Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Autonomous Systems Lab
Prof. Roland Siegwart

Semester Thesis

Sensing and characterization of the motor dynamics on an omnidirectional flying vehicle

Spring Term 2020

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Place, date	**Signature(s)**
20.07.2020	FaustoTapia B

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Contents

Preface

Bla bla . . .

Abstract

Hier kommt der Abstact hin . . .

Symbols

Symbols

τ	Throttle command
V	Voltage
ω	Angular Speed

Indices

x	x axis
y	y axis

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
ASL	Autonomous Systems Lab
BLDC	Brush-less Direct Current
PMSM	Permanent Magnet Synchronous Motor
ESC	Electronic Speed Controller
FC	Flight Controller
MAV	Micro Aerial Vehicle
OMAV	Omni-directional Micro Aerial Vehicle
DOF	Degree of Freedom
PWM	Pulse Width Modulation
FOC	Field Oriented Control
EMF	Electro Motive Force

Chapter 1

Introduction

In the past decade, multi-copter type drones have been developed and spread all around the world for applications ranging from geographical mapping to entertainment. Furthermore, the latest developments on Miniature Aerial Vehicles (MAVs) have involved more physical interactions with the environment, power optimization and more Degrees of Freedom (DoFs) which leads to significantly more complex control pipelines. For instance, the Omnidirectional Miniature Aerial Vehicle (OMAV) at the Autonomous Systems Lab (ASL) in ETH Zurich and outlined in [**?**] consists of 6 pairs of co-axially aligned propellers with tilting axis. Mentioned platform is depicted in Figure 1.1.
Although this novel setup is highly versatile, the current rotor speed control implementation is open-loop, assuming relatively accurate and linear throttle to actual rotor speed mapping. Furthermore, the high number of propellers increases the chance of an individual failure on flight, requiring status information to be sent towards the flight controller (FC). Another important consideration is the aerodynamic interference between coaxial propellers, which surely causes disturbances leading to slower tracking. The extend of this disturbances is still unknown. Therefore, [**?**] recommends to perform a more thorough identification of this OMAV dynamics to decrease disturbances during optimal control design.
Objectives In this context, this report will describe my work during my semester project with the following objectives:

- Familiarize with current firmware available for FC-ESC communication.
- Achieve rotor speed feedback from the ESC to the FC.

Figure 1.1: ASL OMAV

- Explore different ESC typologies and
- Investigate the characteristics of driving the Brush-less Direct Current (BLDC) motors using an ESC.
- Investigate features available in modern ESCs.

Chapter 2

Literature Review

2.1 Brush-less DC motor driving

2.1.1 Brush-less DC motor

Most UAV platforms spin their propellers using Brushless-DC (BLDC) motors due to their low weight, high top speeds and efficiency. Therefore, it is imperative to know the basic principles to analyze ESCs.
A BLDC motor can be 1, 2 or 3-phase. However, the most efficient version at high speeds and the ones used for UAVs is the 3-phase version. Therefore, the BLDC term will refer to 3-phase BLDC motors. Figure 2.1 shows a simplified diagram with only 4 magnetic poles whereas a typical motor used for UAVs would have 14. Here,the stator includes coils and the rotor has permanent magnets.

2.1.2 BLDC motor driving methods

Two configurations can be used to run BLDC motors as mentioned in [**?**], both based on Pulse Width Modulation (PWM). These are Trapezoidal and Sinusoidal. They differ in the ideal driving voltage wave-forms to use when driving the motor coils. In both cases, the best performing phase shift between phases is 120°. The effective instantaneous voltage in each coil is a fraction of the DC power supply. PWM approximates this fraction by providing a pulsing signal with a corresponding duty cycle (fraction of time the signal is high). To generate these PWM signals from a DC power source, power MOSFETs are used in bridge configurations. The

