ESAIL D3.2.2
Design Description
Main Tether Reel

Work Package: **WP 3.2**

Version: **Version 1.0**

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Document Change Record

Issue	Rev.	Date	Pages, Tables, Figures affected	Modification	Name
1	0	30 November 2011	All	Initial issue	Rosta

Table of Contents

List of Acronym and Abbreviation

DLR	Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center)
ESAIL	Electric Sail
EU	European Union
FP-7	Seventh Framework Programme
EPS	Electrical Power Subsystem
OBDH	On board data Handling Subsystem
UH	University of Helsinki
ECSS	European Cooperation on Space Standardization
AMTAG	Alfred MerelbachTechnologie AG

Reference Documents

RD-1	ESAIL Proposal - Part B: Description of Work
RD-2	D3.2.1, Requirements specification of the main tether reel
RD-3	ECSS-E-30 Part 3A Mechanical
RD-4	D3.1.2, Reeling Test plan

1. Scope of this document

This document describes the design of the main tether deployment mechanism [RD-01]. This document is a deliverable item of the EU-FP7 funded Esail-Project.
It includes a detailed description of the CAD main reel concept and a description of the assembled deployment mechanism.

2. Main Reel Deployment Mechanism Design

The following chapter describes the detailed design of the main reel. The chapter includes the motor selection and the design description of the several parts.

2.1.System Overview

The system overview of the deployment system is shown in Figure 8. It shows the several parts and the connections between each other.

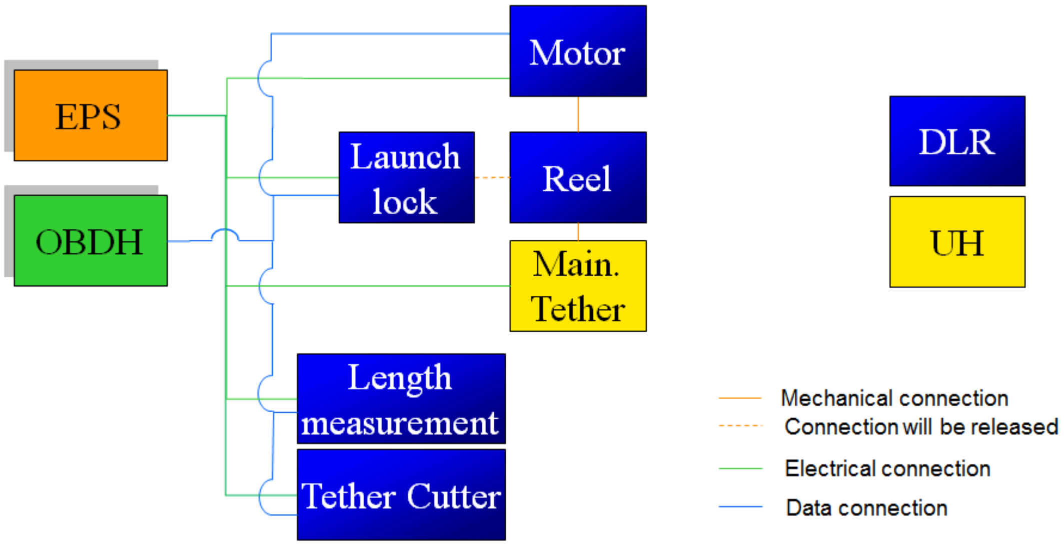


Figure 1: System overview

The blue boxes in Figure 8 are the components of the deployment mechanism. The colored lines are the different connections between the deployment mechanism and the other subsystems of the main spacecraft. The deployment mechanism consists of the tether reel, the motor, the launch lock, the length measurement system and the tether cutter. All parts excluding the reel are electrical connected to the EPS for power supply as well as to the OBDH of the main spacecraft. The motor receives control parameter for rotation speed from the OBDH. To control the unreeling speed as well as the tether length, the length measurement sub system received and transmits data to the OBDH. The launch lock is required to fix the reel unless the signal from the OBDH unlocks the reel for the tether deployment. In case of an failure of the motor the OBDH send a commend to cut the tether, therefore an electrical and data connection to the tether cutter is necessary.

2.2.Geared Motor

The selection of the motor has two main drivers. The first is the required torque and the second is the low rotation speed.

The required torque is calculated as required in MCS-331-03 with a tension load of 0.05 N and a maximal diameter of 300 mm for the tether reel [RD-2].

The tether length on the reel is defined for the Heytether. The Heytether consist of one main wire on which three auxiliary wires are bonded [RD-4].The diameter for the calculation is 0.1 mm. This is the double of the main wire diameter. The multiplication by two is done because the worst case bonding position of two auxiliary wires is direct opposite on the main wire, this will increase the diameter to 0.1 mm.

With the difference of the external and internal radius and the thickness of the tether the layers on top of each other can be calculated with

$$N_L = (r_e - r_i) / t.$$

With this equation $N_L = 750$. The reel has a width of 40 mm with an 1 mm distance between the next main wire it is possible to reel 50 layers side by side.

To calculate the whole tether length the following equation was used

$$L = 2 * \pi * (r_1 + \sum_{n=2}^{NL} (r_n + t))$$

with $r_1 = r_e + t$. The outcome of this is L = 21.1 km tether length.

To improve the reliability of the deployment mechanism the motor required torque calculated above was again calculated with the ECSS document [RD-3].

$$T_{min} = 2.0\, x(1.11 I_T + 1.2S + 3F_R + 3H_Y + 3H_A + 3H_D) + 3T_L.$$

The different factors and their denotation are listed in Table 1.

Component of resistance	Symbol	Factor
Inertia	I_T (or I_F)	1,1
Spring	S	1,2
Friction	F_R	3 # (1,5)
Hysteresis	H_Y	3 # (1,5)
Others (harness)	H_A	3 # (1,5)
Adhesion	H_D	3

Table 1: Minimum uncertainty factors [RD-3]

In the case of the main tether deployment the inertia is calculated with reel mass m_d = 1.06 kg and a reel diameter r_d = 0.3 m. With these values it is I_T = 0.0477 kgm².

