Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Robotic Systems Lab
Prof. Dr. Marco Hutter

Master Thesis

Obstacle Avoidance and Admittance Control in Human-Robot Joint Collaboration

Spring Term 2018

Supervised by:
Professor Jonathan Kelly
Professor Marco Hutter

Author:
Tobias Ulrich

Declaration of Originality

I hereby declare that the written work I have submitted entitled

Your Project Title

is original work which I alone have authored and which is written in my own words.[1]

Author(s)

Tobias	Ulrich

Student supervisor(s)

Jonathan	Kelly

Supervising lecturer

Marco	Hutter

With the signature I declare that I have been informed regarding normal academic citation rules and that I have read and understood the information on 'Citation etiquette' (`https://www.ethz.ch/content/dam/ethz/main/education/rechtliches-abschluesse/leistungskontrollen/plagiarism-citationetiquette.pdf`). The citation conventions usual to the discipline in question here have been respected.

The above written work may be tested electronically for plagiarism.

Place and date	Signature

[1]Co-authored work: The signatures of all authors are required. Each signature attests to the originality of the entire piece of written work in its final form.

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Place and date　　　　　　　　Signature

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

Chapter 2

Related Work

As with many fields in robotics, Human Robot Interaction (HRI) has seen a lot of developement in the last twenty years. Research has come from teleoperated assistive robots tho dynamically and independently collaborating robots. This advancement is expressed by the newly joined terms in literature to differentiate between types of interaction and level of autonomy for the robot.

Chapter 3

Mobile Manipulator

We conduct or research on a mobile manipulator, lovingly called the *Thing*. It is composed of four main components, on which we elaborate in detail in this chapter. The first is the Ridgeback, a omnidirectional robot platform , followed by the UR10, a six degrees of freedom (DOF) robot arm with a three finger gripper as it's end effector. A force torque sensor is embedded in the wrist of the gripper. The whole manipulator is an out of the box system assembled by Clearpath, which collaborates with Universal Robots and Robotiq and mounts the parts on the platform in house.

3.1 Ridgeback

Table 3.1: Clearpath Ridgeback Specifications

Length	960 mm
Width	793 mm
Height	296 mm
Weight	135 kg
Maximum payload	100 kg
Maximum velocity	1.1 $^{m}/_{s}$
Average power consumption	800 W

The ridgeback is an omnidirectional robot platform designed by Clearpath for indoor movement and payload carrying tasks, such as autonomous warehousing for example. It is a fully integrated system with sensors, actuation and control and features a native ROS interface. Onboard sensors consist of an IMU and a front facing Hokuyo laser range finder (LIDAR) and a Kinect2 camera and wheel odometry. Optionally, a second, rear facing LIDAR can be mounted for full 360 ° coverage.The broad range of sensors, it's flexibility and low drift in odometry makes the Ridgeback a suitable and popular platform for research in controlled indoor environments.
Additionally, the Ridgeback houses the onboard computer that runs the low-level drivers of all the elements of the manipulator. On top thereof, there is a high-level driver that ensures accord and offers a ROS interface for the user to connect to.

3.2 Universal Robot 10

The UR10 is an collaborative industrial robot arm by Universal Robots. It has six rotary joints with gives it six DOF and can support payloads up to 10 kg. Together

