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]

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| Tobias | Ulrich |

**Student supervisor(s)**

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|---|---|
| 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.

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| | |
|---|---|
| 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

| | |
|---|---|
| $\phi, \theta, \psi$ | 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

# Mobile Manipulator

We conduct or research on a mobile manipulator, lovingly called the *Thing*. It is composed of three main components, on which we elaborate in detail in this chapter. A robot platform is the first, follow by a 6-DOF robot arm with a gripper at it's end. A force torque sensor is embedded, in the wrist of the gripper. The manipulator is an out of the box product bought from Clearpath, which collaborate with UR and Robotiq and mount the parts on the platform in house.

## 3.1 Ridgeback

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.

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 |

## 3.2 Universal Robot 10

## 3.3 Gripper and Force-Torque Sensor

Chapter 4

# Admittance Control

# Chapter 5

# Obstacle Avoidance

# Chapter 6

# Results

## Chapter 7

# Discussion

# Chapter 8

# Future Work

# 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 [**?** ], 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 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}
```

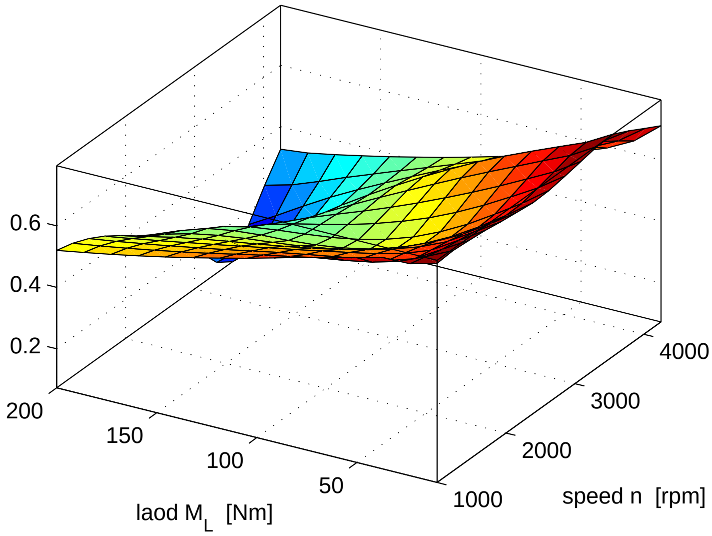



Figure 9.1: Ein Bild

## 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:

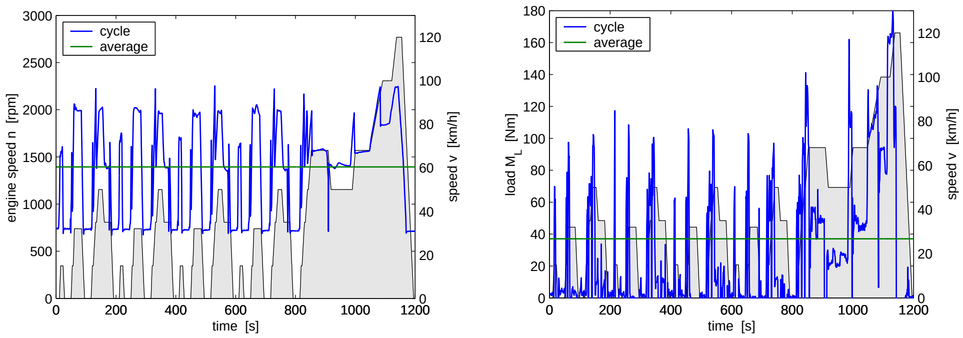



Figure 9.2: Zwei Bilder nebeneinander

```
\begin{equation}
 p_{meOf}(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 m) und `\unitfrac[1]{m}{s}` (z.B. 1 m/s) gesetzt.

# Appendix A

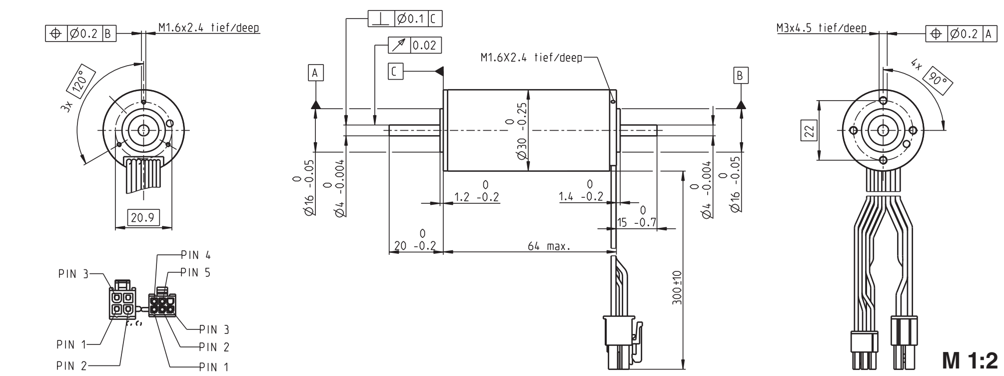
# Irgendwas

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)

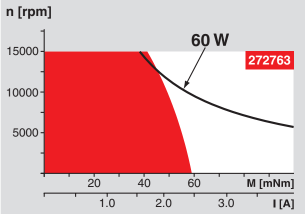
| | | |
|---|---|---|
| red | Motor winding 1 | Pin 1 |
| black | Motor winding 2 | Pin 2 |
| white | Motor winding 3 | Pin 3 |
| | N.C. | Pin 4 |
| **Connector** | **Part number** | |
| Molex | 39-01-2040 | |

**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**

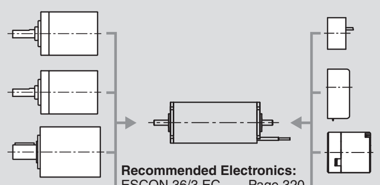
## maxon Modular System

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

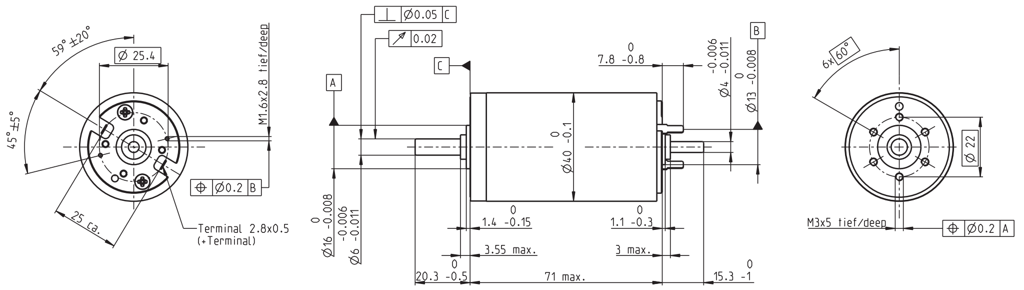
**Recommended Electronics:**

| | |
|---|---|
| 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

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 |

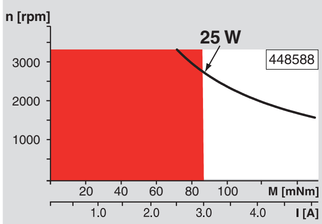
**Other specifications**

| | | |
|---|---|---|
| 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

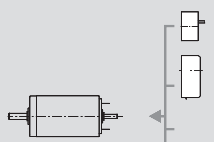
**Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

**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:**

| | Page |
|---|---|
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| 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 |
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