The friction in this system is assumed to be F_r= 0.0301 N

The also needed value for the tether bending force is calculated with the static beam equation. The calculated force F_b = 0.153 N.

The required torque according to the ECSS simplified to

$$T_{min} = 2.0\,x(1.11 I_T + 3F_r + 3F_b) + 3T_L.$$

Therefore the required Torque is 29.76 Ncm.

To accomplish this required torque the brushless DC servomotor with an planetary gear from Faulhaber company was chosen. The motor with the denotation 1628 B has a torque of 2.6 mNm. With the gearbox 16/7 and a reduction of 256:1 the generated torque is 0.3 Nm. To drive the motor, a motion controller MCBL 3003 S/C with a RS232/CAN interface is chosen. For all three components the data sheet are listed in chapter 3.

For the implementation the gear and motor is realized in CAD, and shown in Figure 2.

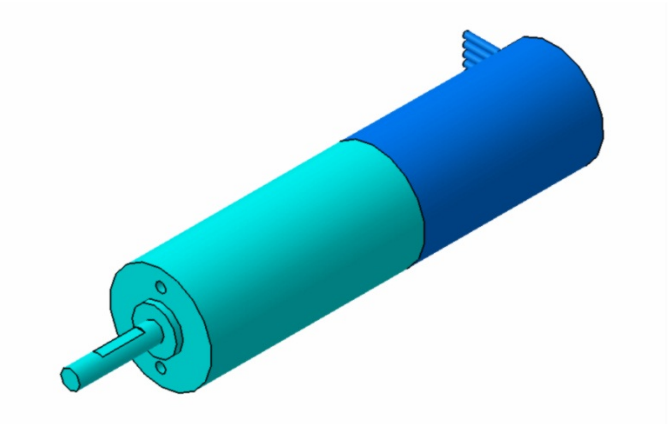


Figure 2: Motor 1628 B combined with 16/7 gearbox

2.3. Design details of deployment mechanism

2.3.1. Modularity of the deployment mechanism

The main reel deployment mechanism is designed to unreel the Heytether. Furthermore the deployment mechanism must be capable to cut the tether in case of a malfunction. This is necessary to avoid the mission failure if one deployment mechanism fails. That means if one deployer fails the remote unit on the end of the tether cannot be unreeled further and will lead to a not fully deployed sail. To avoid this, the tether must be cut. Although the cut tether will be unsuitable, the remote unit can be further deployed and the whole mission can be continued.

The main idea behind that concept was to find a deployment solution which can be used for every space craft configuration independent from the number of tethers which was resulting in a modular built structure of the deployment mechanism.

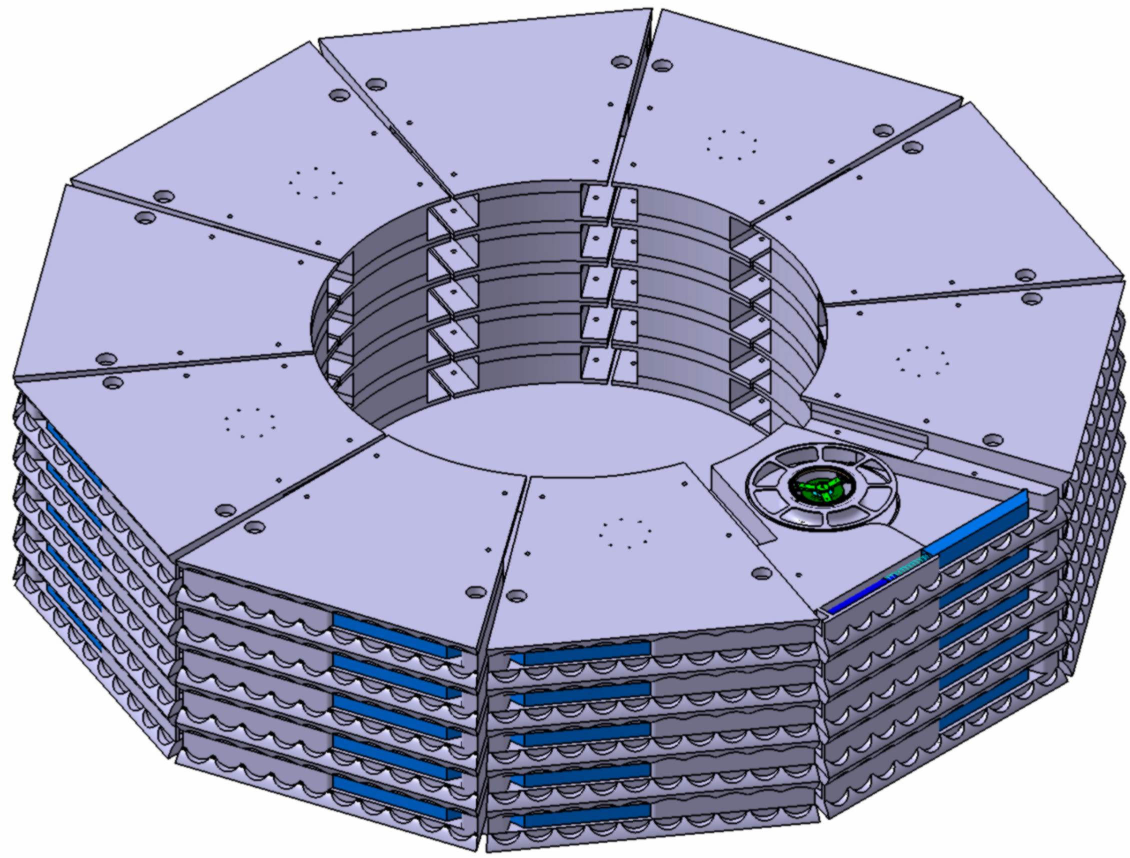


Figure 3: Spacecraft configuration with 50 main tethers

Figure 3 shows a possible configuration of the main reel deployment mechanism in case of a spacecraft with 50 main tethers. The figure shows that the tether opening has a variable position on the left and right side. Due to the placement of the remote units, favorable as close as possible to each other, the side of the opening has to be changed to have a continuous remote unit distance. The dotted line shows the placement of the remote units on two stacks.