Figure 3.1: Clearpath Ridgeback

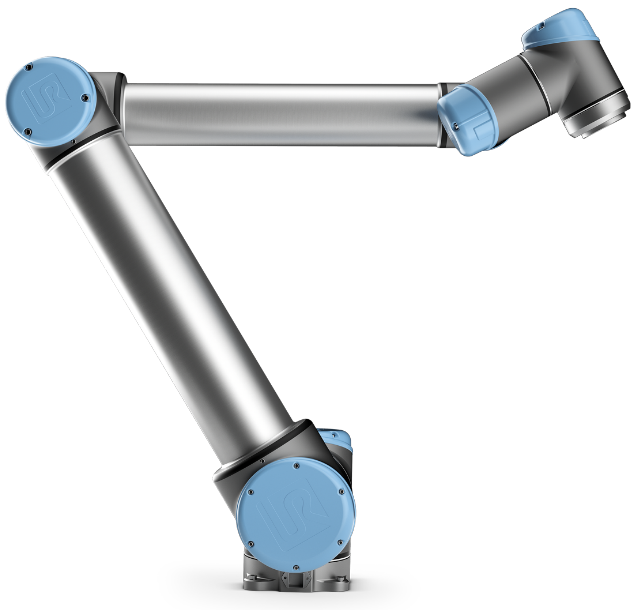


Figure 3.2: Universal Robot 10

Figure 3.3: Robotiq 3-Finger Adaptive Robot Gripper

with it's little brother the UR5, it is widely regarded as the standard manipulator within robotics research. Hence, extensive platform and software integration resources are available and ROS is supported out of the box.

Table 3.2: Universal Robot 10 Specifications

Reach	1300 mm
Weight	1.5 kg
Repeatability	0.1 mm
Maximum payload	10 kg
Maximum tool velocity	1 m/s
Degrees of freedom	6 rotating joints
Average power consumption	W

3.3 Gripper

Table 3.3: Robotiq 3-Finger Adaptive Robot Gripper Specifications

Weight	2.3 kg
Repeatability	0.1 mm
Maximum payload (encompassing grip)	10 kg
Gripper opening	0 to 155 mm
Object diameter for encompassing	20 to 155 mm
Grip force	30 to 70 N
Minimum power consumption	4.1 W
Peak power (at maximum gripping force)	36 W

3.4 Force-Torque Sensor

[1]Signal noise is the standard deviation of the signal measured over a period of one second.

Figure 3.4: Robotiq FT 300 Force Torque Sensor

Table 3.4: Robotiq FT 300 Force Torque Sensor Specifications

Measuring range	
Force F_x, F_y, F_z	$\pm 300\,\mathrm{N}$
Moment M_x, M_y, M_z	$\pm 30\,\mathrm{Nm}$
Signal noise[1]	
Force F_x, F_y, F_z	$0.1\,\mathrm{N}$ / $1\,\mathrm{N}$
Moment M_x, M_y	$0.05\,\mathrm{Nm}$ / $0.02\,\mathrm{Nm}$
Moment M_z	$0.03\,\mathrm{Nm}$ / $0.01\,\mathrm{Nm}$
Data output rate	$100\,\mathrm{Hz}$
Weight	$300\,\mathrm{g}$

Chapter 4

Thing Control Structure

Chapter 5

Admittance Control

Chapter 6

Obstacle Avoidance

6.1 Global Planner

6.2 Local Planner

We use the Dynamic Window Approach (DWA) [1] for local collision avoidance. This well-known algorithm produces command velocities for a planar robot given vehicle dynamics and obstacle measurements. The basic assumption is that the robot moves instantaneously on circular arcs with a translational velocity v and a rotational velocity ω. Thus, the complexity is greatly simplified and calculations are be performed in the 2D velocity space (v, ω). Within this space, we compute three sets of velocity pairs, subsequently called *windows* for every iteration of the algorithm.
The obstacle window V_o are the measurements of any obstacles, e.g. taken by a range laser sensor and transformed from cartesian to v, ω space.
The static window V_s expresses the constraint velocities of the vehicle, i.e., absolute maximum and minimum velocity.
The dynamic window V_d are the vehicle dynamics, i.e., velocities that are physically feasible for the robot to reach within one timestep. It's size is defined by the maximal acceleration and the current velocity of the robot.

$$V_r = V_o \cap V_s \cap V_d \tag{6.1}$$

The resulting window V_r of feasible velocity pairs , that guarantee no collision with an obstacle for the next step is then defined by the intersection of these three sets **??**.
A cost function is then applied to find the (v, ω) pair, that maximizes the objective within V_r. Elements are heading, distance to goal and velocity terms.

