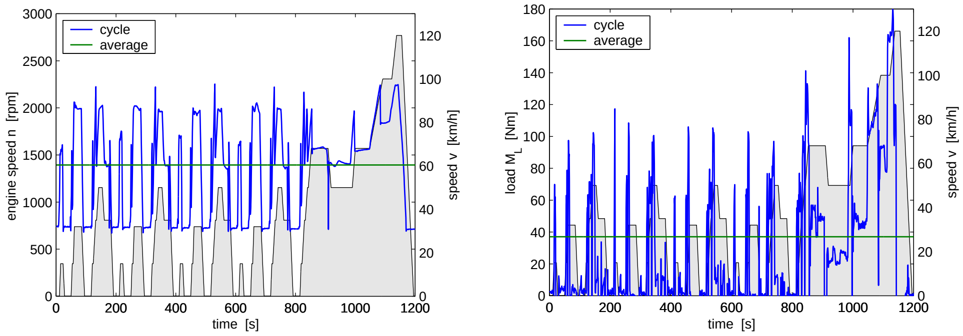


Figure 3.2: Zwei Bilder nebeneinander

```
  \caption{Ein Bild.}
  \label{fig:k_surf}
\end{figure}
```

oder bei zwei Bildern nebeneinander mit:

```
\begin{figure}
  \begin{minipage}[t]{0.48\textwidth}
    \includegraphics[width = \textwidth]{images/cycle_we.pdf}
  \end{minipage}
  \hfill
  \begin{minipage}[t]{0.48\textwidth}
    \includegraphics[width = \textwidth]{images/cycle_ml.pdf}
  \end{minipage}
  \caption{Zwei Bilder nebeneinander.}
  \label{pics:cycle}
\end{figure}
```

3.6 Mathematische Formeln

Einfache mathematische Formeln werden mit der equation-Umgebung erzeugt:

$$p_{me0f}(T_e,\omega_e) \ = \ k_1(T_e) \cdot (k_2+k_3 S^2 \omega_e^2) \cdot \Pi_{\max} \cdot \sqrt{\frac{k_4}{B}} \, . \tag{3.1}$$

Der Code dazu lautet:

```
\begin{equation}
  p_{me0f}(T_e,\omega_e) \ = \ k_1(T_e) \cdot (k_2+k_3 S^2
  \omega_e^2) \cdot \Pi_{max} \cdot \sqrt{\frac{k_4}{B}} \, .
\end{equation}
```

Mathematische Ausdrücke im Text werden mit \$formel\$ erzeugt (z.B.: $a^2+b^2=c^2$). Vektoren und Matrizen werden mit den Befehlen `\vec{.}` und `\mat{.}` erzeugt (z.B. $\boldsymbol{v}$, $\boldsymbol{M}$).

3.7 Weitere nützliche Befehle

Hervorhebungen im Text sehen so aus: *hervorgehoben*. Erzeugt werden sie mit dem `\epmh{.}` Befehl.
Einheiten werden mit den Befehlen `\unit[1]{m}` (z.B. 1 m) und `\unitfrac[1]{m}{s}` (z.B. 1 m/s) gesetzt.

Bibliography

[1] M. Raibert, *Legged Robots That Balance.* Cambridge, MA: MIT Press, 1986.

[2] M. Vukobratović and B. Borovac, "Zero-moment point — thirty five years of its life," *International Journal of Humanoid Robotics*, vol. 1, no. 01, pp. 157–173, 2004.

[3] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 1995, pp. 3137–3181.

Appendix A

Irgendwas

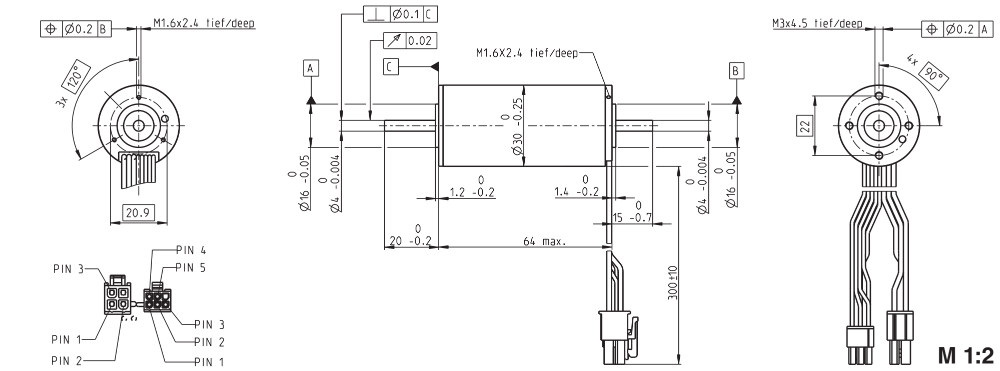
Bla bla . . .

