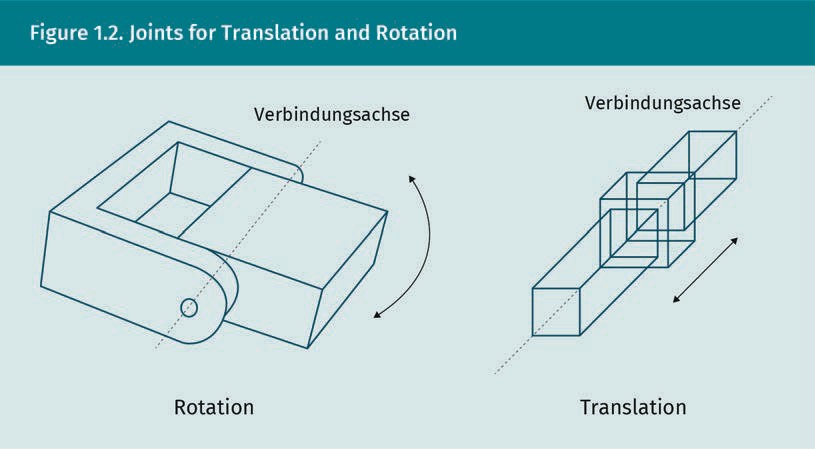
Figure 1.1 Industrial Robot and Mobile Robot

Diagram

Description automatically generated Abbildung 1.1 Industrieroboter und mobiler Roboter

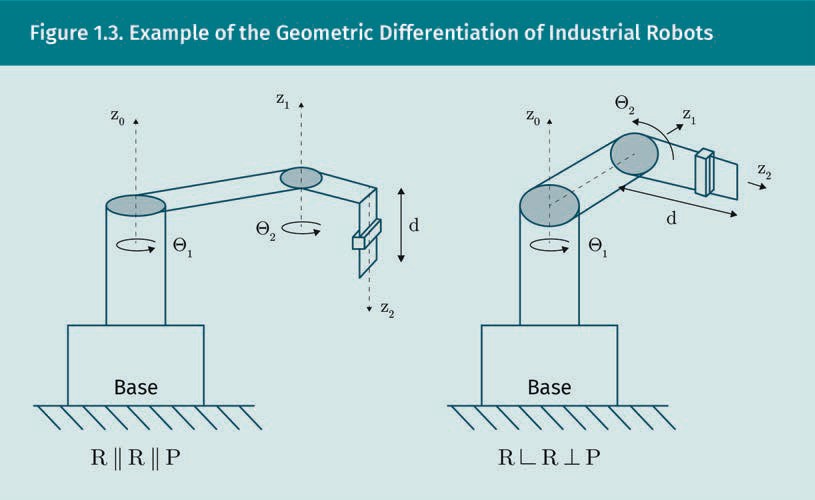
|  |  |
| --- | --- |
| Control unit | Steuerungseinheit |
| Industrial robot | Industrieroboter |
| Mobile robot | Mobiler Roboter |

Figure 1.2 Joints for translation and Rotation

Abbildung 1.2 Gelenke für Translation und Rotation

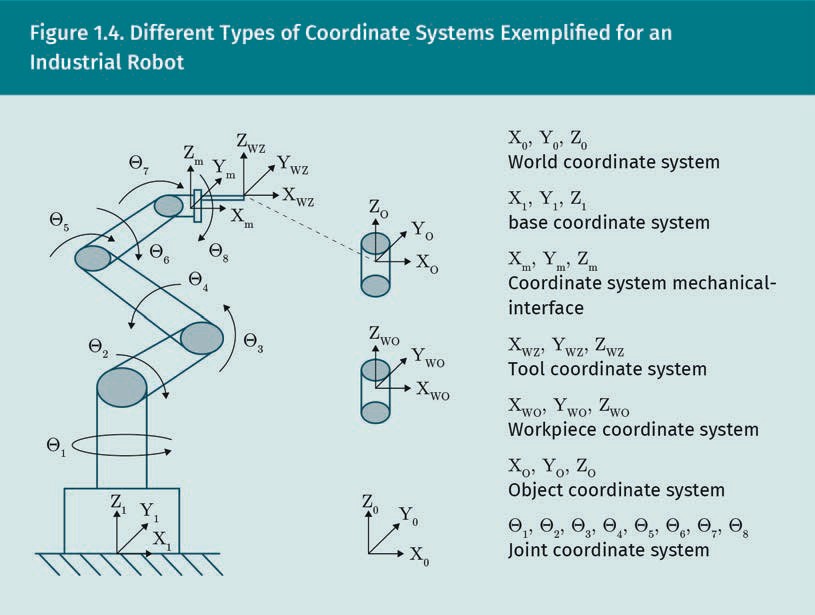
|  |  |
| --- | --- |
| Rotation | Rotation |
| Translation | Translation |

Figure 1.3 Example of the Geometric Differentiation of Industrial Robots

Abbildung 1.3 Beispiel für die geometrische Differentiation von Industrierobotern

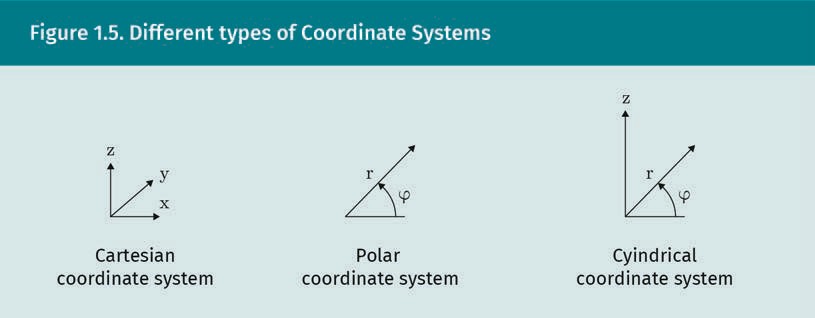
|  |  |
| --- | --- |
| Base | Basis |

Figure 1.4 Different Types of Coordinate Systems Exemplified for an Industrial Robot

Abbildung 1.4 Verschiedene Arten von Koordinatensystemen am Beispiel eines Industrieroboters

|  |  |
| --- | --- |
| World coordinate system | Weltkoordinatensystem |
| base coordinate system | Basiskoordinatensystem |
| Coordinate system mechanical-interface | Koordinatensystem Mechanische Schnittstelle |
| Tool coordinate system | Werkzeugkoordinatensystem |
| Object coordinate system | Objektkoordinatensystem |
| Joint coordinate system | Gelenkkoordinatensystem |

Figure 1.5 Different Types of Coordinate Systems

Abbildung 1.5 Verschiedene Arten von Koordinatensystemen

Kartesisches Koordinatensystem

Polarkoordinatensystem

Zylindrisches Koordinatensystem

Cartesian coordinate system

Polar coordinate system

Cylindrical coordinate system

Figure 1.6 The MIT Arm

Abbildung 1.6 Der MIT-Arm

A picture containing sewing machine, appliance, indoor

Description automatically generated

Figure 1.7 The Robot Shakey

Abbildung 1.7 Der Roboter Shakey

A picture containing wall, indoor, floor

Description automatically generated

Figure 1.8 Robot ASIMO by Honda: Example of a Humanoid Robot

Abbildung 1.8 Roboter ASIMO von Honda: Beispiel für einen humanoiden Roboter

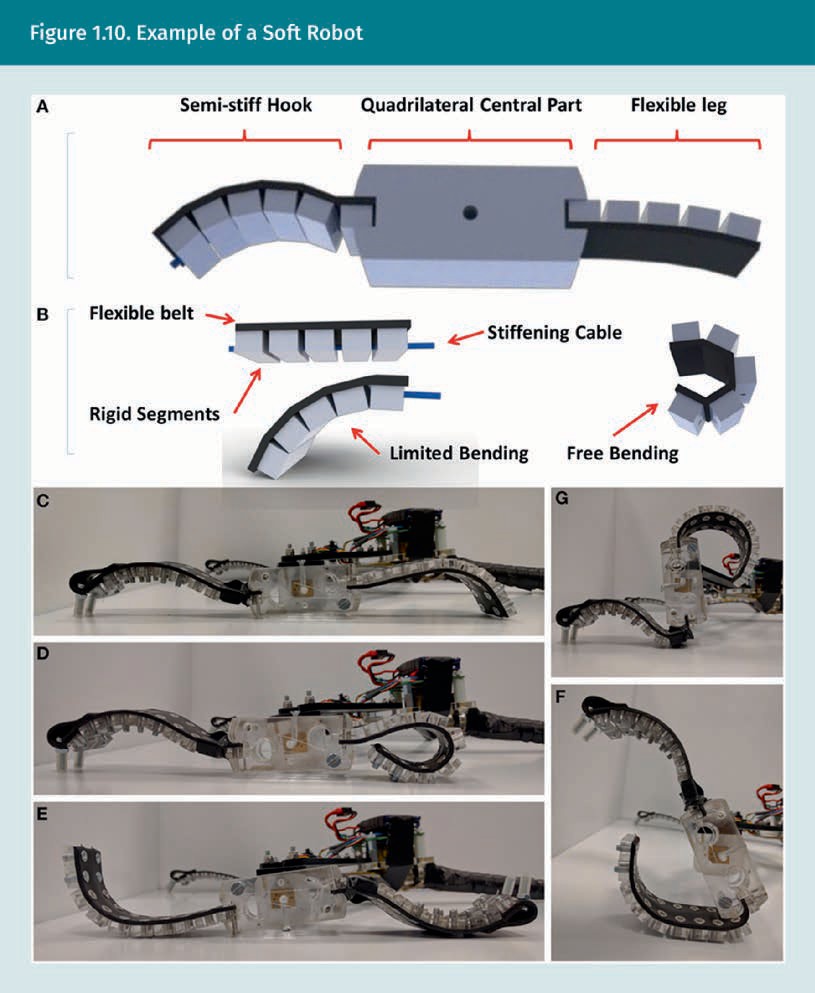
A person in a white suit

Description automatically generated with medium confidence

Figure 1.9 Walking Assist Device by Honda

Abbildung 1.9 Gehhilfe von Honda

Figure 1.10 Example of a Soft Robot

Abbildung 1.10 Beispiel für einen Softroboter

|  |  |
| --- | --- |
| Semi-stiff hook | Halbsteifer Haken |
| Quadrilateral central part | Viereckiger Mittelteil |
| Flexible leg | Flexibles Bein |
| Flexible belt | Flexibler Gürtel |
| Rigid segments | Starre Segmente |
| Stiffening cable | Versteifungskabel |
| Limited bending | Begrenzte Biegefähigkeit |
| Free bending | Freie Biegefähigkeit |