Chapter 7

Results

Chapter 8

Conclusions

Chapter 9

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].

9.1 Gliederungen

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

9.2 Referenzen und Verweise

Literaturreferenzen werden mit dem Befehl `\citep{.}` und `\citet{.}` erzeugt. Beispiele: ein Buch [2], ein Buch und ein Journal Paper [2, 3], ein Konferenz Paper mit Erwähnung des Autors: Pratt and Williamson [4].
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 9.

9.3 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}
```

9.4 Erstellen einer Tabelle

Ein Beispiel einer Tabelle:

Table 9.1: 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}
```

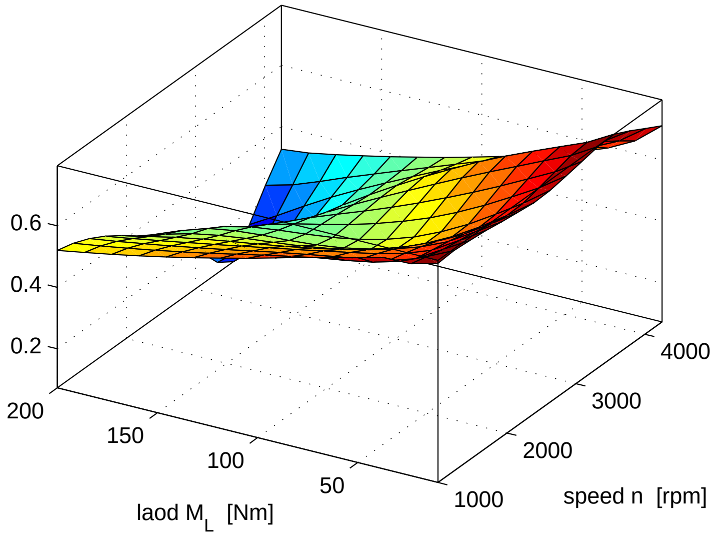


Figure 9.1: Ein Bild

9.5 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}
```

9.6 Mathematische Formeln

Einfache mathematische Formeln werden mit der equation-Umgebung erzeugt:

$$p_{me0f}(T_e, \omega_e) \;=\; k_1(T_e) \cdot (k_2 + k_3 S^2 \omega_e^2) \cdot \mathit{\Pi}_{\max} \cdot \sqrt{\frac{k_4}{B}}\,. \tag{9.1}$$

Der Code dazu lautet:

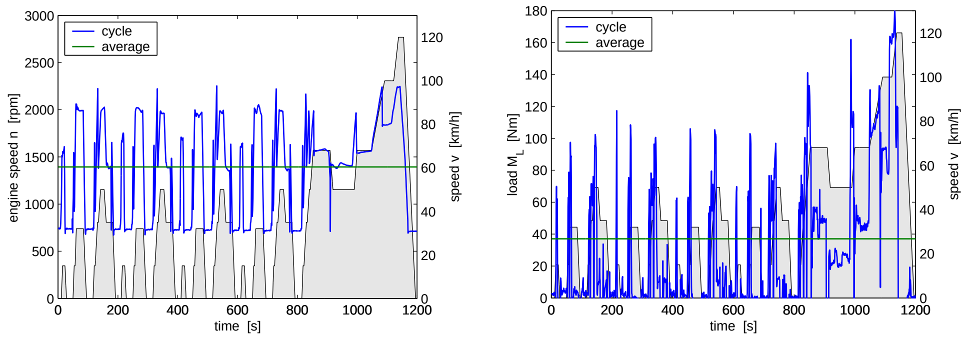


Figure 9.2: Zwei Bilder nebeneinander

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

9.7 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. $1\,\mathrm{m}$) und `\unitfrac[1]{m}{s}` (z.B. $1\,{}^{\mathrm{m}}/_{\mathrm{s}}$) gesetzt.

Bibliography