Therefore, with this main reel deployment mechanism design every possible spacecraft configuration is feasible.

The support structure of the deployment mechanism has a shape which has similarity to a trapeze. This shape is caused by the main tether reel configuration in case of a full scale mission as well as the modularity. In this case the main

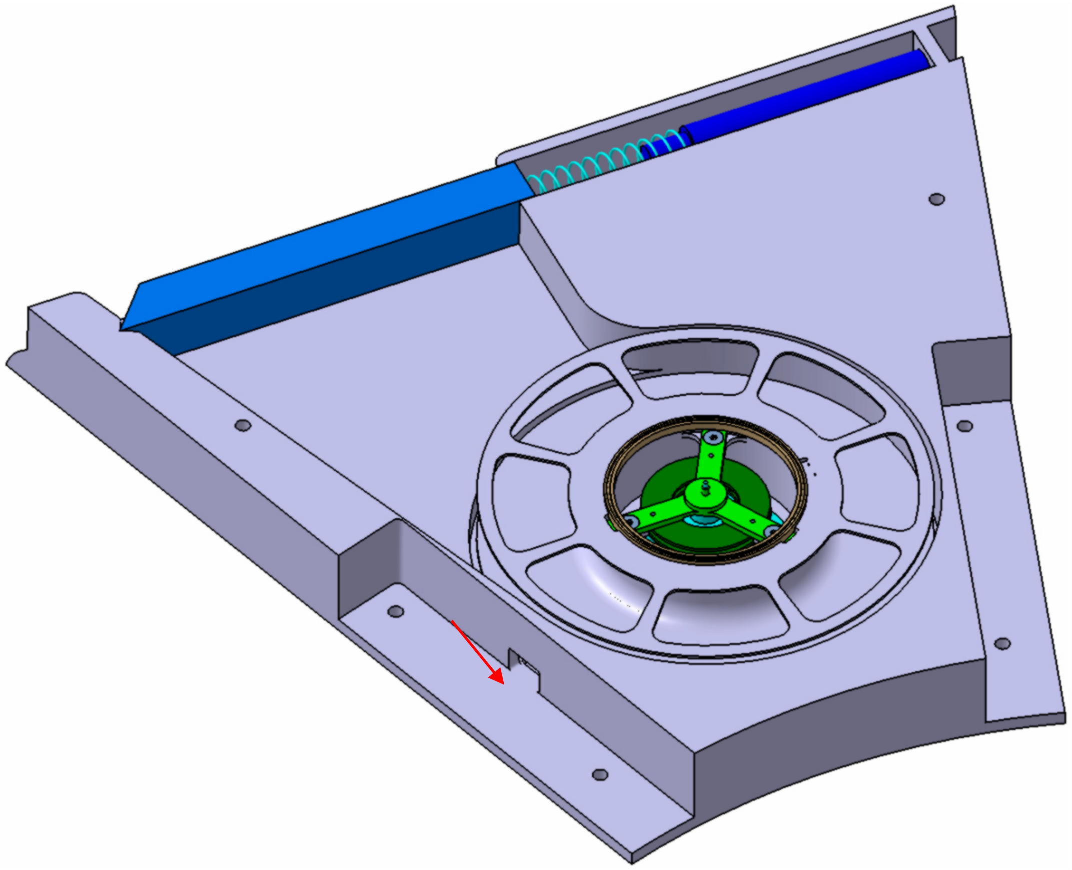


Figure 4: Deployment mechanism main reel

spacecraft has an external diameter of 1.5 m and should have 10 tethers on the same level. And with this trapeze shape it will be possible to use the whole available volume as good as possible. On the front part of the structure the attachment points for the remote units are placed. These attachment points are only place holders, because the final design of the remote unit was not finished while this description was written. On the side of the support structure the electrical and data connection is placed, marked with an arrow. Through this connection point the motor supply power, the driving commands and the telemetry of the motor as well as the main tether power supply are conducted.

Behind the front, the tether cutter is placed (blue in Figure 4). The tether cutter consists of three parts: the sliding blade (light blue), the spring (turquoise) and the base cylinder (dark blue) with the release mechanism. The sliding blade is made of a polyimide with a low friction factor like. The spring is used to create the force to cut the tether. The breaking force of the tether is about 15g. To cut the tether a force of 0.2 N is needed. The final design is still in an evaluation phase and will be finished soon. Therefore only the geometrical dimensions are fixed to make sure that the cutter will fit in the support structure (gray). The sliding blade is locked with a dynemar melting wire. In case of a malfunction, the wire will be melt and unlock the sliding blade which will be accelerate to the spring and cut the tether if the top it the wall of the support structure.