Figure 1.11 Six-Legged Bio-Inspired Robot by Boston Dynamics

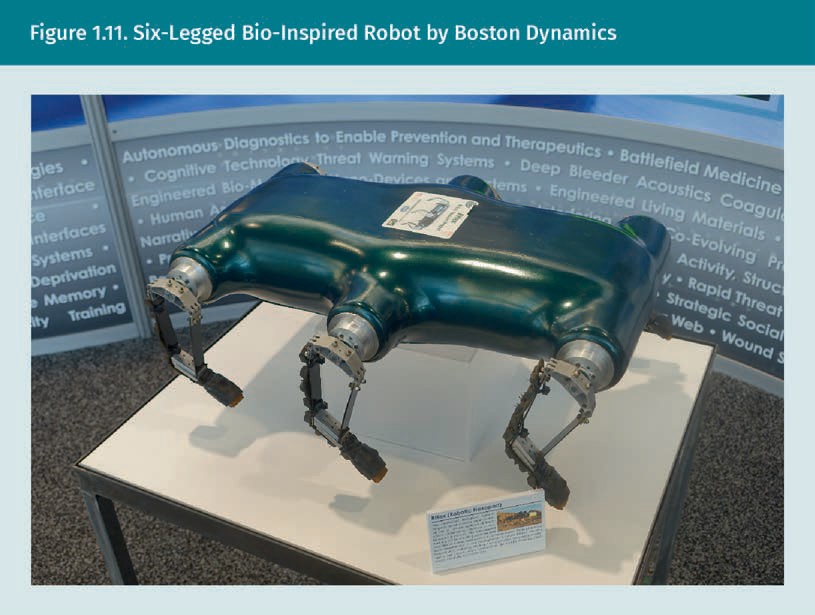
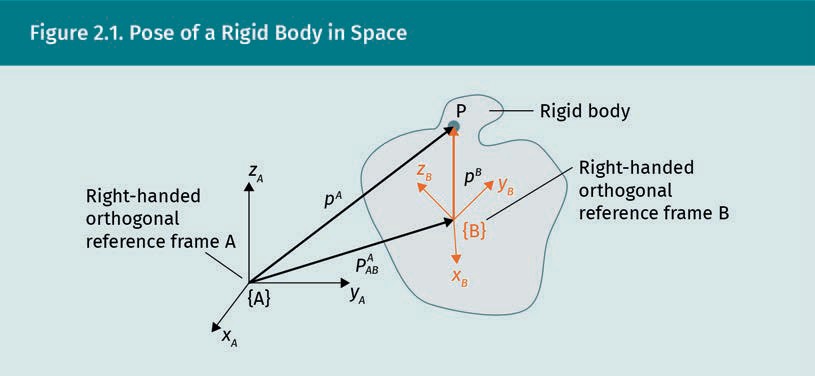
Abbildung 1.11 Sechsbeiniger bio-inspirierter Roboter von Boston Dynamics

Figure 2.1 Pose of a Rigid Body in Space

Abbildung 2.1 Pose eines starren Körpers im Raum

|  |  |
| --- | --- |
| Right-handed orthogonal reference frame A | Rechtshändiges orthogonales Bezugssystem A |
| Rigid body | Starrer Körper |
| Right-handed orthogonal reference frame B | Rechtshändiges orthogonales Bezugssystem B |

Figure 2.2 The Rotation Matrix as a Rotation Operator in the Reference Frame

Abbildung 2.2 Die Rotationsmatrix als Rotationsoperator im Bezugssystem

Chart, scatter chart

Description automatically generated

Figure 2.3 The Rotation Matrix as Orientation of a New Frame {B} with Respect to Frame {A}

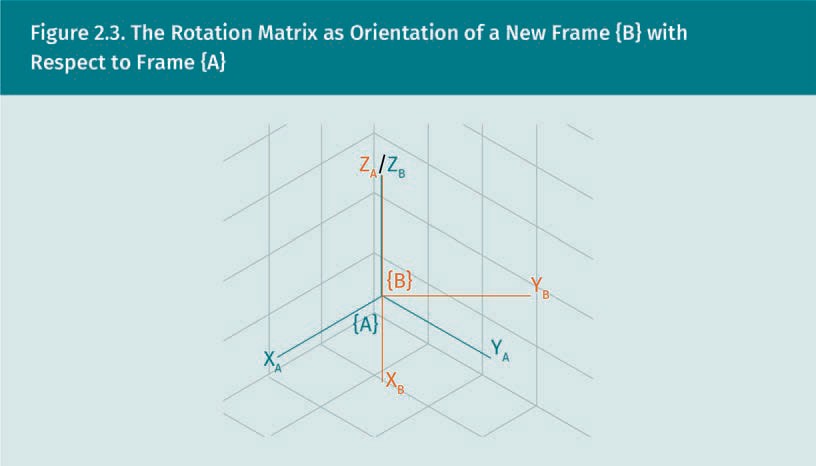
Abbildung 2.3 Die Rotationsmatrix als Orientierung eines neuen Bezugssystems {B} bezogen auf das Bezugssystem {A}

Figure 2.4 Composition of Rotations About Current Axis

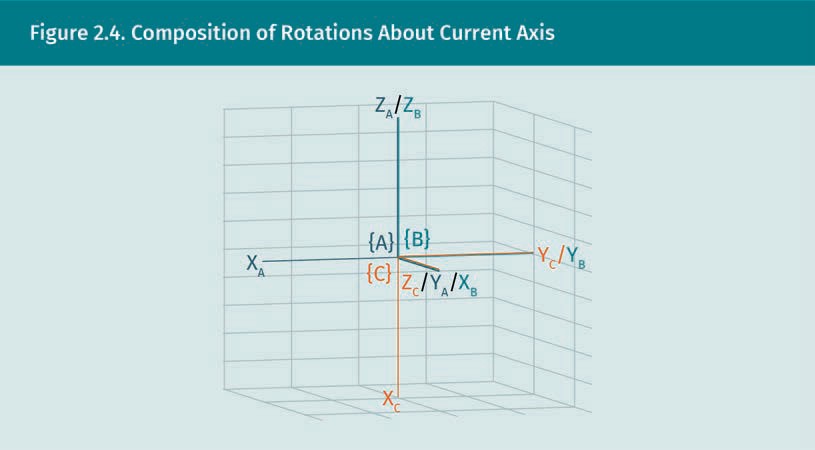
Abbildung 2.4 Zusammensetzung der Rotationen um die aktuelle Achse

Figure 2.5 Sketch of the Kinematic Chain of a Simple (Planar) Robot Manipulator

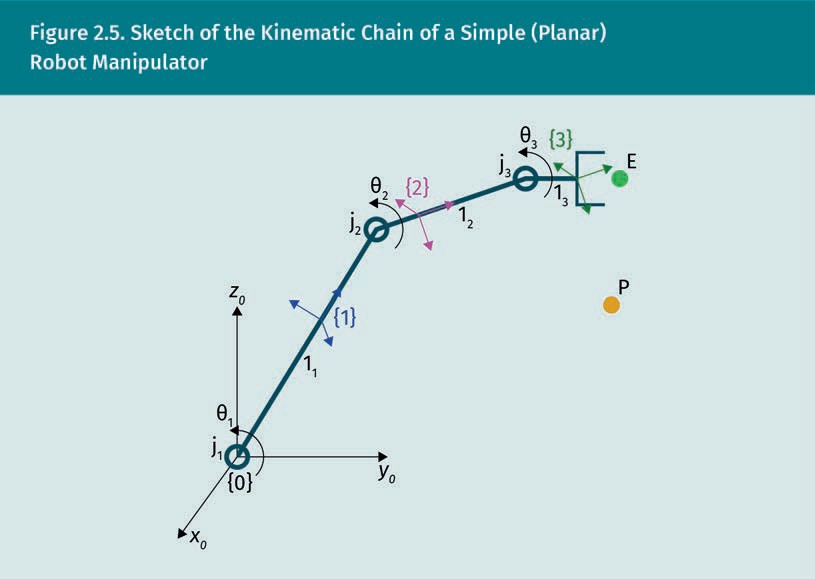
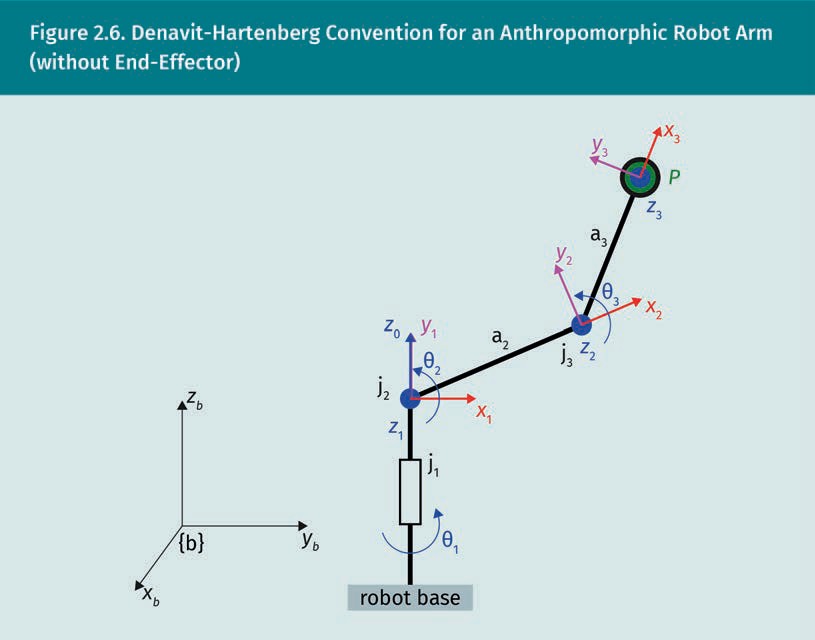
Abbildung 2.5 Skizze der kinematischen Kette eines einfachen (planaren) Robotermanipulators