[1] D. Fox, W. Burgard, and S. Thrun, "The dynamic window approach to collision avoidance," *IEEE Robotics & Automation Magazine*, vol. 4, no. 1, pp. 23–33, 1997.

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

[3] 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.

[4] 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

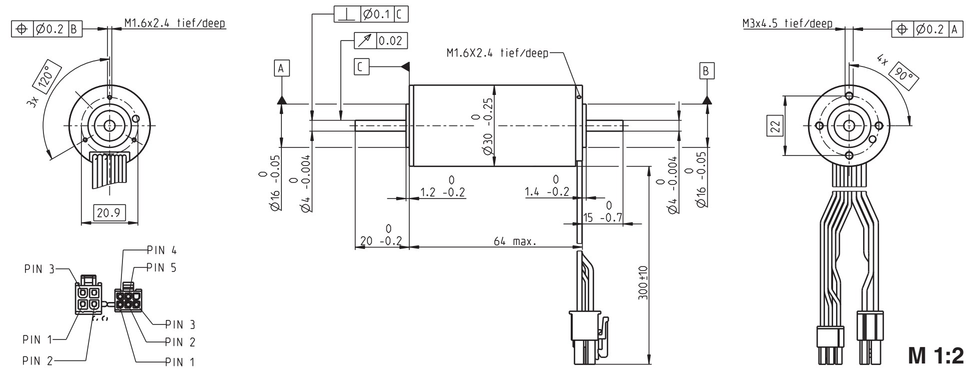
Irgendwas

Bla bla ...

Appendix B

Datasheets

EC-max 30 ∅30 mm, brushless, 60 Watt



Stock program
Standard program
Special program (on request)

Part Numbers

Motor Data		272762	272763	272764	272765
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

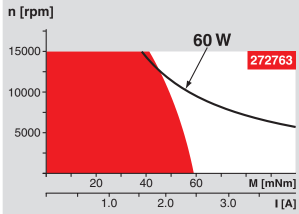
Connector **Part number**
Molex 39-01-2040

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

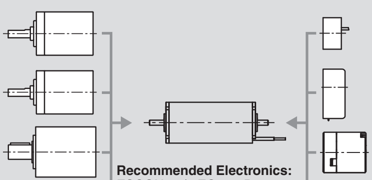
maxon Modular System

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

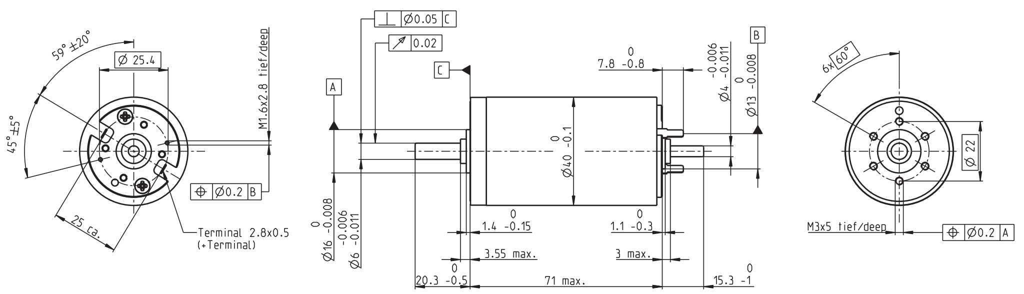
Brake AB 20
24 VDC
0.1 Nm
Page 346

Recommended Electronics:

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



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	gcm^2	142	137	119	121	120

Specifications

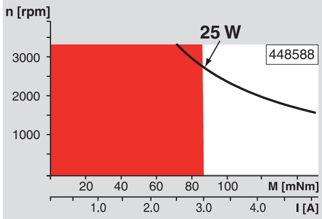
Thermal data

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

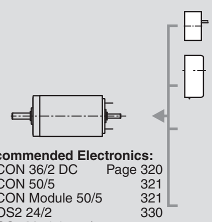
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

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**