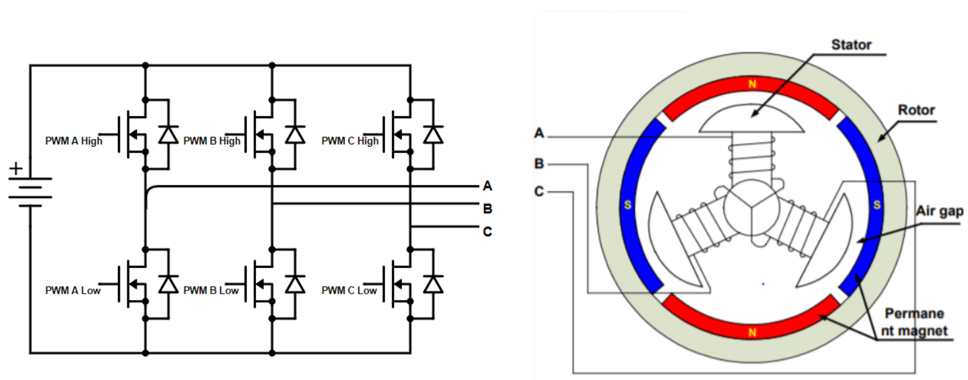

Figure 2.1: *Left* MOSFET bridge driver. *Right* BLDC motor simplified [**?**]

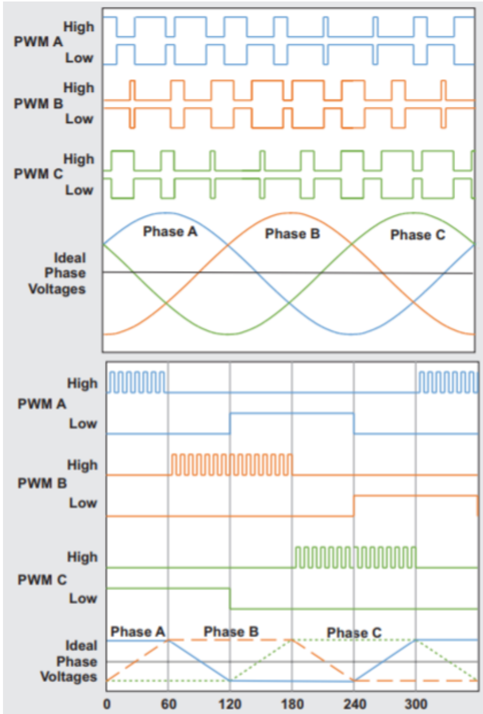

Figure 2.2: PWM Phase signals vs Rotor Position. *Top* Sinusoidal FOC, *Bottom* Trapezoidal. Adapted from [**?**]

specific configuration used for BLDC motors is shown in Figure 2.1

Trapezoidal: Here the ideal driving waveform is a trapezoidal wave. As shown in Figure 2.2 bottom. This method is easier to implement in hardware since a relatively low accuracy in rotor angular position estimation is needed. However, there are significant power loses caused by many spikes in the signal and also because the electrical magnetic field caused by the stator is only instantaneously at the optimal orientation relative to the rotor magnetic field (perpendicular). Here, the duty cycle put through the active phases is constant for the same rotor speed

Sinusoidal: In this case, the ideal driving waveform is a sinusoid as seen in figure 2.2 top. Note that for the same rotor speed, the duty cycle continuously changes over an electrical period to mimic the ideal sinewave. This is because of the waveform continuously changing and because feedback control [1] is used to maintain the relative orientation rotor-startor magnetic field orientation optimal (90°). Since the duty cycle is changed more often and depending on the rotor position, this method requires a significantly higher accuracy in rotor angular position estimation. Higher efficiency is obtained in two fronts:less pulsing implies less spikes and therefore switching power losses; the magnetic fields relative orientation is controlled to be optimal.

[1]This is not rotor speed control

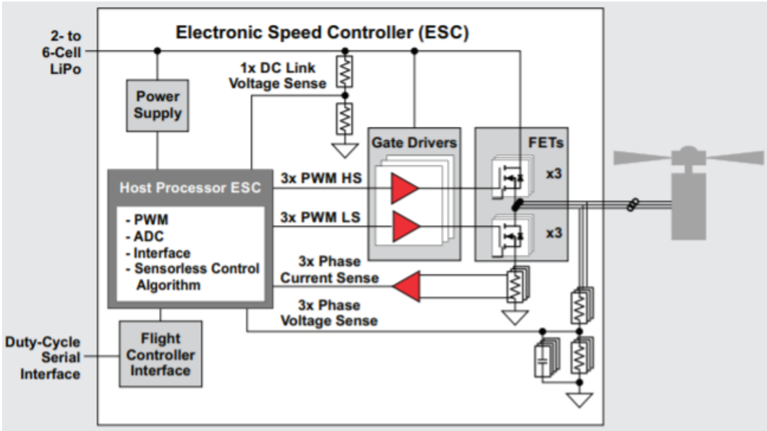

Figure 2.3: ESC general architecture [?]