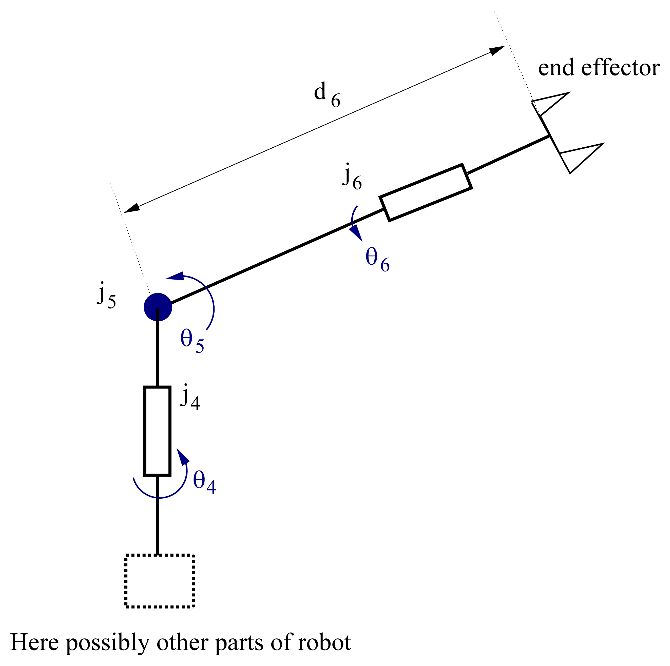
Figure 2.6 Denavit-Hartenberg Convention for an Anthropomorphic Robot Arm (without End-Effector)

Abbildung 2.6 Denavit-Hartenberg-Konvention für einen anthropomorphen Roboterarm (ohne Endeffektor)

|  |  |
| --- | --- |
| Robot base | Roboterbasis |

Self-Check Question: Unit 2.2, No. 2 (Question)

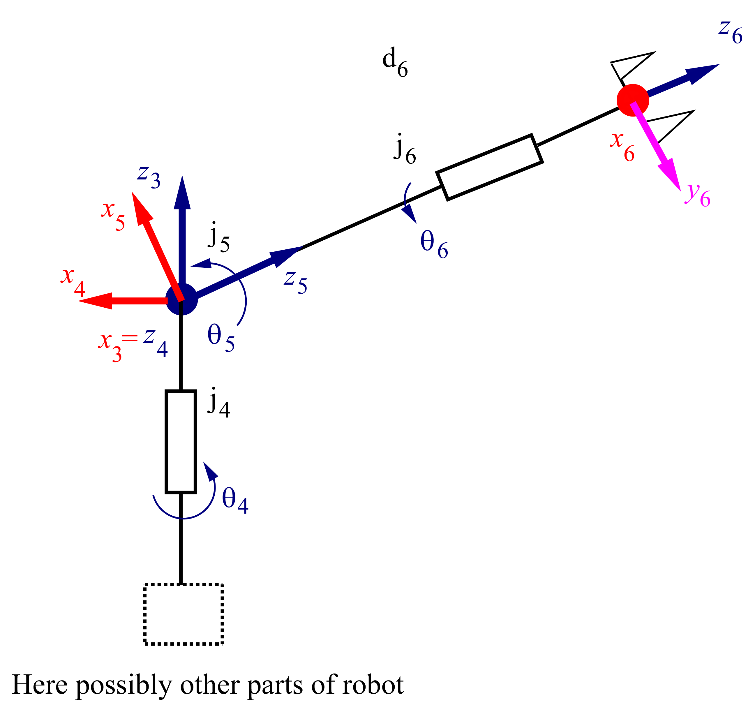
Frage zur Selbstkontrolle: Lektion 2.2, Nr. 2 (Frage)



|  |  |
| --- | --- |
| Here possibly other parts of the robot | Hier möglicherweise andere Teile des Roboters |
| End effector | Endeffektor |

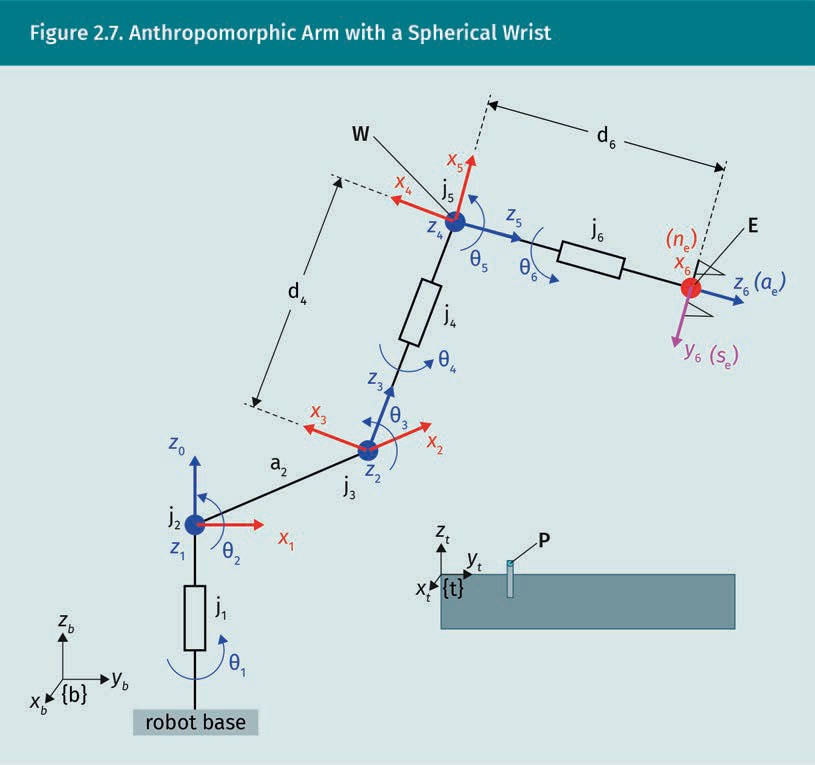
Self-Check Question: Unit 2.2, No. 2 (Answer)

Frage zur Selbstkontrolle: Lektion 2.2, Nr. 2 (Antwort)



|  |  |
| --- | --- |
| Here possibly other parts of the robot | Hier möglicherweise andere Teile des Roboters |

Figure 2.7 Anthropomorphic Arm with a Spherical Wrist

Abbildung 2.7 Anthropomorpher Arm mit Kugelgelenk

|  |  |
| --- | --- |
| Robot base | Roboterbasis |

Figure 2.8 Linear and Angular Velocity of a Two-Link Robot

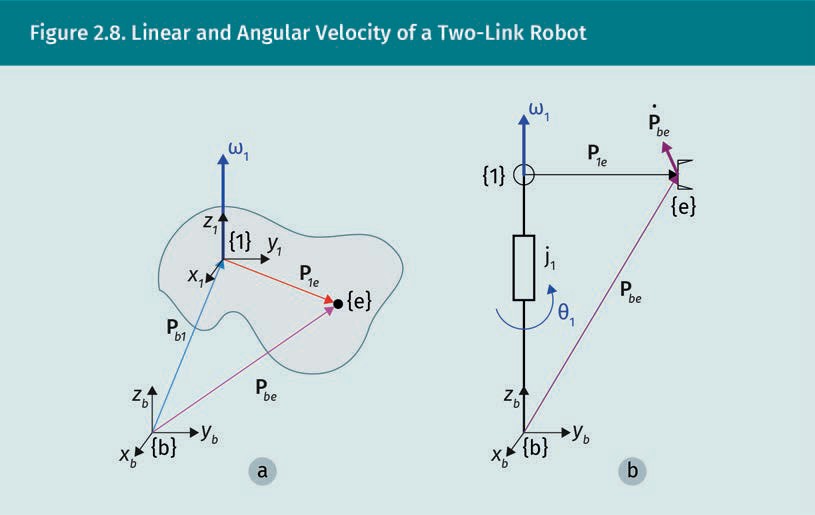
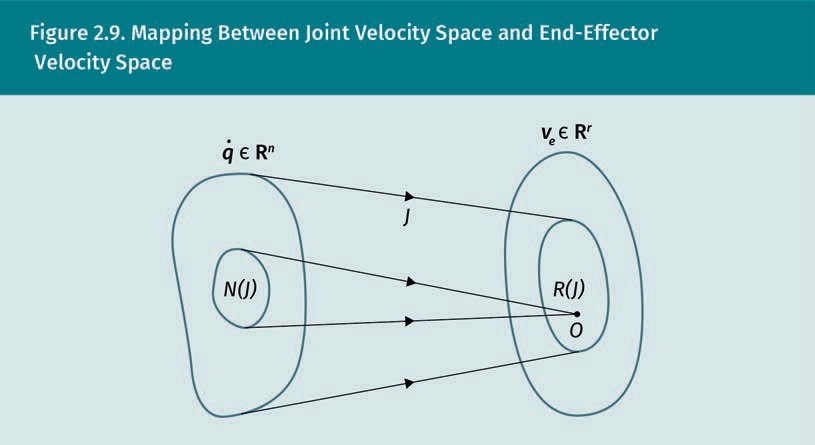
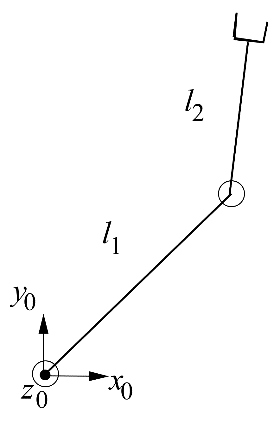
Abbildung 2.8 Linear- und Winkelgeschwindigkeit eines zweigliedrigen Roboters

