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Jonathan Terfurth

Integrated Multi-Motor Actuators for Medical and Industrial Robotics

Band 13

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Integrated Multi-Motor Actuators for Medical and Industrial Robotics

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zur Erlangung der Würde des Doktor-Ingenieurs (Dr.-Ing.)
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Preface

This thesis emerged during my work as a research associate at the Institute of Electrical Energy Conversion at the University of Stuttgart and as part of the International Research Training Group *Soft Tissue Robotics* (GRK 2198/1, funded by the German Research Foundation (Deutsche Forschungsgemeinschaft)) of which I was an associated doctoral research member.

I want to express a special thanks to Prof. Dr.–Ing. Nejila Parspour, who encouraged and supported me throughout my thesis as my main doctoral supervisor and examiner and overall during my time and work at the institute.

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The final big thank you goes to my family and friends who always supported me, did not hold back on telling me their opinions no matter what, and pushed me in achieving this thesis and doctoral degree.

Stuttgart, March 2022 — Jonathan Theo Terfurth

Abstract

In this doctoral thesis, an integrated robotic joint actuator concept consisting of more than one distributed electromagnetic torque source is presented. It is stated where current robotic joint actuators are limited for certain applications and how the suggested concept can improve the behavior in those regards.

The joint actuator concept is formulated from the ground up, giving design guidelines and evaluating optimal topologies for certain applications. To reach the set goals of this thesis, the integration of mechanics, mostly in the form of a gearbox, and electromagnetic torque sources is advanced further than the typical state-of-the-art of robotic joint actuation. This is combined with the design of a small high-torque outer rotor motor and a control structure, thus enabling a multitude of operating strategies, specifically targeting aspects like high efficiency or output precision. Deep integration is, among other things, enabled by the evaluation of suitable materials.

Two different exemplary prototype designs with either distributed motors or distributed motorphases are suggested, including electromagnetic as well as mechanical design, and evaluated in detail. With the given multi-motor joint actuator design characteristics, these can be adapted to specific applications, for example by changing the underlying topology or the electric drive topology.

Finalizing this thesis, an extensive evaluation of the made decisions and created designs is performed, based on which the overall concept is classified.

Zusammenfassung

In dieser Dissertation wird ein integriertes Robotergelenk-Aktuatorkonzept vorgestellt, das aus mehr als einer verteilten elektromagnetischen Drehmomentquelle besteht. Es wird aufgezeigt, bei welchen Anwendungen aktuelle Ansätze in welcher Hinsicht limitiert sind und wie das vorgeschlagene Konzept das Verhalten in diesen Bereichen verbessern kann.

Das Konzept des Gelenkaktuators wird von Grund auf definiert, wobei Designrichtlinien und optimale Topologien für spezifische Anwendungsfälle evaluiert werden. Auf dem Weg die Ziele dieser Arbeit zu erreichen wird die Integration von Mechanik, meist in Form eines Getriebes, und elektromagnetischer Drehmomentquellen weiter vorangetrieben, als es typischerweise dem aktuellen Stand der Technik in der Robotik entspricht. Dies wird kombiniert mit dem Design eines kleinen Außenläufermotors mit hohem Drehmoment sowie einer Regelungsstruktur, wodurch eine Vielzahl von Betriebsstrategien ermöglicht wird, die speziell auf Aspekte wie hohe Effizienz oder Präzision am Abtrieb ausgerichtet sind. Eine starke Integration wird unter anderem durch die Evaluierung geeigneter Materialien ermöglicht.

Es werden beispielhaft zwei unterschiedliche Prototypen zum einen mit verteilten Motoren und zum anderen mit verteilten Motorphasen auf elektromagnetischer und mechanischer Ebene ausgelegt und im Detail ausgewertet. Mit den gegebenen Charakteristiken der Mehrmotoren-Gelenkaktuatoren können diese an spezifische Anwendungen angepasst werden, zum Beispiel durch Variation der zugrunde liegenden Topologie oder Änderung der elektrischen Antriebstopologie.

Abgeschlossen wird diese Dissertation mit einer umfangreichen Auswertung und Bewertung der getroffenen Entscheidungen und entwickelten Konzepte, mit der das Gesamtkonzept eingeordnet wird.