2.2 Electronic Speed Controllers

2.2.1 General structure

The circuits that run the BLDC motors are commonly known as Electronic Speed Controllers (ESC). However, the majority of current available ones do not perform direct motor speed control. Their core components are a micro-controller, gate drivers, back Electro-motive foce (EMF) measurement resistors and the MOSFETs (shown in Figure 2.1). In essence, what they do is receive a throttle signal from a Flight Controller (FC) representing the amplitude of the ideal driving signal (explained in previous subsection, Fig. 2.2). The diagram in Figure 2.3 shows a general electrical architecture of ESCs. Note that gate drivers are simply interface circuits that allow to turn on/off the MOSFETs.

2.2.2 Communications

ESCs need to communicate with the FC to receive throttle commands and in some cases they also send status messages. Hence, some protocols have been used and other have been developed in the context of UAVs.

Analog Protocols

All of these protocols are based on Pulse width modulation given a maximum and a minimum pulse width to be set as maximum and minimum throttle. Hence, these protocols are commonly called RCPWM. Thee different protocols in this category merely differ in the pulse period. Figure 2.4 depicts these kind of signals on the top and Table 2.1 shows their transmission parameters.

Digital Protocols

Even though most of these protocols are widely known as digital, the true purely digital protocol is UAVCAN. The rest define certain specific pulse time durations to high or low. Dshot will be explained thoroughly in particular given that it's the basis of all the other methods but UAVCAN.
Dshot: This method consists of a 16-bit packet streamed continuously. Each bit is encoded as a pulse with one of to widths, depending on the pulse width version. Figure 2.4 show a comparison of the Dshot signals with PWM signals and Figure

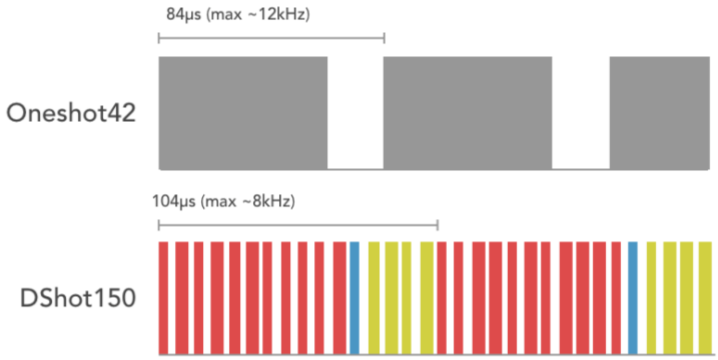

Figure 2.4: Oneshot vs Dshot comparison [?]

Table 2.1: ESC protocols' speeds

Protocol	Type	Pulse width range [μs]	Max Update Rate [kHz]
PWM	Analog	1000 - 2000	0.490
Oneshot125	Analog	125 - 250	4
Oneshot42	Analog	42 - 84	12
Multishot	Analog	5 - 25	40
Dshot150	Digital	106.8	9
Dshot300	Digital	53.4	18
Dshot600	Digital	26.7	37
Dshot1200	Digital	13.4	75
Bidirectional Dshot	Digital	Dshot values	Dshot values
Proshot	Digital	Dshot values	Dshot values
UAVCAN	Digital	NA	NA

XXXXX shows the information organization in each packet. The packet is divided into three sections as shown in Figure :

- Throttle command: Consists of 11 bits (Decimal values 0 -2047). Commands in the range [0,47] are status request commands whereas values in the range [48,2047] encode a 2000 levels throttle command.
- Telemetry request: When this bit is high, telemetry is hight, the ESC is sends a telemetry information packet from the to the FC. Including information such as: Motor Electrical RPM, ESC Temperature, Supply Voltage, Current (Available only in certain ESCs).
- Cyclic Redundancy Check (CRC): Used to check for data corruption during transmission.

2.3 Pixhawk 4 and PX4 architecture

Flight controllers are the core component of a UAV as they order the ESCs to provide rotor speeds that stabilize and move the aircraft.