Figure 2.9 Mapping Between Joint Velocity Space and End-Effector Velocity Space

Abbildung 2.9 Abbildung zwischen dem Geschwindigkeitsraum des Gelenks und dem Geschwindigkeitsraum des Endeffektors

Self-Check Question, Unit 2.4, No. 1 (Question)

Frage zur Selbstkontrolle, Lektion 2.4, Nr. 1 (Frage)



Self-Check Question, Unit 2.4, No. 1 (Answer)

Frage zur Selbstkontrolle, Lektion 2.4, Nr. 1 (Antwort)

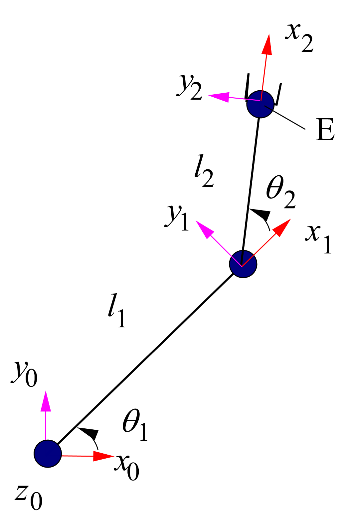


Figure 2.10 Bicycle Model of a Car-Like Robot

Abbildung 2.10 Zweiradmodell eines Auto-ähnlichen Roboters

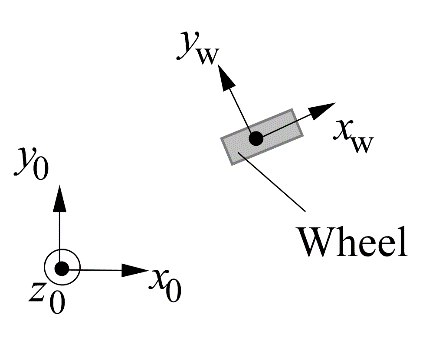
Diagram

Description automatically generated

|  |  |
| --- | --- |
| ICR | ICR |
| Instantaneous Center of Rotation | Momentanpol |
| Steering wheel angle | Lenkradwinkel |
| Steered wheel | Gelenktes Rad |
| Velocity | Geschwindigkeit |
| Wheel base | Radstand |

Self-Check Question, Unit 2.5, No. 3 (Question)

Frage zur Selbstkontrolle, Lektion 2.5, Nr. 3 (Frage)



|  |  |
| --- | --- |
| Wheel | Rad |

Figure 3.1 The Role of Trajectory Planning

Abbildung 3.1 Die Rolle der Trajektorienplanung

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Goal | Ziel |
| Task planner | Aufgabenplaner |
| Constraints | Zwangsbedingungen |
| Points | Punkte |
| Trajectory planner | Trajektorienplaner |
| Robot constraints | Roboter-Zwangsbedingungen |
| Sensors | Sensoren |
| Environment | Umwelt |
| Trajectory | Trajektorie |
| Control systems | Steuerungssysteme |
| Actuation | Betätigung |
| Measurements | Messungen |
| Robot | Roboter |

Figure 3.2 Paths in the Cartesian Space

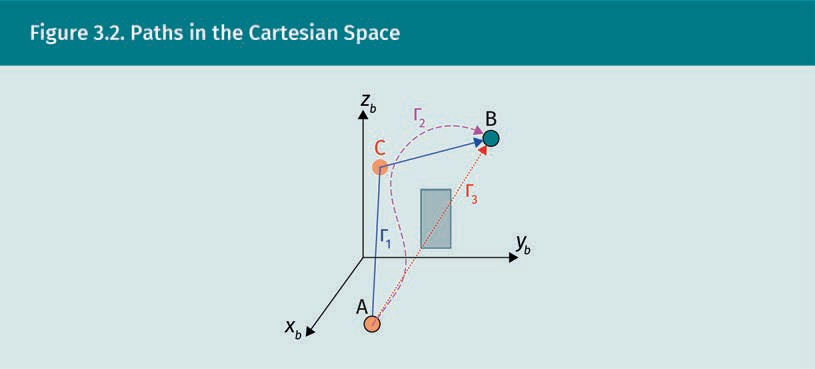
Abbildung 3.2 Pfade im kartesischen Raum

Figure 3.3 Trapezoidal Velocity Profile and Resulting Position and Acceleration

Abbildung 3.3 Trapezförmiges Geschwindigkeitsprofil und daraus resultierende Position und Beschleunigung

Chart, diagram

Description automatically generated

Self-Check Question, Unit 3.2, No. 1 (Answer)

Frage zur Selbstkontrolle, Lektion 3.2, Nr. 1 (Antwort)



|  |  |
| --- | --- |
| Time | Zeit |

Frage zur Selbstkontrolle, Lektion 3.2, Nr. 2 (Antwort)



|  |  |
| --- | --- |
| Time | Zeit |

Figure 3.4 (a) Generic Path in Space, (b) Rectilinear Path Between Two Points in Space

Abbildung 3.4 (a) Allgemeiner Pfad im Raum, (b) Geradliniger Pfad zwischen zwei Punkten im Raum

Chart

Description automatically generated

Self-Check Question, Unit 3.3, No. 1 (Answer)

Frage zur Selbstkontrolle, Lektion 3.3, Nr. 1 (Antwort)

(A)



(B)

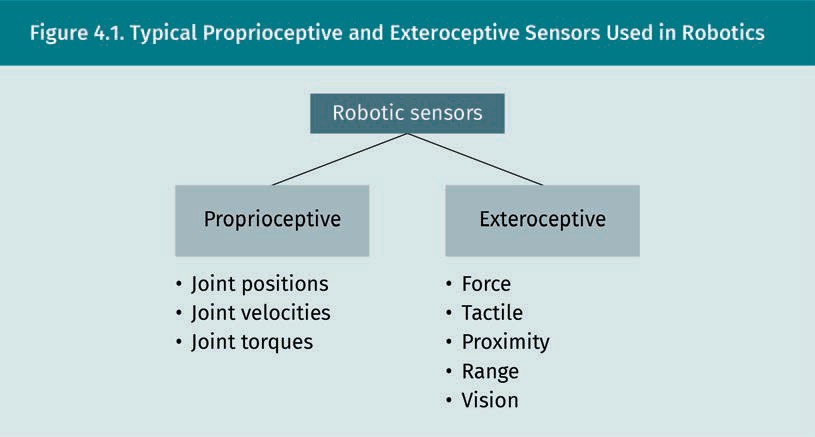


(C)



|  |  |
| --- | --- |
| Time | Zeit |

Figure 4.1 Typical Proprioceptive and Exteroceptive Sensors Used in Robotics

Abbildung 4.1 Typische propriozeptive und exterozeptive Sensoren für die Robotik

|  |  |
| --- | --- |
| Robotic sensors | Robotersensoren |
| Proprioceptive | Propriozeptiv |
| Joint positions | Gelenkpositionen |
| Joint velocities | Gelenkgeschwindigkeiten |
| Joint torques | Gelenkdrehmomente |
| Exteroceptive | Exterozeptiv |
| Force | Kraft |
| Tactile | Berührung |
| Proximity | Annäherung |
| Range | Abstand |
| Vision | Sicht |

Figure 4.2 Absolute Encoder, (a) Working Principle and (b) Front View of the Disk with Alternating Sequences of Transparent and Matte Sectors

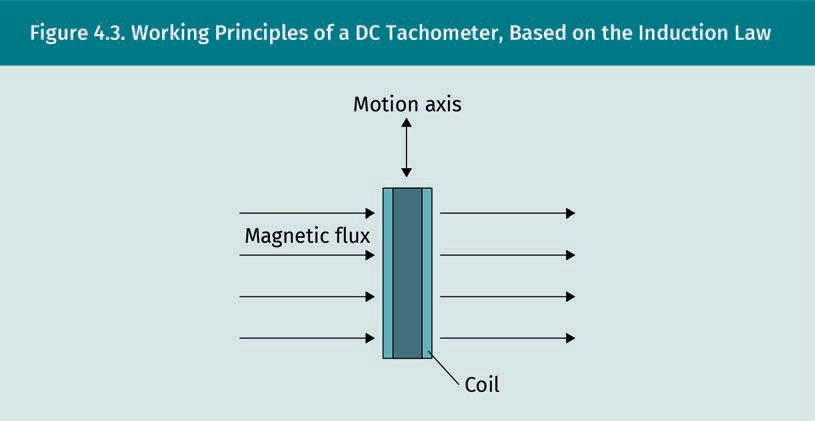
Abbildung 4.2 Absolutwertdrehgeber, (a) Funktionsprinzip und (b) Vorderansicht der Scheibe mit abwechselnden Sequenzen von transparenten und matten Sektoren