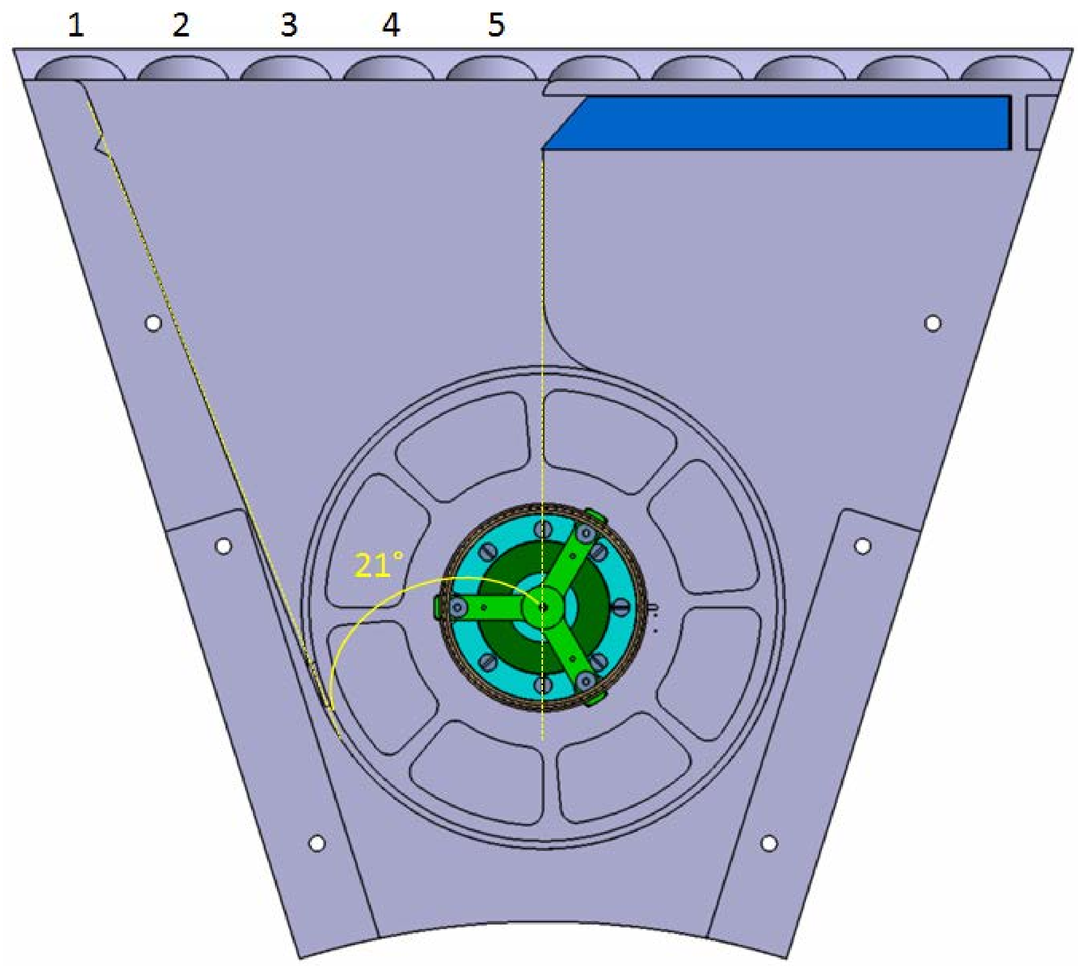


Figure 5: Top view of the deployment mechanism

The opening angel of the tether bay is 21° (shown in Figure 5). Due to the fact that the deployment mechanism is modular the palace of the attached remote unit is unknown. There are five possible attachment points which begin at the middle of the support structure to the outside. They are numbered in Figure 5 with the numbers from one to five. Due to the fact that every position could be needed which depends on how the remote units will be placed on the main space craft, the tether bay should cover every of the five attachment points.

The tether reel has an diameter of 300 mm and a total height of 44 mm

The reel is mounted to a rotation transmitter (light green in Figure 6). This part is only for the transmission of the rotation from the motor to the tether reel and therefore it is mounted with a press fit to the motor axis and with screws to the reel. Additional on this part the slip ring is mounted. The slip ring (colored dark green) is electrical connected to the main tether, bonded on the slip ring, which comes through the small hole on the side (see arrow in Figure 6). To separate the electrical and mechanical connection the main tether will be fixed with two grub screws on the main reel. These are the small spots nearby the marked tether hole in Figure 6.

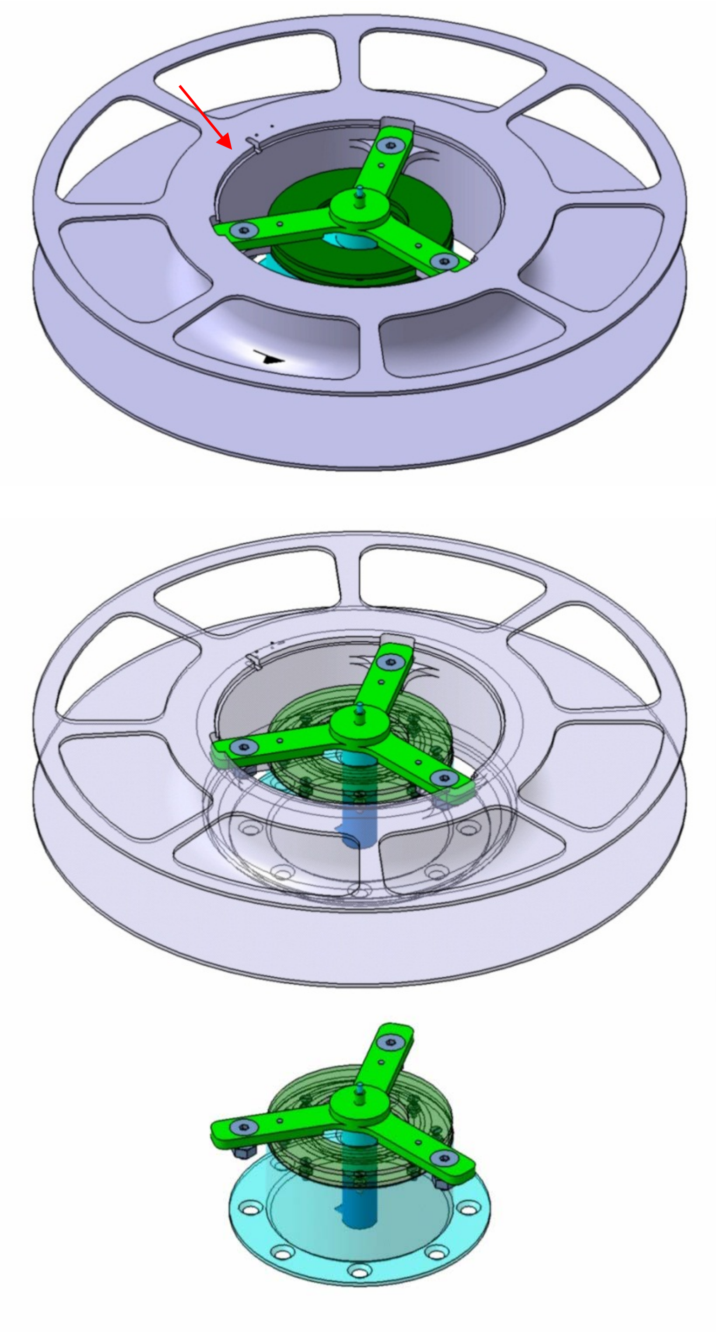


Figure 6: Reel configuration, on top the position of the tether hole is marked with an arrow, in the middle the reel (gray) and the motor holder (turquoise) are Transparent to show the position of the motor, below the ... is shown without the reel

The pair of the slip ring is the contactor, mounted on the motor holder (turquoise in Figure 6), to realize the electrical contact between the high voltage source of the space craft and the main tether. The slip ring is manufactured by the “RieTech” company.