Appendix B

Datasheets

EC-max 30 ∅30 mm, brushless, 60 Watt

maxon *EC*-max



Stock program
Standard program
Special program (on request)

Part Numbers

		272762	272763	272764	272765
Motor Data					
Values at nominal voltage					
1 Nominal voltage	V	12	24	36	48
2 No load speed	rpm	7980	9340	9490	9350
3 No load current	mA	302	191	130	95.4
4 Nominal speed	rpm	6590	8040	8270	8130
5 Nominal torque (max. continuous torque)	mNm	63.6	60.7	63.7	64.1
6 Nominal current (max. continuous current)	A	4.72	2.66	1.88	1.4
7 Stall torque	mNm	381	458	522	519
8 Starting current	A	26.8	18.8	14.5	10.7
9 Max. efficiency	%	80	81	82	82
Characteristics					
10 Terminal resistance phase to phase	Ω	0.447	1.27	2.48	4.49
11 Terminal inductance phase to phase	mH	0.049	0.143	0.312	0.573
12 Torque constant	mNm/A	14.2	24.3	35.9	48.6
13 Speed constant	rpm/V	672	393	266	197
14 Speed/torque gradient	rpm/mNm	21.2	20.6	18.4	18.2
15 Mechanical time constant	ms	4.86	4.73	4.21	4.17
16 Rotor inertia	gcm^2	21.9	21.9	21.9	21.9

Specifications

Thermal data

17 Thermal resistance housing-ambient	7.4 K/W
18 Thermal resistance winding-housing	0.5 K/W
19 Thermal time constant winding	2.76 s
20 Thermal time constant motor	1000 s
21 Ambient temperature	-40…+100°C
22 Max. permissible winding temperature	+155°C

Mechanical data (preloaded ball bearings)

23 Max. permissible speed	15000 rpm
24 Axial play at axial load < 6.0 N	0 mm
> 6.0 N	0.14 mm
25 Radial play	preloaded
26 Max. axial load (dynamic)	5 N
27 Max. force for press fits (static)	98 N
(static, shaft supported)	1300 N
28 Max. radial loading, 5 mm from flange	25 N

Other specifications

29 Number of pole pairs	1
30 Number of phases	3
31 Weight of motor	305 g

Values listed in the table are nominal.

Connection motor (Cable AWG 20)

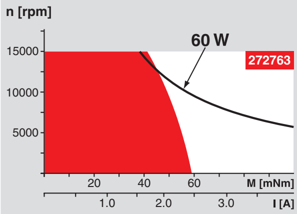
red	Motor winding 1	Pin 1
black	Motor winding 2	Pin 2
white	Motor winding 3	Pin 3
	N.C.	Pin 4
Connector	**Part number**	
Molex	39-01-2040	

Connection Sensors (Cable AWG 26)

yellow	Hall sensor 1	Pin 1
brown	Hall sensor 2	Pin 2
grey	Hall sensor 3	Pin 3
blue	GND	Pin 4
green	V_{Hall} 3…24 VDC	Pin 5
	N.C.	Pin 6
Connector	**Part number**	
Molex	430-25-0600	

Wiring diagram for Hall sensors see p. 35

Operating Range



Comments

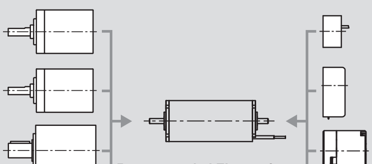
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Overview on page 20 - 25