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Light | Licht |
| Disk | Scheibe |
| Photodiodes | Photodioden |

Figure 4.3 Working Principles of a DC Tachometer, Based on the Induction Law

Abbildung 4.3 Funktionsprinzip eines Gleichstromtachometers, basierend auf dem Induktionsgesetz

|  |  |
| --- | --- |
| Motion axis | Bewegungsachse |
| Magnetic flux | Magnetischer Fluss |
| Coil | Spule |

Figure 4.4 A Strain Gauge (left) and its Typical Electrical Arrangement within a Wheatstone Bridge Circuit

Abbildung 4.4 Ein Dehnungsmessstreifen (links) und seine typische elektrische Anordnung in einer Wheatstoneschen Messbrücke

Diagram

Description automatically generated

Figure 4.5 Force Sensor on the Wrist of a Manipulator

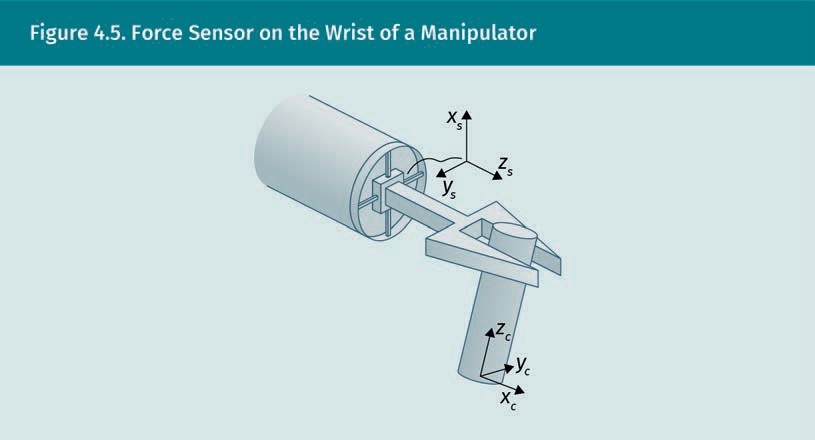
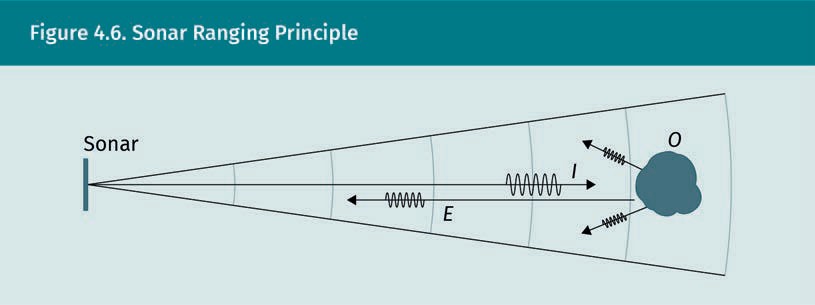
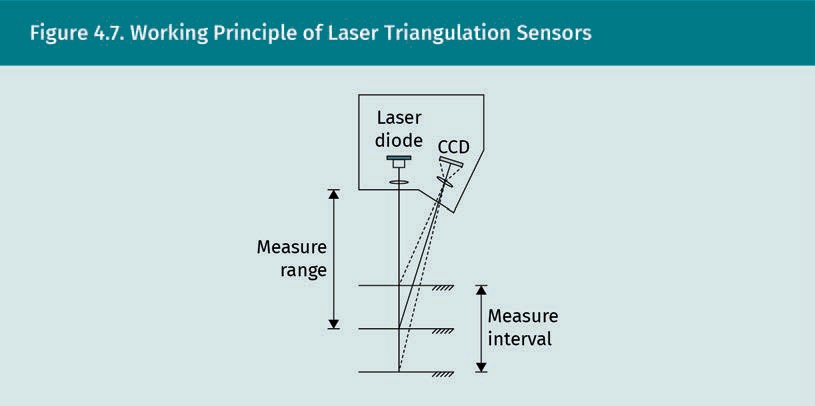
Abbildung 4.5 Kraftsensor am Kugelgelenk eines Manipulators

Figure 4.6 Sonar Ranging Principle

Abbildung 4.6 Prinzip der Sonarentfernungsmessung

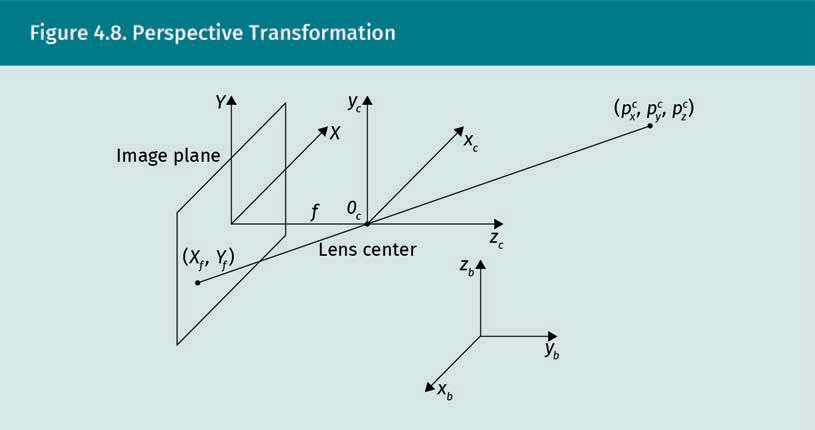
|  |  |
| --- | --- |
| Sonar | Sonar |

Figure 4.7 Working Principle of Laser Triangulation Sensors

Abbildung 4.7 Funktionsprinzip von Laser-Triangulationssensoren

|  |  |
| --- | --- |
| Measure range | Abstand messen |
| Laser diode | Laserdiode |
| CCD | CCD |
| Measure interval | Intervall messen |

Figure 4.8 Perspective Transformation

Abbildung 4.8 Perspektivische Transformation

|  |  |
| --- | --- |
| Image plane | Bildebene |
| Lens center | Linsenzentrum |

Figure 5.1 Example of a Dynamic Task

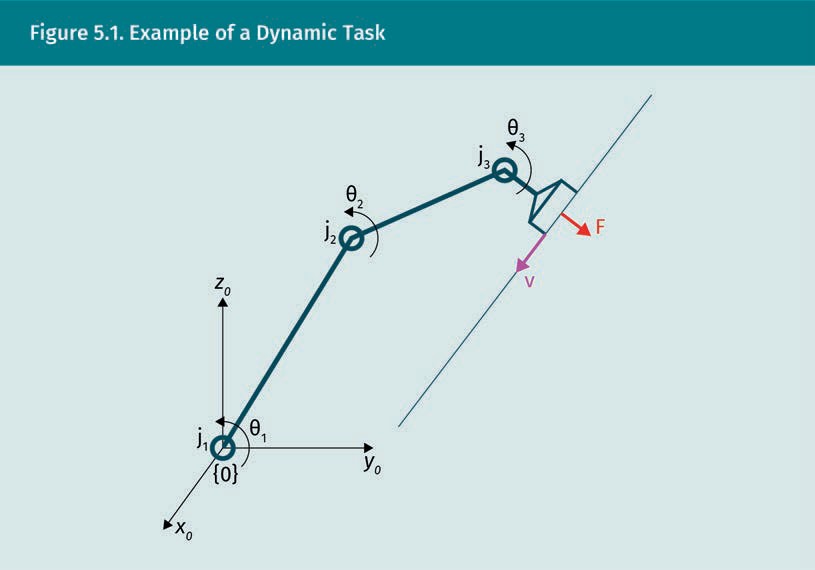
Abbildung 5.1 Beispiel für eine dynamische Aufgabe

Figure 5.2 Dynamics of Robots

Abbildung 5.2 Dynamik von Robotern

A picture containing diagram

Description automatically generated

|  |  |
| --- | --- |
| Dynamics | Dynamik |

Figure 5.3 Kinetic Energy of a Rigid Body

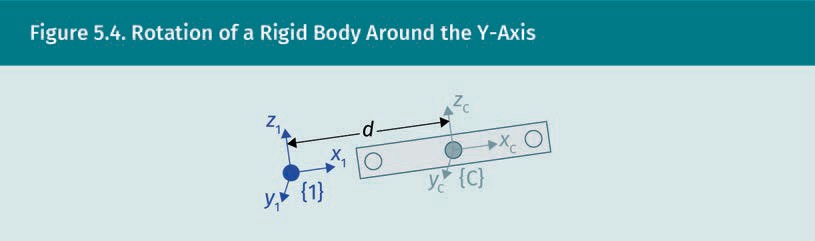
Abbildung 5.3 Kinetische Energie eines starren Körpers