Table of Contents

List of Abbreviations

Notation	Description
3D	Three-Dimensional
AC	Alternating Current
BEMF	Back Electromotive Force
BLDC	Brushless DC
CAD	Computer-Aided Design
DC	Direct Current
DEA	Dielectric Elastomeric Actuator
DFG	German Research Foundation (Deutsche Forschungsgemeinschaft)
EDM	Electrical Discharge Machining
EM	Electrical Motor
FEA	Finite Element Analysis
FEM	Finite Element Method
GA	Genetic Algorithm
GUI	Graphical User Interface
HEV	Hybrid Electric Vehicle
HR	Hard Robot
IRTG	International Research Training Group

Notation	Description
JA	Joint Actuator
JAM	Jiles-Atherton Model
LCM	Least Common Multiple
LUT	Lookup-table
MD	Main Drive
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
PC	Personal Computer
PCB	Printed Circuit Board
PD	Planet-Integrated Drive
PG	Planet Spur Gear
PGT	Planetary Gear Train
Ph.D.	Philosophical Doctorate
PID	Proportional–Integral–Derivative
PMSM	Permanent Magnet Synchronous Motor
RG	Ring Spur Gear
SFLA	Shuffled Frog Leaping Algorithm
SG	Sun Spur Gear
SLM	Selective Laser Melting
SMA	Shape-Memory Alloy
SMC	Soft Magnetic Composite
SR	Soft Robot
ST	Soft Tissue
STR	Soft Tissue Robotics
TFM	Transverse Flux Machine

List of Symbols

Symbol	Unit	Description
A	mm^2	Area
A_{cs}	mm^2	Cross section area
a_{JA}	$\mathrm{A/m}$	Domain wall density, Jiles-Atherton model
B	T	Magnetic flux density
C_0	kN	Static bearing load rating
c_{JA}	–	Magnetization reversibility, Jiles-Atherton model
C_{r}	kN	Dynamic bearing load rating
d	mm	Distance
d_{act}	mm	Actuator diameter
d_{δ}	mm	Air gap diameter
d_{i}	mm	Inner diameter
d_{o}	mm	Outer diameter
d_{PD}	mm	Active outer diameter planet drive
d_{pi}	mm	Gear pitch diameter
f	Hz	Frequency
f_{cog}	Hz	Mechanical cogging torque frequency
f_{cost}	–	Cost / objective function
F_{r}	kN	Radial bearing load
F_{rad}	N	Radial force component
g	–	Gear module
H	$\mathrm{A/m}$	Magnetic field strength

Symbol	Unit	Description
h	mm	Height
H_{C}	$\mathrm{A/m}$	Magnetic coercitivity
h_{mag}	mm	Radial magnet height
H_{max}	$\mathrm{A/m}$	Maximum magnetic field strength
I	A	Electrical current
I_1	A	Primary side current
i_{ph}	A	Electrical phase current
I	$\mathrm{kg\,mm^2}$	Moment of inertia
I_{Cl}	$\mathrm{kg\,mm^2}$	Moment of inertia of clutch
I_{IS}	$\mathrm{kg\,mm^2}$	Moment of inertia of input shaft
I_{JA}	$\mathrm{kg\,mm^2}$	Moment of inertia of joint actuator
I_{L1}	$\mathrm{kg\,mm^2}$	Moment of inertia at gearbox level 1
I_{L2}	$\mathrm{kg\,mm^2}$	Moment of inertia at gearbox level 2
I_{L3}	$\mathrm{kg\,mm^2}$	Moment of inertia at gearbox level 3
I_{MA}	$\mathrm{kg\,mm^2}$	Moment of inertia of main motor adapter
I_{MD}	$\mathrm{kg\,mm^2}$	Moment of inertia of main motor rotor
I_{OS}	$\mathrm{kg\,mm^2}$	Moment of inertia of output shaft
I_{PD}	$\mathrm{kg\,mm^2}$	Moment of inertia of planet drive rotor
I_{PG}	$\mathrm{kg\,mm^2}$	Moment of inertia of planet spur gear
I_{RG}	$\mathrm{kg\,mm^2}$	Moment of inertia of ring spur gear
I_{SG}	$\mathrm{kg\,mm^2}$	Moment of inertia of sun spur gear
J	T	Magnetic polarization
j_{t}	mm	Gear mesh allowance
k_{JA}	$\mathrm{A/m}$	Pinning loss, Jiles-Atherton model
k_{w}	–	Winding factor
l	mm	Length
l_{10h}	s	Bearing lifetime
l_{act}	mm	Active length
l_{mag}	mm	Magnet radial length