To separate the mechanical loads from the motor axis the reel is placed on two angular thin section bearings (colored brown in Figure 7).

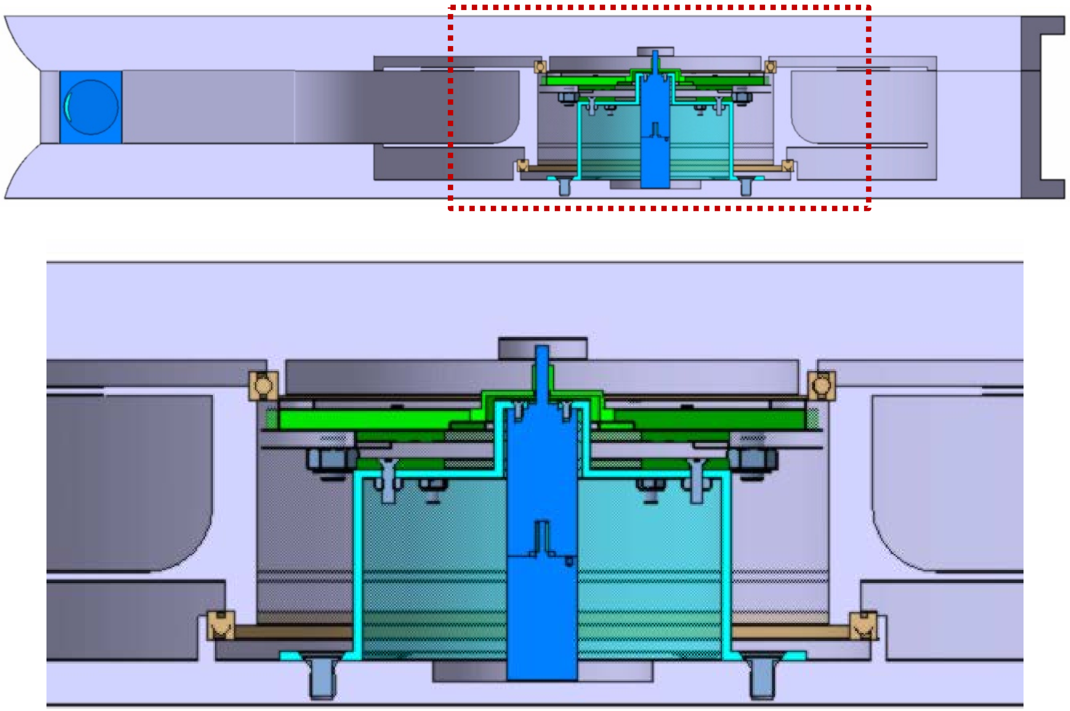


Figure 7:Section view of the reel axis: on top the whole deployment mechanism with cutter and cut out; below cut out: ball bearings (light brown), motor holder (turquoise), motor with gear box (blue), Slip ring and slip ring contactor (dark green), torque transmitter (light green), screws (dark gray), reel (gray), support structure (gray)

3. Appendix

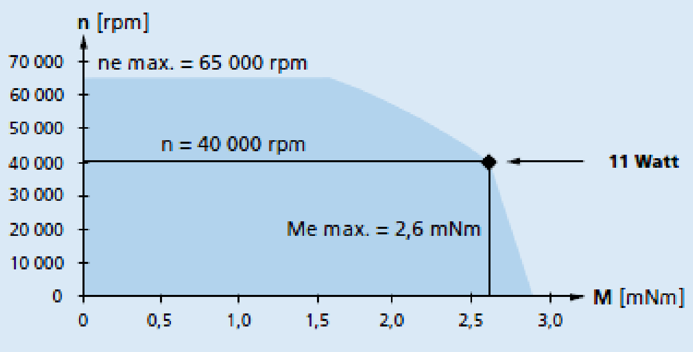
Bürstenlose DC-Servomotoren 2,6 mNm

Kombinierbar mit
Getriebe:
16/7
Encoder:
IE2-1024
Steuerungen:
Speed Controller, Motion Controller