Chart, diagram

Description automatically generated

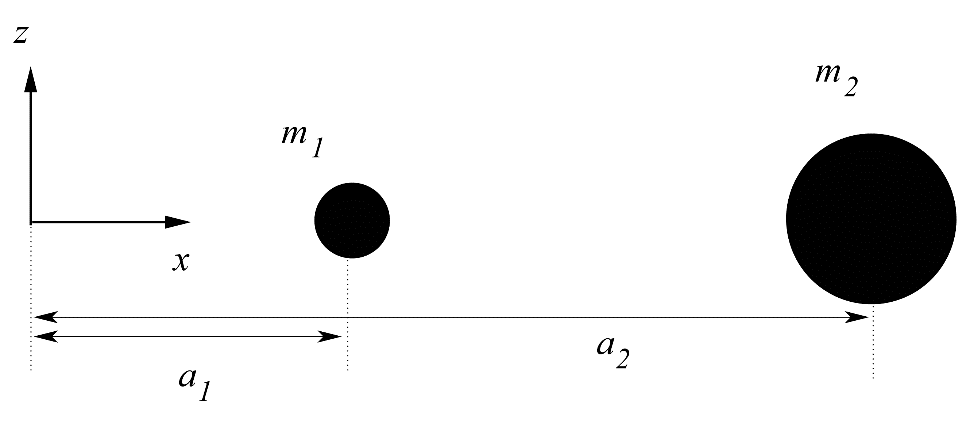
|  |  |
| --- | --- |
| Elementary particle of volume dV | Elementarteilchen mit dem Volumen dV |

Figure 5.4 Rotation of a Rigid Body Around the Y-Axis

Abbildung 5.4 Rotation eines starren Körpers um die Y-Achse

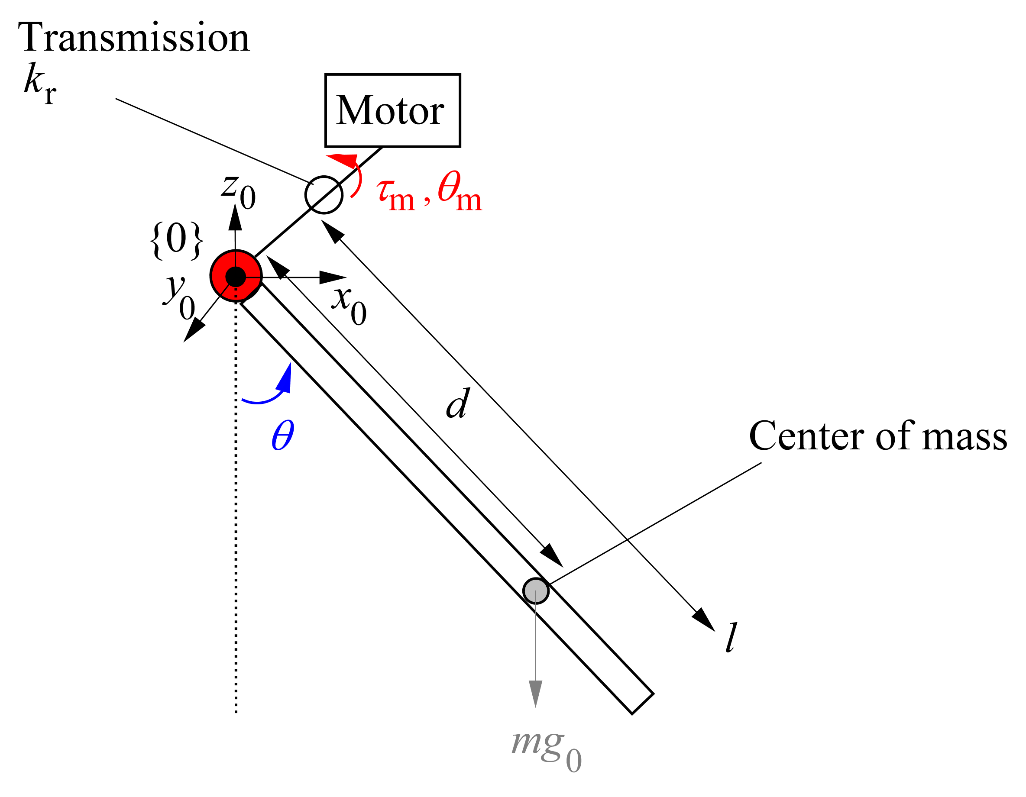
Self-Check Question, Unit 5.1, No. 1 (Question)

Frage zur Selbstkontrolle, Lektion 5.1, Nr. 1 (Frage)



Self-Check Question, Unit 5.1, No. 2 (Question)

Frage zur Selbstkontrolle, Lektion 5.1, Nr. 2 (Frage)



|  |  |
| --- | --- |
| Transmission | Übertragung |
| Motor | Motor |
| Center of mass | Massenmittelpunkt |

Self-Check Question, Unit 5.1, No. 3 (Question)

Frage zur Selbstkontrolle, Lektion 5.1, Nr. 3 (Frage)

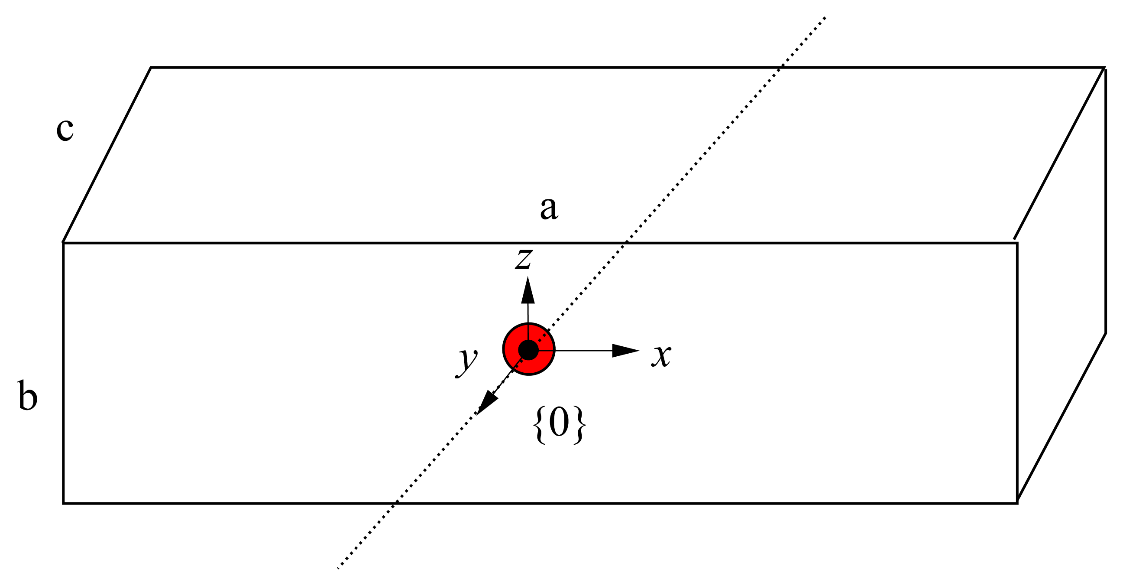
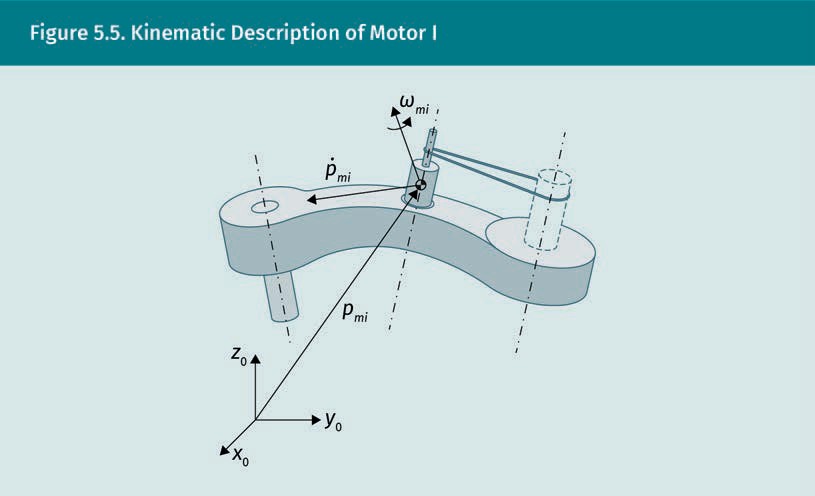
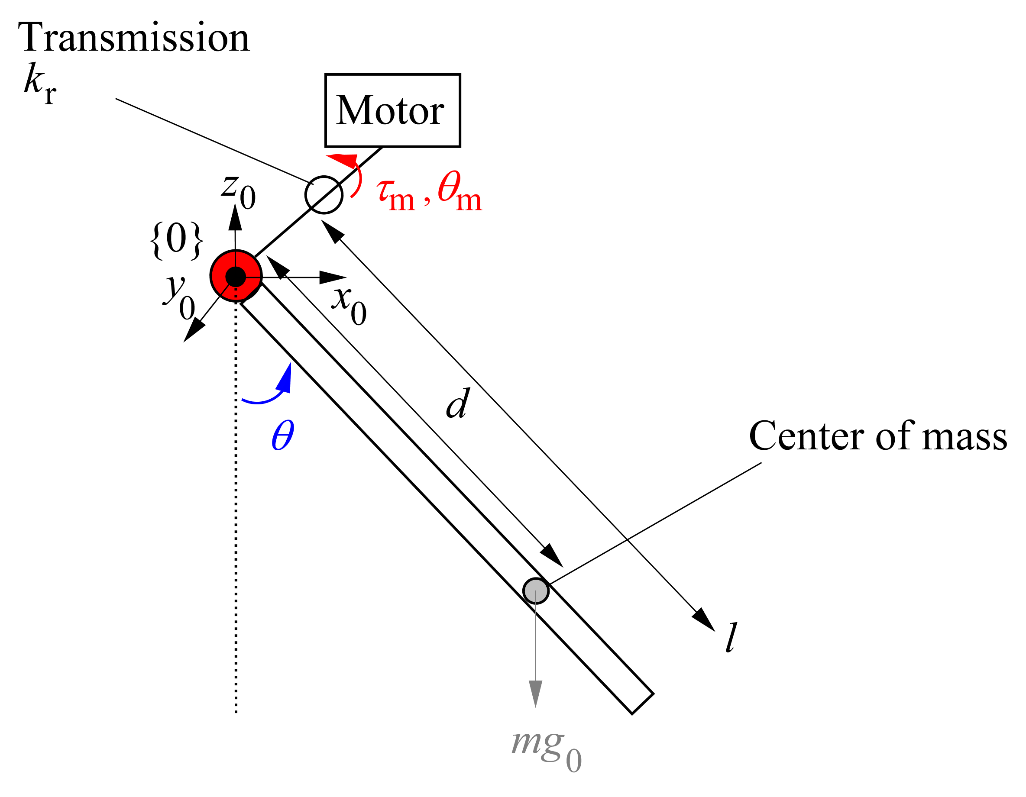


