

Master Thesis

# Manipulability Optimization and Obstacle Avoidance in Human-Robot Joint Collaboration

Spring Term 2018



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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.<sup>1</sup>

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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.

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Place and date

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Signature

---

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Place and date

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Signature

# Contents

<b>Preface</b>	<b>v</b>
<b>Abstract</b>	<b>vii</b>
<b>Symbols</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 Einige wichtige Hinweise zum Arbeiten mit <math>\text{\LaTeX}</math></b>	<b>3</b>
2.1 Gliederungen . . . . .	3
2.2 Referenzen und Verweise . . . . .	3
2.3 Aufzählungen . . . . .	3
2.4 Erstellen einer Tabelle . . . . .	4
2.5 Einbinden einer Grafik . . . . .	5
2.6 Mathematische Formeln . . . . .	5
2.7 Weitere nützliche Befehle . . . . .	6
<b>Bibliography</b>	<b>7</b>
<b>A Irgendwas</b>	<b>7</b>
<b>B Datasheets</b>	<b>9</b>



# Preface

Bla bla ...





# Abstract

Hier kommt der Abstact hin ...



# Symbols

## Symbols

$\phi, \theta, \psi$	roll, pitch and yaw angle
$b$	gyroscope bias
$\Omega_m$	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 Works

## Chapter 3

# Admittance Control



## Chapter 4

# Obstacle Avoidance

## Chapter 5

# Manipulability Optimization

## Chapter 6

# Results

## **Chapter 7**

# **Discussion**

## Chapter 8

# Future Work

## Chapter 9

# Einige wichtige Hinweise zum Arbeiten mit L<sup>A</sup>T<sub>E</sub>X

Nachfolgend wird die Codierung einiger oft verwendeten Elemente kurz beschrieben. Das Einbinden von Bildern ist in L<sup>A</sup>T<sub>E</sub>X nicht ganz unproblematisch und hängt auch stark vom verwendeten Compiler ab. Typisches Format für Bilder in L<sup>A</sup>T<sub>E</sub>X ist EPS<sup>1</sup> oder PDF<sup>2</sup>.

### 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 [? ], 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<sup>3</sup>.

Querverweise im Text werden mit `\label{.}` verankert und mit `\cref{.}` erzeugt. Beispiel einer Referenz auf das zweite Kapitel: chapter 2.

### 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}
```

---

<sup>1</sup>Encapsulated Postscript

<sup>2</sup>Portable Document Format

<sup>3</sup>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
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}
```

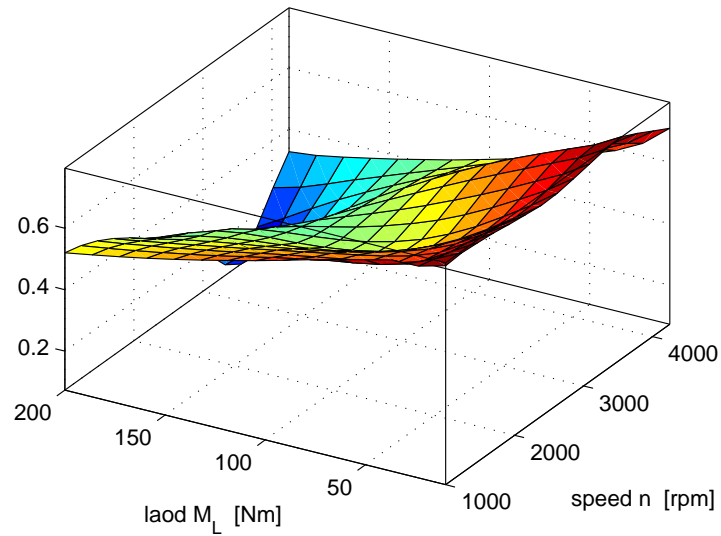


Figure 9.1: Ein Bild

## 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:

$$p_{me0f}(T_e, \omega_e) = k_1(T_e) \cdot (k_2 + k_3 S^2 \omega_e^2) \cdot \Pi_{\max} \cdot \sqrt{\frac{k_4}{B}}. \quad (9.1)$$

Der Code dazu lautet:



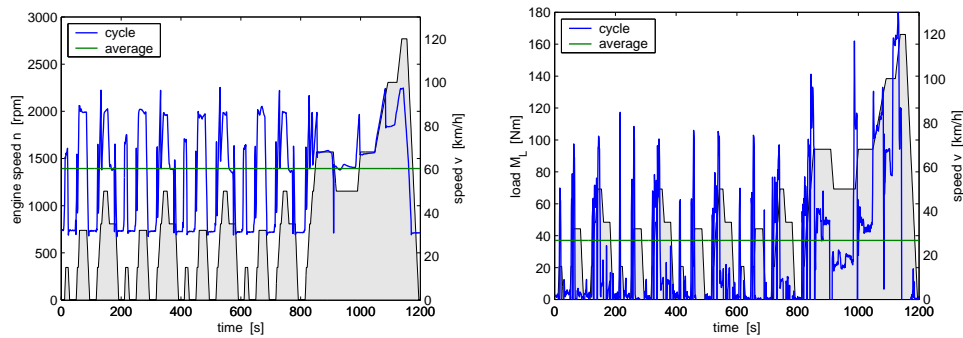


Figure 9.2: Zwei Bilder nebeneinander

```

\begin{equation}
p_{\text{meOf}}(T_e, \omega_e) \setminus = \setminus k_1(T_e) \setminus \text{cdot} (k_2 + k_3 S^2
\omega_e^2) \setminus \text{cdot} \setminus \Pi_{\text{max}} \setminus \text{cdot} \setminus \sqrt{\frac{k_4}{B}} \setminus , .
\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  $\backslash\text{vec}\{.\}$  und  $\backslash\text{mat}\{.\}$  erzeugt  
 (z.B.  $\mathbf{v}$ ,  $\mathbf{M}$ ).

## 9.7 Weitere nützliche Befehle

Hervorhebungen im Text sehen so aus: *hervorgehoben*. Erzeugt werden sie mit dem  $\backslash\text{epmh}\{.\}$  Befehl.

Einheiten werden mit den Befehlen  $\backslash\text{unit}[1]\{\text{m}\}$  (z.B. 1 m) und  $\backslash\text{unitfrac}[1]\{\text{m}\}\{\text{s}\}$  (z.B. 1 m/s) gesetzt.



# Appendix A

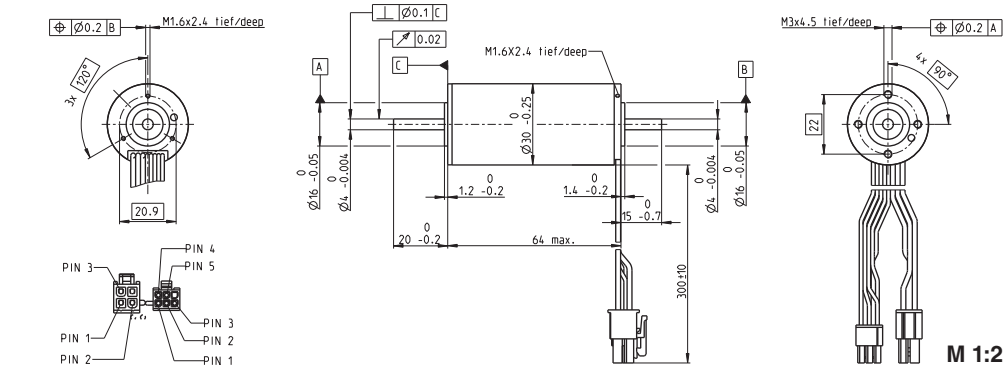
## Irgendwas

Bla bla ...



# Appendix B

## Datasheets

**EC-max 30** Ø30 mm, brushless, 60 Watt

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

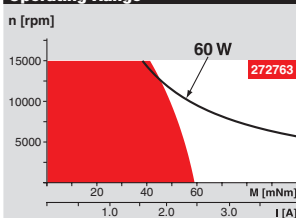
<b>Connection motor</b> (Cable AWG 20)	
red	Motor winding 1 Pin 1
black	Motor winding 2 Pin 2
white	Motor winding 3 Pin 3
N.C.	N.C. Pin 4

<b>Connector</b>	Part number
Molex	39-01-2040

<b>Connection Sensors</b> (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 <sub>DD</sub> 3...24 VDC Pin 5
N.C.	N.C. Pin 6

<b>Connector</b>	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****Planetary Gearhead**

Ø32 mm

8.0 Nm

Page 266

**Koaxdrive**

Ø32 mm

1.0 - 4.5 Nm

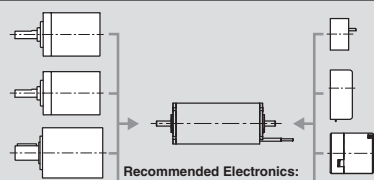
Page 268

**Planetary Gearhead**

Ø42 mm

3 - 15 Nm

Page 271

**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

**Overview on page 20 - 25**

**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

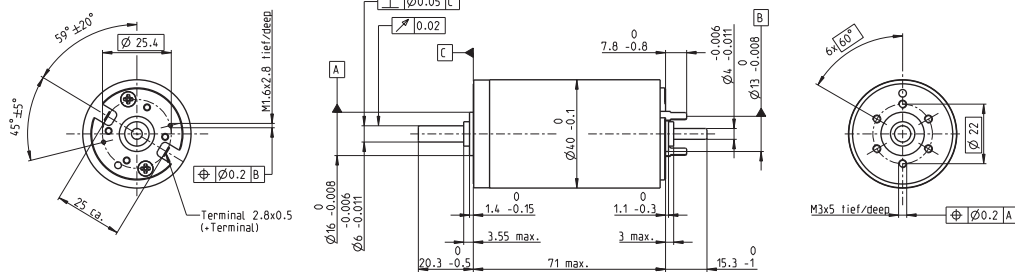
maxon EC motor 193

maxon EC-max

# RE 40 Ø40 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
<b>Values at nominal voltage</b>						
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
<b>Characteristics</b>						
10 Terminal resistance	Ω	0.311	1.14	2.49	6.43	9.97
11 Terminal inductance	mH	0.0624	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 <sup>2</sup>	142	137	119	121	120

## Specifications

<b>Thermal data</b>	
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

<b>Mechanical data (ball bearings)</b>	
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) (static, shaft supported)	110 N
28 Max. radial loading, 5 mm from flange	1200 N
	28 N

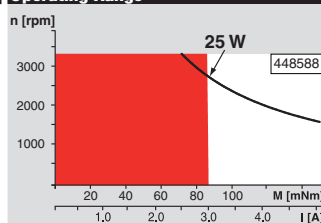
<b>Other specifications</b>	
29 Number of pole pairs	1
30 Number of commutator segments	13
31 Weight of motor	480 g

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