2.4 Related Work on ESCs characterization

Chapter 3

Experimental Setup

Chapter 4

ESC charaterization

Chapter 5

Conclusions and Recommendations

Chapter 6

Einige wichtige Hinweise zum Arbeiten mit LaTeX

Nachfolgend wird die Codierung einiger oft verwendeten Elemente kurz beschrieben. Das Einbinden von Bildern ist in LaTeX nicht ganz unproblematisch und hängt auch stark vom verwendeten Compiler ab. Typisches Format für Bilder in LaTeX ist EPS[1] oder PDF[2].

6.1 Gliederungen

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

6.2 Referenzen und Verweise

Literaturreferenzen werden mit dem Befehl `\citep{.}` und `\citet{.}` erzeugt. Beispiele: ein Buch [**?**], ein Buch und ein Journal Paper [**? ?**], ein Konferenz Paper mit Erwähnung des Autors: **?**].
Zur Erzeugung von Fussnoten wird der Befehl `\footnote{.}` verwendet. Auch hier ein Beispiel[3].
Querverweise im Text werden mit `\label{.}` verankert und mit `\cref{.}` erzeugt. Beispiel einer Referenz auf das zweite Kapitel: chapter 6.

6.3 Aufzählungen

Folgendes Beispiel einer Aufzählung ohne Numerierung,

- Punkt 1
- Punkt 2

wurde erzeugt mit:

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

[1] Encapsulated Postscript
[2] Portable Document Format
[3] Bla bla.

Folgendes Beispiel einer Aufzählung mit Numerierung,

1. Punkt 1
2. Punkt 2

wurde erzeugt mit:

```
\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}
```

6.4 Erstellen einer Tabelle

Ein Beispiel einer Tabelle:

Table 6.1: 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}
```

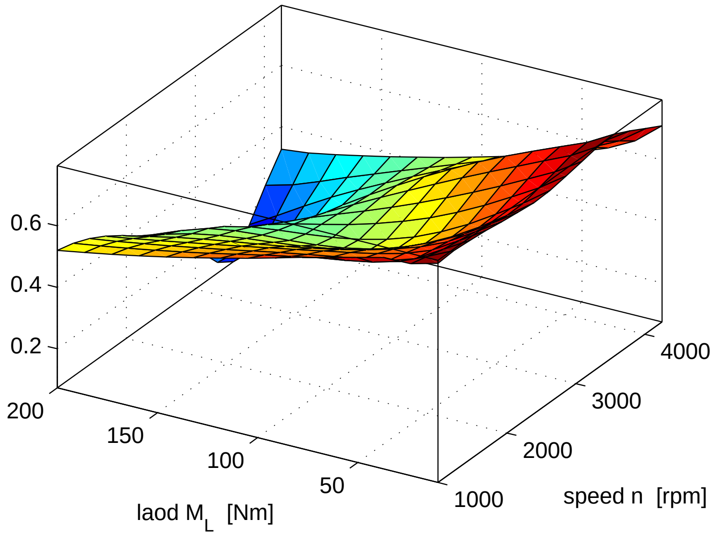

Figure 6.1: Ein Bild

6.5 Einbinden einer Grafik

Das Einbinden von Graphiken kann wie folgt bewerkstelligt werden:

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

6.6 Mathematische Formeln

Einfache mathematische Formeln werden mit der equation-Umgebung erzeugt:

$$p_{me0f}(T_e, \omega_e) \;=\; k_1(T_e) \cdot (k_2 + k_3 S^2 \omega_e^2) \cdot \mathit{\Pi}_{\max} \cdot \sqrt{\frac{k_4}{B}}\,. \tag{6.1}$$

Der Code dazu lautet:

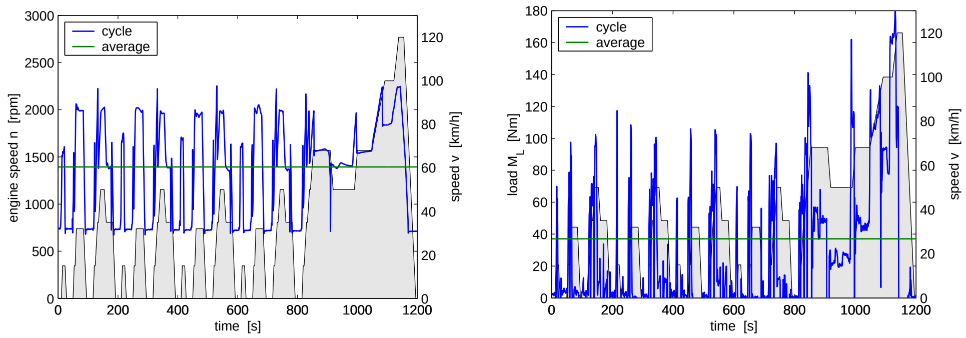

Figure 6.2: Zwei Bilder nebeneinander

