ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Autonomous Systems Lab
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Master Thesis

Morphology Optimization of a Tilt-Rotor MAV

Spring Term 2018

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Declaration of Originality

I hereby declare that the written work I have submitted entitled

Morphology Optimization of a Tilt-Rotor MAV

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

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Place and date	Signature

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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

Introduce Problem Presentation Literatur review Goals [1] [2] [3] [4] [5] [6] [7] [8] [9]

Chapter 2

Optimization Problem

Define morphology optimization problem

Chapter 3

Modelling

Describe the modeling for the optimization engine

Chapter 4

Results

Show results produced by the engine. $\cos(\beta) = \sqrt{(\frac{2}{3})} => \beta = 35.26°$
$F_{min} = 34.74, F_{max} = 42.55, M_{min} = 17.42, M_{max} = 21.34, H_{eff,min} = 81.65\%, H_{eff,max} = 100\%$
$F_{min} = 26.6, F_{max} = 52.11, M_{min} = 15.1, M_{max} = 26.13, H_{eff,min} = 75\%, H_{eff,max} = 100\%$
Design 1: $F_{min} = 23.18, F_{max} = 28.56, M_{min} = 11.61, M_{max} = 14.3, H_{eff,min} = 81.11\%, H_{eff,max} = 95.2\%$
Design 2: $F_{min} = 23.22, F_{max} = 28.37, M_{min} = 11.65, M_{max} = 14.23, H_{eff,min} = 81.65\%, H_{eff,max} = 94.73\%$
$F_{min} = 44.7, F_{max} = 58.8, M_{min} = 22.4, M_{max} = 29.5, H_{eff,min} = 81.78\%, H_{eff,max} = 96.65\%$
$F_{min} = 46.46, F_{max} = 56.73, M_{min} = 23.3, M_{max} = 28.45, H_{eff,min} = 81.64\%, H_{eff,max} = 94.77\%$

Chapter 5

Result Evaluation

Evaluate results in simulation.

Chapter 6

Conclusion

Bibliography

[1] D. Brescianini and R. D'Andrea, "Design, modeling and control of an omni-directional aerial vehicle," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, May 2016, pp. 3261–3266.

[2] A. Nikou, G. C. Gavridis, and K. J. Kyriakopoulos, "Mechanical design, modelling and control of a novel aerial manipulator," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, May 2015, pp. 4698–4703.

[3] M. Kamel, S. Verling, O. Elkhatib, C. Sprecher, P. Wulkop, Z. Taylor, R. Siegwart, and I. Gilitschenski, "Voliro: An Omnidirectional Hexacopter With Tiltable Rotors," *arXiv:1801.04581 [cs]*, Jan. 2018, arXiv: 1801.04581.

[4] M. Tognon and A. Franchi, "Omnidirectional Aerial Vehicles with Unidirectional Thrusters: Analysis, Optimal Design, and Motion Control," *IEEE Robotics and Automation Letters*, p. 11, 2018.

[5] S. Rajappa, M. Ryll, H. H. Bülthoff, and A. Franchi, "Modeling, control and design optimization for a fully-actuated hexarotor aerial vehicle with tilted propellers," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, May 2015, pp. 4006–4013.

[6] R. Rashad, P. Kuipers, J. Engelen, and S. Stramigioli, "Design, Modeling, and Geometric Control on SE(3) of a Fully-Actuated Hexarotor for Aerial Interaction," *arXiv:1709.05398 [math]*, Sep. 2017, arXiv: 1709.05398.

[7] S. Park, J. Her, J. Kim, and D. Lee, "Design, modeling and control of omni-directional aerial robot," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2016, pp. 1570–1575.

[8] M. Ryll, H. H. Bülthoff, and P. R. Giordano, "Modeling and control of a quadrotor UAV with tilting propellers," in *2012 IEEE International Conference on Robotics and Automation*, May 2012, pp. 4606–4613.