Serie 1628 ... B

	1628 T			012 B	024 B	
1	Nennspannung	U_N		12	24	Volt
2	Anschlusswiderstand, Phase-Phase	R		4,3	15,1	Ω
3	Abgabeleistung [1]	$P_{2\,max.}$		10	11	W
4	Wirkungsgrad	$\eta_{max.}$		68	68	%
5	Leerlaufdrehzahl	n_o		28 650	29 900	rpm
6	Leerlaufstrom (bei Wellen ø 1,5 mm)	I_o		0,098	0,052	A
7	Anhaltemoment	M_H		11	12	mNm
8	Reibungsdrehmoment, statisch	C_o		0,15	0,15	mNm
9	Reibungsdrehmoment, dynamisch	C_v		$8{,}0 \cdot 10^{-6}$	$8{,}0 \cdot 10^{-6}$	mNm/rpm
10	Drehzahlkonstante	k_n		2 474	1 287	rpm/V
11	Generator-Spannungskonstante	k_E		0,404	0,777	mV/rpm
12	Drehmomentkonstante	k_M		3,86	7,42	mNm/A
13	Stromkonstante	k_I		0,259	0,135	A/mNm
14	Steigung der n-M-Kennlinie	$\Delta n/\Delta M$		2 737	2 610	rpm/mNm
15	Anschlussinduktivität, Phase-Phase	L		141	525	µH
16	Mechanische Anlaufzeitkonstante	τ_m		15	14	ms
17	Rotorträgheitsmoment	J		0,54	0,54	gcm²
18	Winkelbeschleunigung	$\alpha_{max.}$		198	217	·10³rad/s²
19	Wärmewiderstände	R_{th1} / R_{th2}	7,8 / 30,1			K/W
20	Thermische Zeitkonstante	τ_{w1} / τ_{w2}	8 / 379			s
21	Betriebstemperaturbereich		– 30 ... +125			°C
22	Wellenlagerung		Kugellager, vorgespannt			
23	Wellenbelastung, max. zulässig:					
	– radial bei 3 000/20 000 rpm (4,5 mm vom Befestigungsflansch)		17 / 10			N
	– axial bei 3 000/20 000 rpm (auf Druckbelastung)		10 / 6			N
	– axial im Stillstand (auf Druckbelastung)		20			N
24	Wellenspiel:					
	– radial	≤	0,015			mm
	– axial	=	0			mm
25	Gehäusematerial		Aluminium, schwarz eloxiert			
26	Gewicht		31			g
27	Drehrichtung		ansteuerungsbedingt			
Empfohlene Werte - diese gelten unabhängig voneinander						
28	Drehzahl bis [2]	$n_{e\,max.}$		65 000	65 000	rpm
29	Dauerdrehmoment bis [1,2]	$M_{e\,max.}$		2,5	2,6	mNm
30	Thermisch zulässiger Dauerstrom [1,2]	$I_{e\,max.}$		0,77	0,41	A

[1] bei 40 000 rpm,
[2] Wärmewiderstand R_{th2} um 55% reduziert



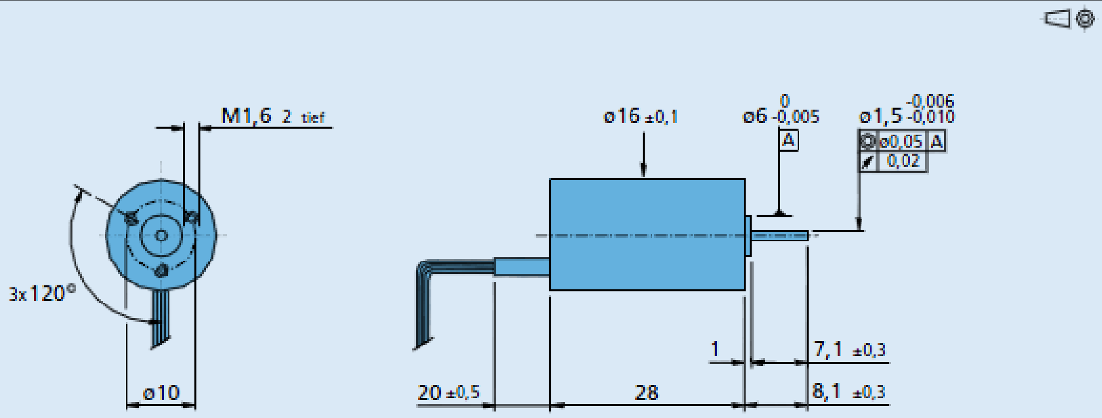
Empfohlener Bereich für Dauerbetrieb

Angaben zu Gewährleistung und Lebensdauer sowie weitere technische Erläuterungen siehe „Technische Informationen".
Edition 2011 – 2012

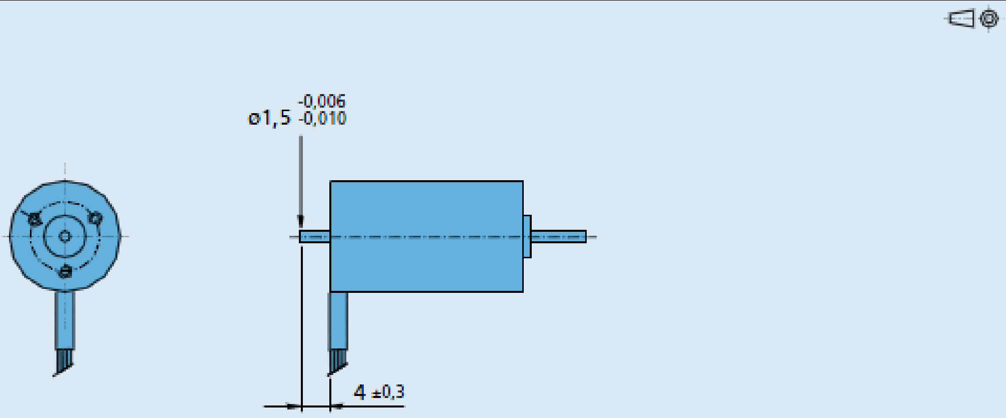
Seite 1/2

Sonderausführungen
K1000:
Motoren in sterilisierbarer Ausführung.
K1155:
Motoren für den Betrieb mit Motion Controller MCBL 3003 S/C, MCBL 3006 S/C.