```
\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. $\boldsymbol{v}$, $\boldsymbol{M}$).

6.7 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.

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Appendix A

Irgendwas

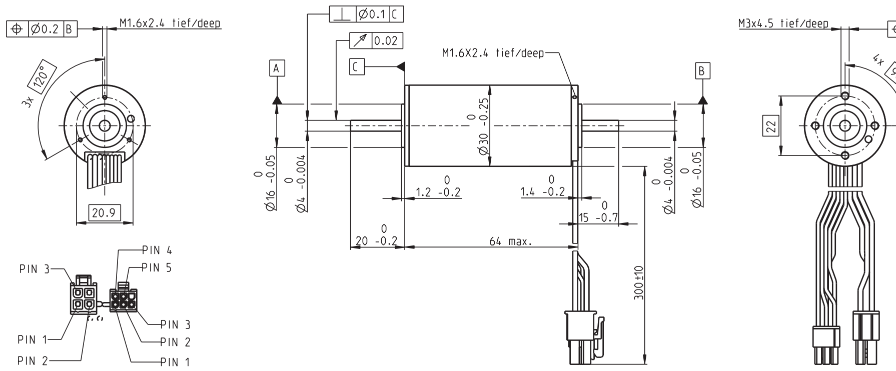
Bla bla ...

Appendix B

Datasheets

EC-max 30 ∅30 mm, brushless, 60 Watt

maxon *EC*-max



M 1:2

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	gcm²	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)

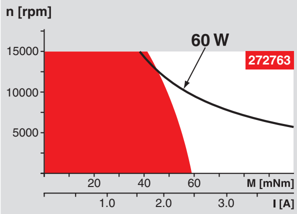
red	Motor winding 1	Pin 1
black	Motor winding 2	Pin 2
white	Motor winding 3	Pin 3
	N.C.	Pin 4
Connector	**Part number**	
Molex	39-01-2040	

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



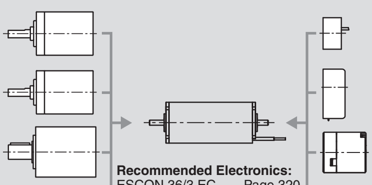
Comments

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

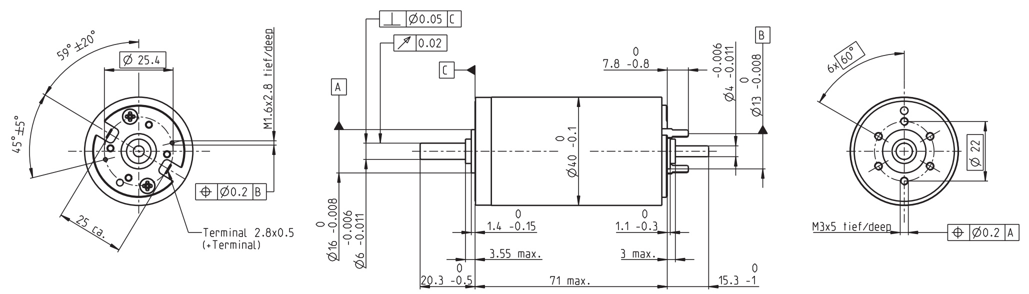
Recommended Electronics:

	Page
ESCON 36/3 EC	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

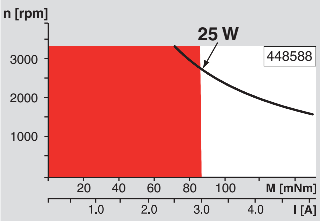
Other specifications

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

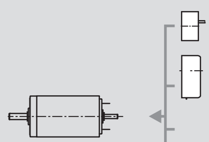
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

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:

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