[9] M. Burri, J. Nikolic, H. Oleynikova, M. W. Achtelik, and R. Siegwart, "Maximum likelihood parameter identification for MAVs," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, May 2016, pp. 4297–4303.

Appendix A

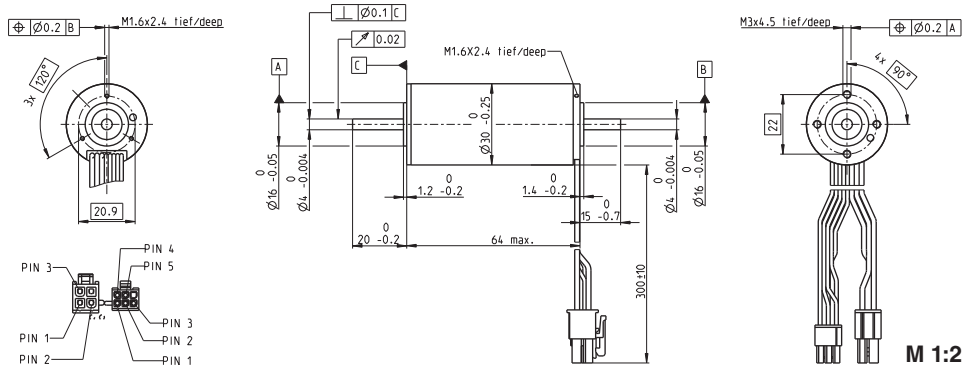
Irgendwas

Bla bla ...

Appendix B

Datasheets

EC-max 30 ∅30 mm, brushless, 60 Watt



Stock program
Standard program
Special program (on request)

Motor Data		Part Numbers 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

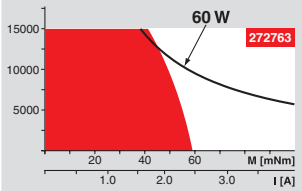
Connection Sensors (Cable AWG 26)

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

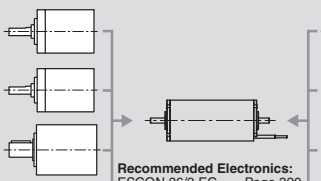
maxon Modular System

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



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**

Encoder MR
500/1000 CPT,
3 channels
Page 302

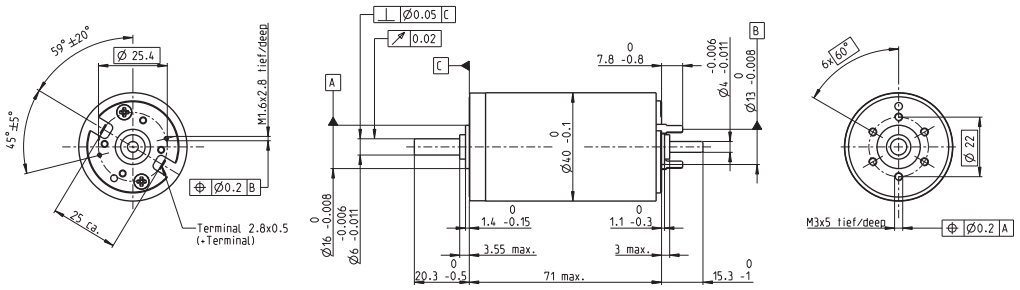
Encoder HEDL 5540
500 CPT,
3 channels
Page 308

Brake AB 20
24 VDC
0.1 Nm
Page 346

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

NEW

maxon DC motor



M 1:2

Stock program
Standard program
Special program (on request)

	Motor Data	Unit	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

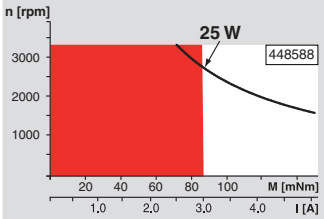
Specifications

	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



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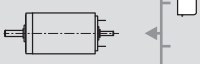
maxon Modular System

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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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**