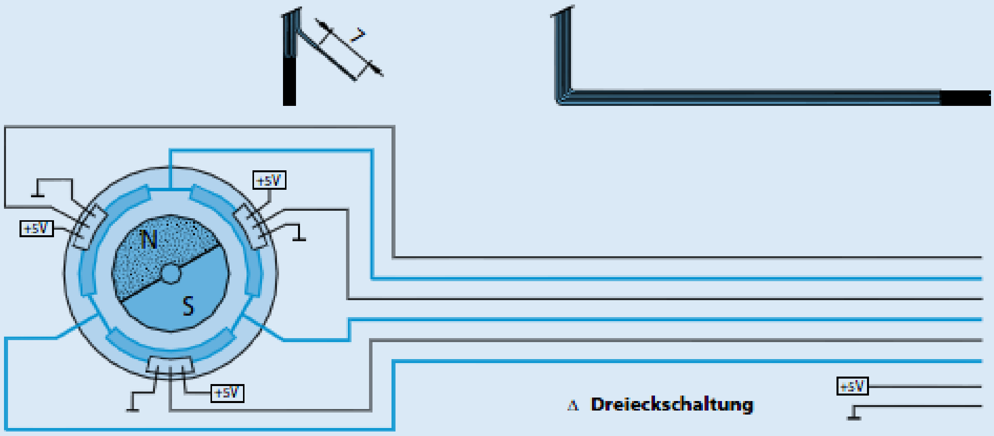
1628 T ... B



1628 T ... B - K312 mit zweitem Wellenende



Kabel- und Anschlussinformationen



Kabel
Einzelne Litzen in PTFE
Länge 300 mm ± 15 mm
8 Litzen, AWG 26

Anschlüsse

	Funktion	Farbe
A	Hall-Sensor	grün
A	Phase	braun
B	Hall-Sensor	blau
B	Phase	orange
C	Hall-Sensor	grau
C	Phase	gelb
+5V	Spannung	rot
GND	Masse	schwarz

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Seite 2/2

Planetengetriebe 0,3 Nm

Kombinierbar mit
DC-Kleinstmotoren
Bürstenlose DC-Motoren
Schrittmotoren

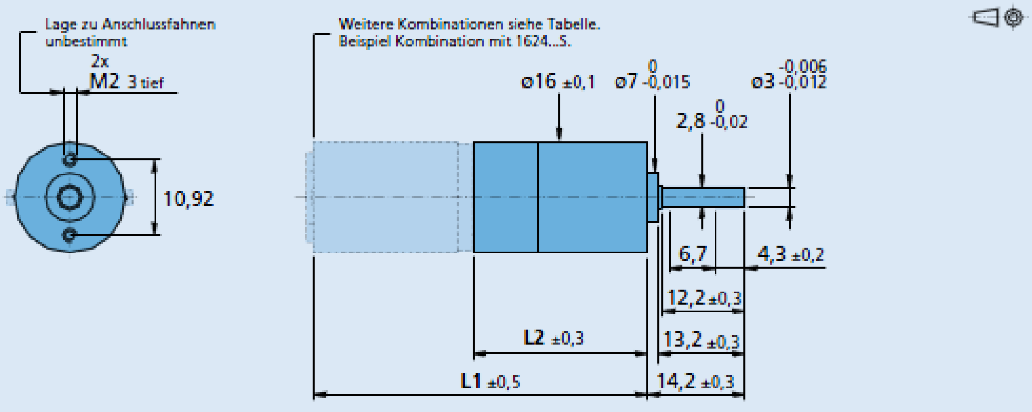
Serie 16/7

	16/7
Gehäusewerkstoff	Metall
Zahnräderwerkstoff	Stahl
Max. empfohlene Eingangsdrehzahl für:	
– Dauerbetrieb	5 000 rpm
Getriebespiel, unbelastet	≤ 1 °
Abtriebswellenlager	Kugellager, vorgespannt
Max. zulässige Wellenbelastung:	
– radial (6,5 mm vom Befestigungsflansch)	≤ 30 N
– axial	≤ 5 N
Maximale Aufpresskraft	≤ 5 N
Wellenspiel:	
– radial (6,5 mm vom Befestigungsflansch)	≤ 0,02 mm
– axial	= 0 mm
Betriebstemperaturbereich	- 30 ... + 100 °C

Technische Daten

Anzahl Getriebestufen			1	2	3	4	5	6
Dauerdrehmoment		mNm	200	300	300	300	300	300
Kurzzeitdrehmoment		mNm	300	450	450	450	450	450
Gewicht ohne Motor, ca.		g	18	23	28	33	38	43
Wirkungsgrad, max.		%	90	80	70	60	55	50
Drehsinn der Welle, Antrieb zu Abtrieb			=	=	=	=	=	=
Untersetzung [1] (gerundet)			**3,71:1**	**9,7:1** **14:1**	**43:1** **66:1**	**94:1** **112:1** **134:1** **159:1** **190:1** **246:1**	**415:1** **592:1** **989:1** **1 526:1**	**2 608:1** **4 365:1** **5 647:1**
L2 [mm] = Getriebelänge			17,0	21,2	25,3	29,4	33,5	37,6
L1 [mm] = Länge mit Motor	1516T...SR		32,8	37,0	41,1	45,2	49,3	53,4
	1524T...SR		40,8	45,0	49,1	53,2	57,3	61,4
	1624T...S		40,8	45,0	49,1	53,2	57,3	61,4
	1717T...SR		34,0	38,2	42,3	46,4	50,5	54,6
	1724T...SR		41,0	45,2	49,3	53,4	57,5	61,6
	1727U...C		44,2	48,4	52,5	56,6	60,7	64,8
	1524U...BSL		41,2	45,4	49,5	53,6	57,7	61,8
	1536U...BSL		53,6	57,8	61,9	66,0	70,1	74,2
	1628T...B		45,0	49,2	53,3	57,4	61,5	65,6
	AM1524...-55		33,5	37,7	41,8	45,9	50,0	54,1

[1] Die angegebenen Untersetzungsverhältnisse sind gerundet, exakte Werte sind auf Anfrage oder unter www.faulhaber.com erhältlich.