Figure 5.5 Kinematic Description of Motor *I*

Abbildung 5.5 Kinematische Beschreibung des Motors *I*

Self-Check Question, Unit 5.2, No. 3 (Question)

Frage zur Selbstkontrolle, Lektion 5.2, Nr. 3 (Frage)



|  |  |
| --- | --- |
| Transmission | Übertragung |
| Motor | Motor |
| Center of mass | Massenmittelpunkt |

Figure 5.6 Forces Acting on Link *i*

Abbildung 5.6 Auf Glied *i* wirkende Kräfte

Chart

Description automatically generated

|  |  |
| --- | --- |
| Motor of joint i+1 | Motor des Gelenks i+1 |
| Link i-1 | Glied i-1 |
| Link i+1 | Glied i+1 |
| Axis i | Achse i |
| Axis i+1 | Achse i+1 |

Figure 5.7 Forces and Torques Acting on Link *i*

Abbildung 5.7 Auf Glied *i* wirkende Kräfte und Drehmomente

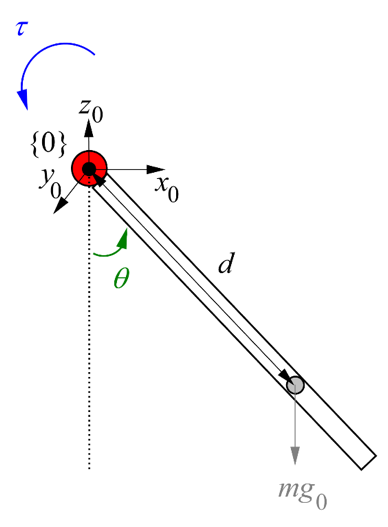
Chart, radar chart

Description automatically generated

|  |  |
| --- | --- |
| Motor of joint i+1 | Motor des Gelenks i+1 |
| Link i-1 | Glied i-1 |
| Link i+1 | Glied i+1 |
| Axis i | Achse i |
| Axis i+1 | Achse i+1 |

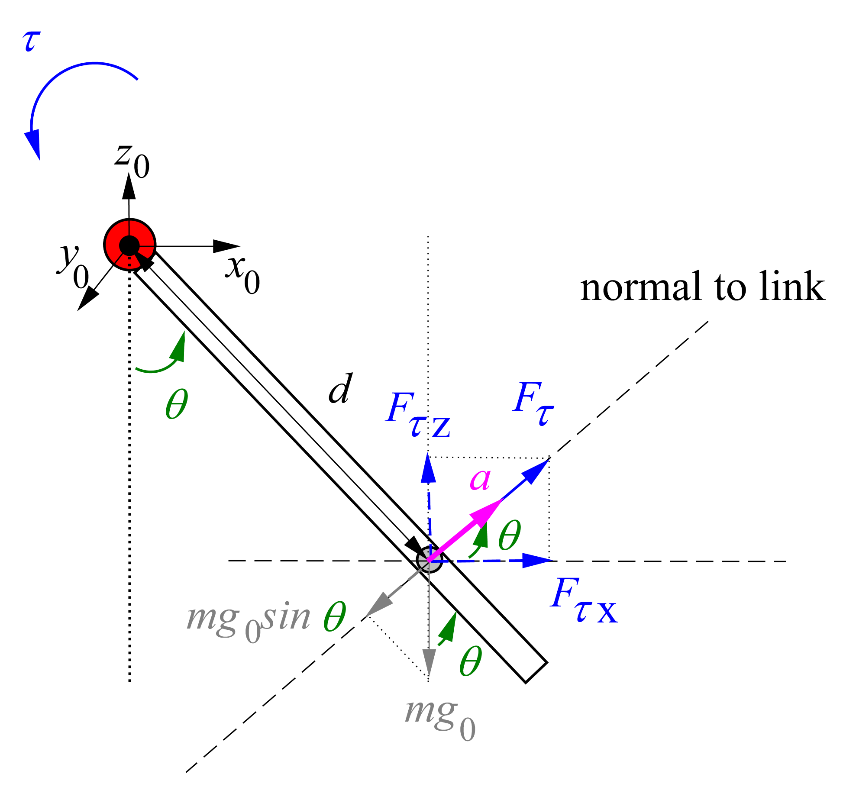
Self-Check Question, Unit 5.3, No. 1 (Question)

Frage zur Selbstkontrolle, Lektion 5.3, Nr. 1 (Frage)



Self-Check Question, Unit 5.3, No. 1 (Answer)

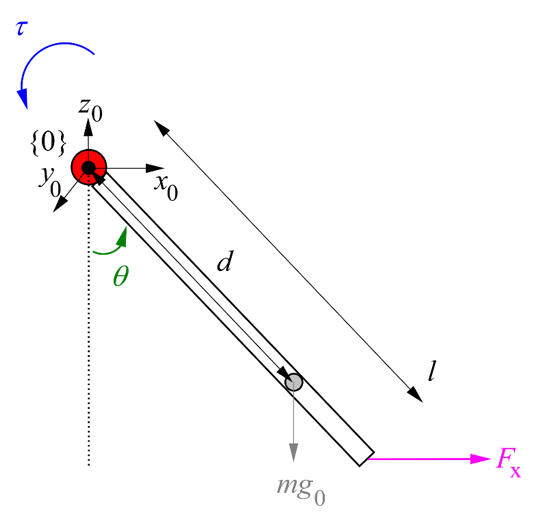
Frage zur Selbstkontrolle, Lektion 5.3, Nr. 1 (Antwort)



|  |  |
| --- | --- |
| Normal to link |  |

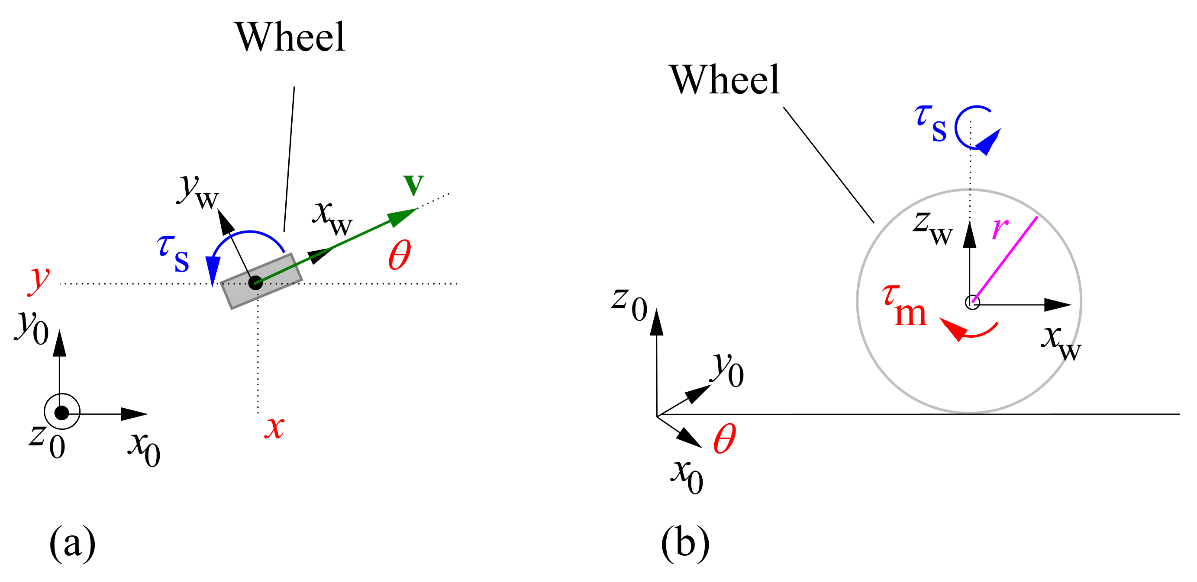
Self-Check Question, Unit 5.4, No. 1 (Question)

Frage zur Selbstkontrolle, Lektion 5.4, Nr. 1 (Frage)



Self-Check Question, Unit 5.5, No. 2 (Question)

Frage zur Selbstkontrolle, Lektion 5.5, Nr. 2 (Frage)



|  |  |
| --- | --- |
| Wheel | Rad |

Self-Check Question, Unit 5.5, No. 2 (Answer)

Frage zur Selbstkontrolle, Lektion 5.5, Nr. 2 (Antwort)