Symbol	Unit	Description
l_{mp}	mm	Magnet path length
l_{PD}	mm	Active axial length planet drive
$l_{\mathrm{TFM,ph}}$	mm	Active axial length transverse flux machine phase
L_{ph}	H	Phase inductance
M	$\mathrm{A/m}$	Magnetization
m	–	Number of phases
M_{an}	$\mathrm{A/m}$	Anhysteretic magnetization
M_{max}	$\mathrm{A/m}$	Maximum magnetization
$M_{\mathrm{S,JA}}$	$\mathrm{A/m}$	Saturation magnetization, Jiles-Atherton model
n	$\mathrm{1/min}$	Rotational speed
N_1	–	Number of toroidal core field winding turns
N_2	–	Number of toroidal core measure winding turns
n_{act}	$\mathrm{1/min}$	Rotational actuator speed
N_{c}	–	Number of coil winding turns
$N_{\mathrm{c,1}}$	–	Number of primary side coil winding turns
$N_{\mathrm{c,2}}$	–	Number of secondary side coil winding turns
$N_{\mathrm{c,ph}}$	–	Number of coil winding turns per phase
$N_{\mathrm{c,t}}$	–	Number of coil winding turns per stator tooth
N_{gt}	–	Number of spur gear teeth
$N_{\mathrm{gt,PG}}$	–	Number of planet spur gear teeth
$N_{\mathrm{gt,RG}}$	–	Number of ring spur gear teeth
$N_{\mathrm{gt,SG}}$	–	Number of sun spur gear teeth
N_{S}	–	Number of stator slots
p	–	Number of pole pairs
P_{L}	W	Power loss
$P_{\mathrm{L,Cu}}$	W	Power loss in electrical conductors, copperlosses
$P_{\mathrm{L,Iron}}$	W	Power loss in soft magnetic components, iron losses
q	–	Slots per pole per phase
R	–	Mechanical reduction ratio

Symbol	**Unit**	**Description**
R	Ω	Electrical resistance
r_δ	mm	Air gap radius
r_{lev}	s	Mechanical lever length
R_{MD}	–	Reduction ratio main drive to output
$R_{MD,PD}$	–	Reduction ratio main drive to planet drive
R_{PD}	–	Reduction ratio planet drive to output
R_{ph}	Ω	Electrical phase resistance
S	–	Safety coefficient
S_F	–	Safety coefficient gear breakage
S_{Fst}	–	Safety coefficient static deflection
S_H	–	Safety coefficient pitting
S_{Hst}	–	Safety coefficient static contact
T	Nm	Torque
t	s	Time
T_{cog}	Nm	Cogging torque
T_{JA}	Nm	Torque joint actuator
T_{MD}	Nm	Torque main drive
$T_{MD,ref}$	Nm	Reference torque main drive
T_{PD}	Nm	Torque planet drives
T_{PD1}	Nm	Torque planet drive 1
$T_{PD1,ref}$	Nm	Reference torque planet drive 1
T_{PD2}	Nm	Torque planet drive 2
$T_{PD2,ref}$	Nm	Reference torque planet drive 2
T_{PD3}	Nm	Torque planet drive 3
$T_{PD3,ref}$	Nm	Reference torque planet drive 3
T_{PD4}	Nm	Torque planet drive 4
$T_{PD4,ref}$	Nm	Reference torque planet drive 4
T_{ph}	Nm	Torque of a single phase
$T_{RG,ref}$	Nm	Reference torque at ring spur gear

Symbol	Unit	Description
$T_{\mathrm{tilt,ph}}$	Nm	Tilting torque on integrated phases
V_2	V	Secondary side voltage
V_{DC}	V	DC-link voltage
V_{i}	V	Induced voltage
α_{JA}	–	Inter-domain coupling, Jiles-Atherton model
α_{PD}	$^{\mathrm{rad}}/_{\mathrm{s}^2}$	Mechanical angular acceleration planet drive
δ	mm	Air gap length
ΔT	%	Relative torque ripple
$\varepsilon_{\mathrm{el}}$	rad	Electrical rotor angle
$\varepsilon_{\mathrm{mech}}$	rad	Mechanical rotor angle
Θ	A	Magnetomotive force
κ	$^{\mathrm{S}}/_{\mathrm{m}}$	Electrical conductivity
μ	$^{\mathrm{V\,s}}/_{\mathrm{A\,m}}$	Magnetic permeabiliy
η	%	Efficiency
η_{g}	%	Gear efficiency
τ_{p}	mm	Pole pitch
Ω	$^{\mathrm{rad}}/_{\mathrm{s}}$	Mechanical angular velocity
χ_{an}	–	Magnetic susceptibility of anhysteretic curve
χ_{in}	–	Magnetic susceptibility of initial curve

List of Figures

List of Tables

List of Algorithms