16/7

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FAULHABER

Motion Controller

4-Quadranten PWM
mit RS232 oder CAN-Schnittstelle

Kombinierbar mit:
Bürstenlosen DC-Servomotoren
mit analogen Hallsensoren

Serie MCBL 3003 S/C

		MCBL 3003 S/C	
Versorgungsspannung	U_B	12 ... 30	V DC
PWM-Schaltfrequenz	f_{PWM}	78,12	kHz
Wirkungsgrad	η	95	%
Max. Dauer-Ausgangsstrom [1]	I_{dauer}	3	A
Max. Spitzen-Ausgangsstrom	I_{max}	10	A
Stromaufnahme der Elektronik	I_{el}	0,06	A
Drehzahlbereich		5 ... 30 000	rpm
Regler Abtastrate	N	100	µs
Encoderauflösung mit linearen Hall-Sensoren		≤ 3 000	Inc./Umdr.
Auflösung mit externem Encoder		≤ 65 535	Inc./Umdr.
Ein-/Ausgänge (teilweise frei konfigurierbar)		3	
Speicher für Ablaufprogramme:			
– Speichergröße		3,3	kWord
– Anzahl der Befehle (abhänging von der Befehlslänge)		ca. 1 000	Befehle
Betriebstemperaturbereich		0 ... + 70	°C
Lagertemperaturbereich		– 25 ... + 85	°C
Gehäusematerial		ohne Gehäuse	
Gewicht		18	g

[1] bei 22°C Umgebungstemperatur

Beschreibung der Anschlüsse				
Anschluss Kommunikation:				
Schnittstelle			RS232 / CAN	
Protokoll			Faulhaber - ASCII / CAN	
Maximale Übertragungsgeschwindigkeit RS232			115 200	baud
Maximale Übertragungsgeschwindigkeit CAN			1	Mbit/s
Anschluss "AGND":				
– Analog Ground			Analog Bezugsmasse	
– Digitaler Eingang	externer Encoder		Kanal B	
		R_{in}	10	kΩ
		f	≤ 400	kHz
Anschluss "Fault":				
– Digitaler Eingang		R_{in}	100	kΩ
– Digitaler Ausgang (open collector)		U	≤ U_B	V
		I	≤ 30	mA
		clear	durchgeschaltet nach GND	
		set	hochohmig	
	Fehlerausgang	kein Fehler	durchgeschaltet nach GND	
		Fehler	hochohmig	
	Impulsausgang	f	≤ 2	kHz
		Auflösung	1...255	Inc./Umdr.
Anschluss "AnIn":			"AGND" als Bezugsmasse	
– Analoger Eingang	Drehzahlsollwert	U_{in}	± 10	V
– Digitaler Eingang	PWM für Drehzahlsollwert	f	100 ... 2 000	Hz
		T	50% ≙ 0 rpm	
	externer Encoder		Kanal A	
		f	≤ 400	kHz
	Schrittfrequenz Eingang	f	≤ 400	kHz
		R_{in}	5	kΩ
Anschluss "+24V":		U_B	12 ... 30	V DC
Anschluss "GND":			Masse	
Anschluss "3. In":				
– Digitaler Eingang		R_{in}	22	kΩ
– Versorgungsspannung Elektronik [2]		U_B	12 ... 30	V DC

[2] Getrennte Spannungsversorgung optional (Sondernummer 2993)

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Edition 2011 – 2012

Seite 1/6

FAULHABER

Beschreibung der Anschlüsse

Anschluss "Ph A", "Ph B", "Ph C":					
Motoranschluss	Ph A		Phase A	braun [1]	
	Ph B		Phase B	orange [1]	
	Ph C		Phase C	gelb [1]	
		U_{out}	0 … U_B		V
PWM-Schaltfrequenz		f_{PWM}	78,12		kHz
Anschluss "Hall A", "Hall B", "Hall C":					
Hall-Sensoreingang	Hall A		Hall-Sensor A	grün [1]	
	Hall B		Hall-Sensor B	blau [1]	
	Hall C		Hall-Sensor C	grau [1]	
		U_{in}	≤ 5		V
Anschluss "SGND":					
Signal GND			Signalmasse	schwarz [1]	
Anschluss "+5V":					
Ausgangsspannung für externen Gebrauch [2]		U_{out}	5	rot [1]	V DC
Laststrom		I_{out}	≤ 60		mA

[1] Farbkennung für "Bürstenlose DC-Servomotoren" von FAULHABER
[2] z.B. Hall-Sensoren

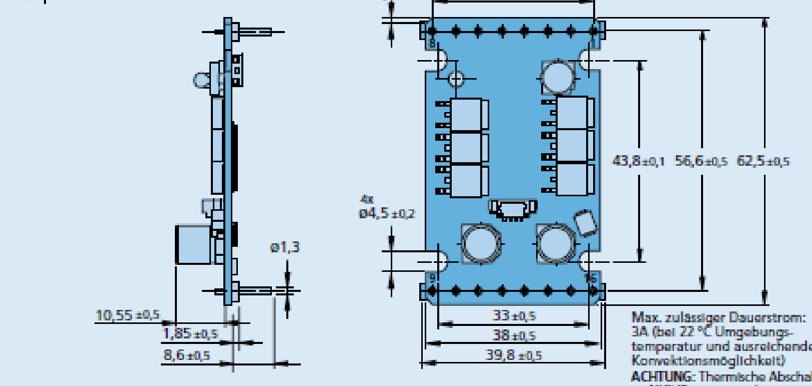
Digitale Eingänge Allgemein

- PLC (SPS), standard	high	12,5 … U_B	V
	low	0 … 7	V
- TTL	high	3,5 … U_B	V
	low	0 … 0,5	V

Der Pegel (PLC oder TTL) der digitalen Eingänge kann über die Schnittstelle konfiguriert werden (siehe Bedienungsanleitung).

Masszeichnung und Anschlussinformation MCBL 3003 S/C

Abbildungen verkleinert



Max. zulässiger Dauerstrom:
3A (bei 22 °C Umgebungstemperatur und ausreichender Konvektionsmöglichkeit)
ACHTUNG: Thermische Abschaltung ist NICHT garantiert!

Anschlussbelegung

Pin	Anschluss
1	Ph C
2	Hall A
3	+ 5V
4	SGND
5	Hall B
6	Hall C
7	Ph B
8	Ph A
9	TxD / CAN_H
10	RxD / CAN_L
11	AGND
12	Fault
13	AnIn
14	+ 24V
15	GND
16	3. In

Angaben zu Gewährleistung und Lebensdauer sowie weitere technische Erläuterungen siehe „Technische Informationen“.
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Seite 2/6