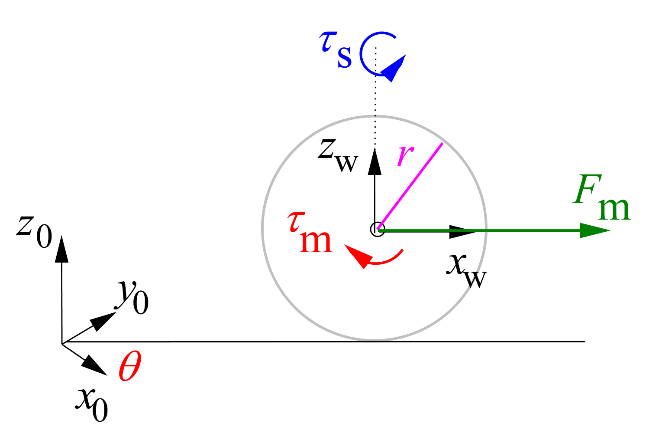


Figure 6.1 The Sense-Plan-Act Paradigm

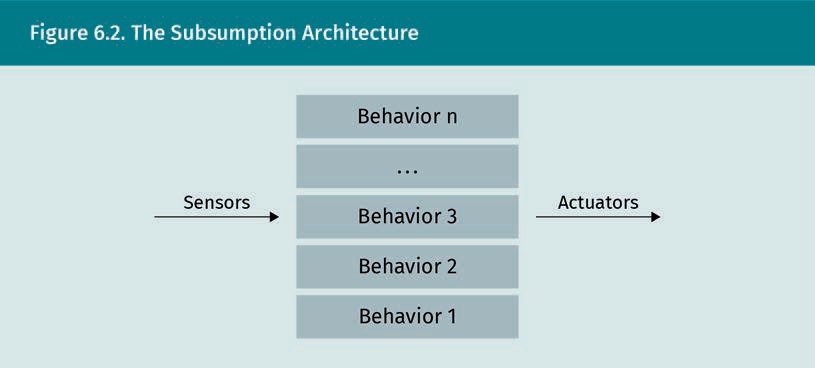
Abbildung 6.1 Das Wahrnehmen-Planen-Handeln-Paradigma

Diagram

Description automatically generated

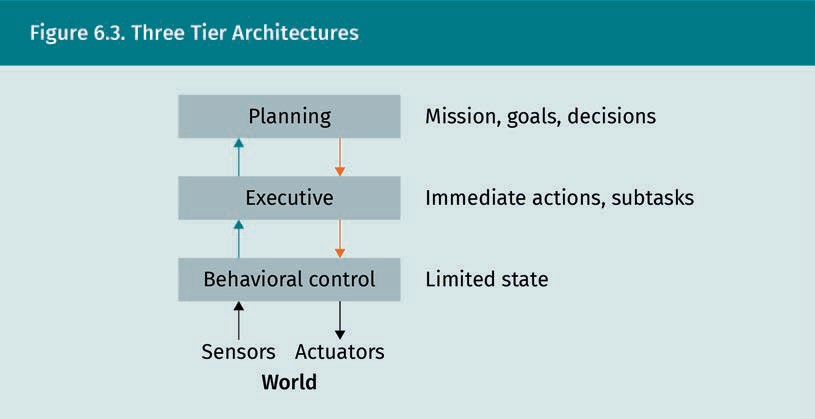
|  |  |
| --- | --- |
| Sensors | Sensoren |
| Sense | Wahrnehmen |
| Perception | Wahrnehmung |
| Knowledge models | Wissensmodelle |
| Decision strategies | Entscheidungsstrategien |
| Plan | Planen |
| Act | Handeln |
| Control | Steuerung |
| Actuators | Aktoren |

Figure 6.2 The Subsumption Architecture

Abbildung 6.2 Die Subsumptionsarchitektur

|  |  |
| --- | --- |
| Sensors | Sensoren |
| Actuators | Aktoren |
| Behavior | Verhalten |

Figure 6.3 Three Tier Architectures

Abbildung 6.3 Dreistufige Architekturen

|  |  |
| --- | --- |
| Planning | Planung |
| Executive | Ausführung |
| Behavioral control | Verhaltenssteuerung |
| Sensors | Sensoren |
| Actuators | Aktoren |
| World | Welt |
| Mission, goals, decisions | Auftrag, Ziele, Entscheidungen |
| Immediate actions, subtasks | Unmittelbare Handlungen, Teilaufgaben |
| Limited state | Eingeschränkter Zustand |

Figure 6.4 Generic Functional Architecture of a Robotic System

Abbildung 6.4 Allgemeine funktionale Architektur eines Robotersystems

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Global memory | Globaler Speicher |
| Sensing perception | Wahrnehmung |
| Knowledge models | Wissensmodelle |
| Decision strategies | Entscheidungsstrategien |
| Sensing | Sensorik |
| Actuating | Betätigung |
| Task | Aufgabe |
| Action | Handlung |
| Primitive | Primitiv |
| Servo | Servo |
| Operator interface | Bedienerschnittstelle |

Figure 6.5 Typical Dynamic Profiles for Reaching a Commanded Reference Value

Abbildung 6.5 Typische dynamische Profile für das Erreichen eines befohlenen Referenzwerts

Chart, line chart

Description automatically generated

|  |  |
| --- | --- |
| Reference | Referenzwert |

Figure 6.6 Step Response of First Order System with a1 = 1, a0 = 1, b0 = 1

Abbildung 6.6 Stufenantwort eines Systems erster Ordnung mit a1 = 1, a0 = 1, b0 = 1

Chart

Description automatically generated with medium confidence

|  |  |
| --- | --- |
| Output | Ausgabe |
| Time (seconds) | Zeit (Sekunden) |

Figure 6.7 Step Response of Second Order System with a2 = 1, a1 = 1, b0 = 1

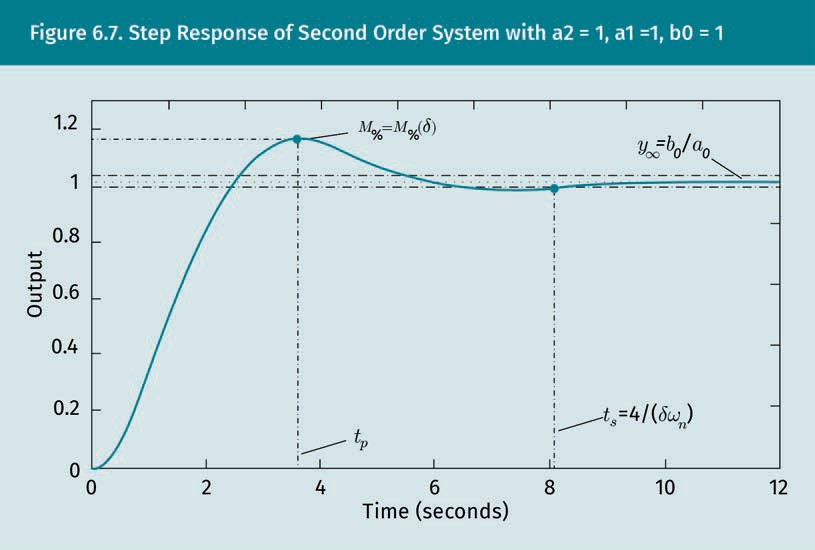
Abbildung 6.7 Stufenantwort eines Systems zweiter Ordnung mit a2 = 1, a1 = 1, b0 = 1

Figure 6.8 Feedback Control Schema

Abbildung 6.8 Schema der Rückkopplungssteuerung (Regelung)

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Reference | Referenzwert |
| Control | Steuerung |
| Robot | Roboter |
| World | Welt |

Figure 6.9 Joint Space Control Schema

Abbildung 6.9 Schema der Gelenkraumsteuerung

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Inverse kinematics | Inverse Kinematik |
| Controller | Controller |
| Actuators | Aktoren |
| Drives | Antriebe |
| Manipulator | Manipulator |
| Transducers | Umformer |

Figure 6.10 Operational Space Control

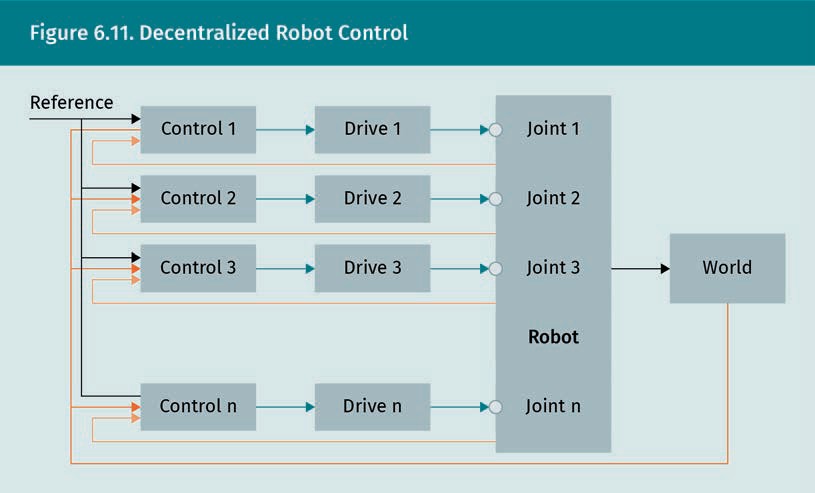
Abbildung 6.10 Betriebsraumsteuerung

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Controller | Controller |
| Actuators | Aktoren |
| Drives | Antriebe |
| Manipulator | Manipulator |
| Transducers | Umformer |

Figure 6.11 Decentralized Robot Control

Abbildung 6.11 Dezentrale Robotersteuerung

|  |  |
| --- | --- |
| Reference | Referenzwert |
| Control | Steuerung |
| Drive | Antrieb |
| Joint | Gelenk |
| Robot | Roboter |
| World | Welt |

Figure 6.12 Centralized Robot Control

Abbildung 6.12 Zentrale Robotersteuerung

Diagram

Description automatically generated

|  |  |
| --- | --- |
| Reference | Referenzwert |
| Control | Steuerung |
| Drive n | Antrieb n |
| Joint n | Gelenk n |
| Robot | Roboter |
| World | Welt |