Planetary Gearhead
∅32 mm
8.0 Nm
Page 266

Koaxdrive
∅32 mm
1.0 - 4.5 Nm
Page 268

Planetary Gearhead
∅42 mm
3 - 15 Nm
Page 271

Encoder MR
500/1000 CPT,
3 channels
Page 302

Encoder HEDL 5540
500 CPT,
3 channels
Page 308

Brake AB 20
24 VDC
0.1 Nm
Page 346

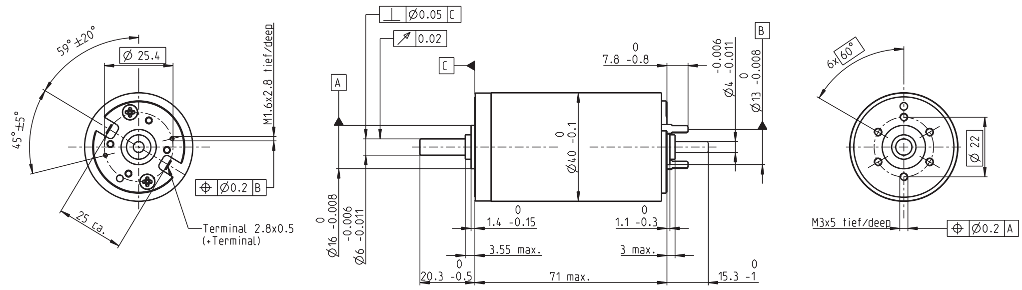
Recommended Electronics:

ESCON 36/3 EC	Page 320
ESCON 50/5, Module 50/5	321
ESCON 70/10	321
DECS 50/5	324
DEC Module 24/2	325
DEC Module 50/5	325
EPOS2 24/5, 50/5	331
EPOS2 P 24/5	334
EPOS3 70/10 EtherCAT	337
Notes	**24**

RE 40 ∅40 mm, Precious Metal Brushes, 25 Watt

NEW

maxon DC motor



M 1:2

- Stock program
- Standard program
- Special program (on request)

Part Numbers

Motor Data		448588	448589	448590	448591	448592
Values at nominal voltage						
1 Nominal voltage	V	9	18	24	42	48
2 No load speed	rpm	2850	2850	2780	2920	2690
3 No load current	mA	49.7	24.8	18.1	11	8.62
4 Nominal speed	rpm	2610	2600	2480	2640	2410
5 Nominal torque (max. continuous torque)	mNm	87.8	87.8	88.2	87.6	87.6
6 Nominal current (max. continuous current)	A	2.96	1.48	1.09	0.65	0.524
7 Stall torque	mNm	873	956	794	895	818
8 Starting current	A	29	15.9	9.66	6.53	4.81
9 Max. efficiency	%	92	92	92	92	92
Characteristics						
10 Terminal resistance	Ω	0.311	1.14	2.49	6.43	9.97
11 Terminal inductance	mH	0.0824	0.33	0.613	1.7	2.62
12 Torque constant	mNm/A	30.2	60.3	82.2	137	170
13 Speed constant	rpm/V	317	158	116	69.7	56.2
14 Speed / torque gradient	rpm/mNm	3.27	2.98	3.51	3.27	3.3
15 Mechanical time constant	ms	4.85	4.29	4.36	4.14	4.13
16 Rotor inertia	gcm²	142	137	119	121	120

Specifications

Thermal data

17 Thermal resistance housing-ambient	4.65 K/W
18 Thermal resistance winding-housing	1.93 K/W
19 Thermal time constant winding	41.5 s
20 Thermal time constant motor	809 s
21 Ambient temperature	-20…+85°C
22 Max. permissible winding temperature	+100°C

Mechanical data (ball bearings)

23 Max. permissible speed	3330 rpm
24 Axial play	0.05 - 0.15 mm
25 Radial play	0.025 mm
26 Max. axial load (dynamic)	5.6 N
27 Max. force for press fits (static)	110 N
(static, shaft supported)	1200 N
28 Max. radial loading, 5 mm from flange	28 N

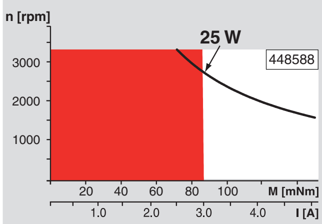
Other specifications

29 Number of pole pairs	1
30 Number of commutator segments	13
31 Weight of motor	480 g

Values listed in the table are nominal.
Explanation of the figures on page 71.

Option
Preloaded ball bearings

Operating Range



Comments

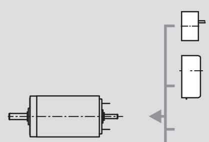
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Overview on page 20 - 25



Encoder MR
256 - 1024 CPT,
3 channels
Page 303

Encoder HED_ 5540
500 CPT,
3 channels
Page 305/307

Recommended Electronics:

ESCON 36/2 DC	Page 320
ESCON 50/5	321
ESCON Module 50/5	321
EPOS2 24/2	330
EPOS2 Module 36/2	330
EPOS2 24/5	331
EPOS2 50/5	331
EPOS2 P 24/5	334
EPOS3 70/10 EtherCAT	337
Notes	**22**