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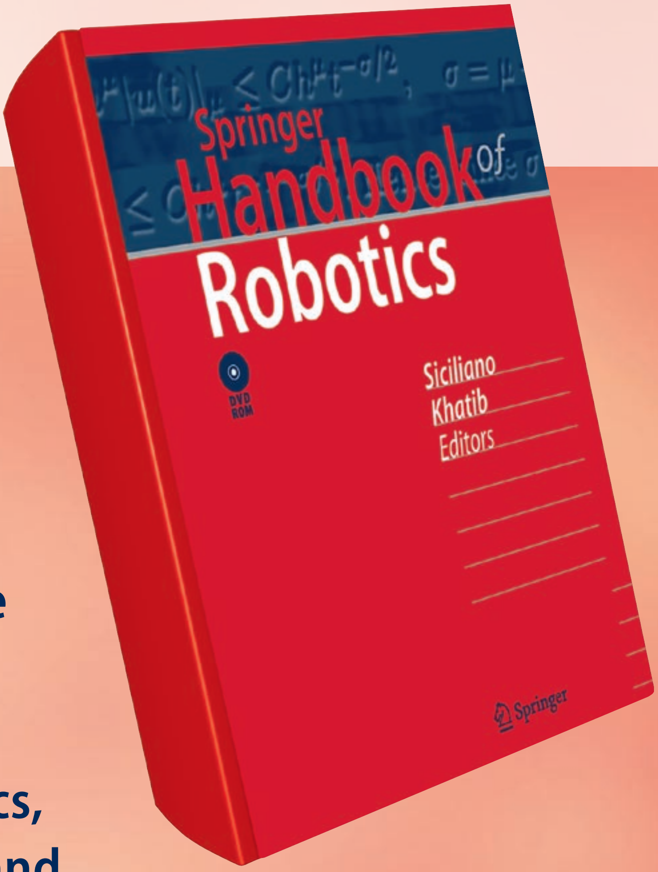
Springer Handbook of Robotics

Edited by **B. Siciliano, O. Khatib**



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Springer Handbook of Robotics

B. Siciliano, Università degli Studi di Napoli Federico II, Naples, Italy; **O. Khatib**, Stanford University, Stanford, CA, USA (Eds.)

Robotics is undergoing a major transformation in scope and dimension. Starting from a predominantly industrial focus, robotics has been rapidly expanding into the challenges of unstructured environments. **The Springer Handbook of Robotics** incorporates these new developments and therefore basically differs from other handbooks of robotics focusing on industrial applications. It presents a widespread and well-structured coverage from the foundations of robotics, through the consolidated methodologies and technologies, up to the new emerging application areas of robotics. The handbook is an ideal resource for robotics experts but also for people new to this expanding field such as engineers, medical doctors, computer scientists, designers; edited by two internationally renowned experts.

- ► Research- and application-oriented handbook covering one of the hottest topics in science and technology
- ► A timely and up-to-date reference, edited by two internationally renowned experts
- ► Surveys developments and applications of robotics, in industrial settings and beyond
- ► Ideal for experts as well as people new to this growing field: computer scientists, medical doctors and engineers

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Oussama Khatib is Professor at Stanford University, President of IFRR, the International Foundation of Robotics Research, Distinguished Lecturer of the IEEE Robotics and Automation Society and a recipient of the JARA (Japan Robot Association) Award in Research and Development.

Part Editors

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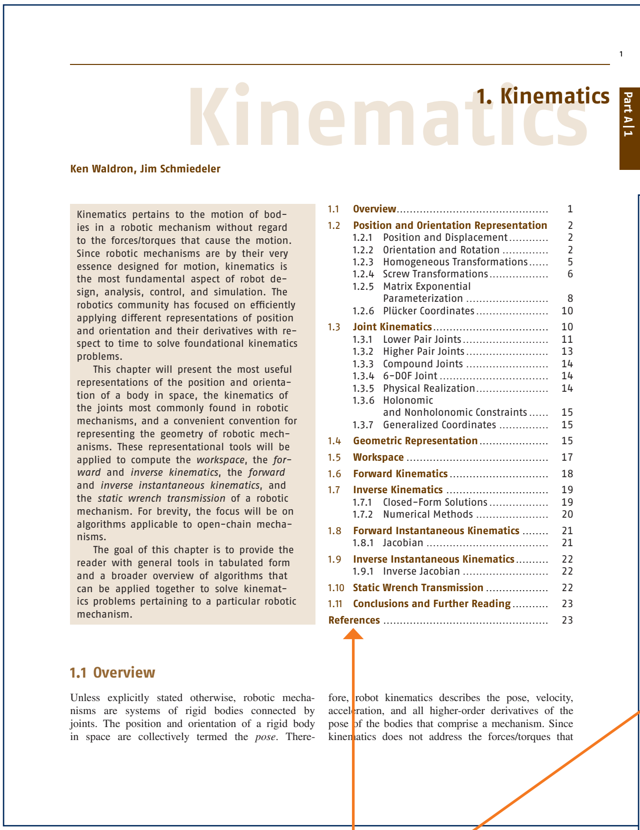

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1. Kinematics

Part A | 1

Ken Waldron, Jim Schmiedeler

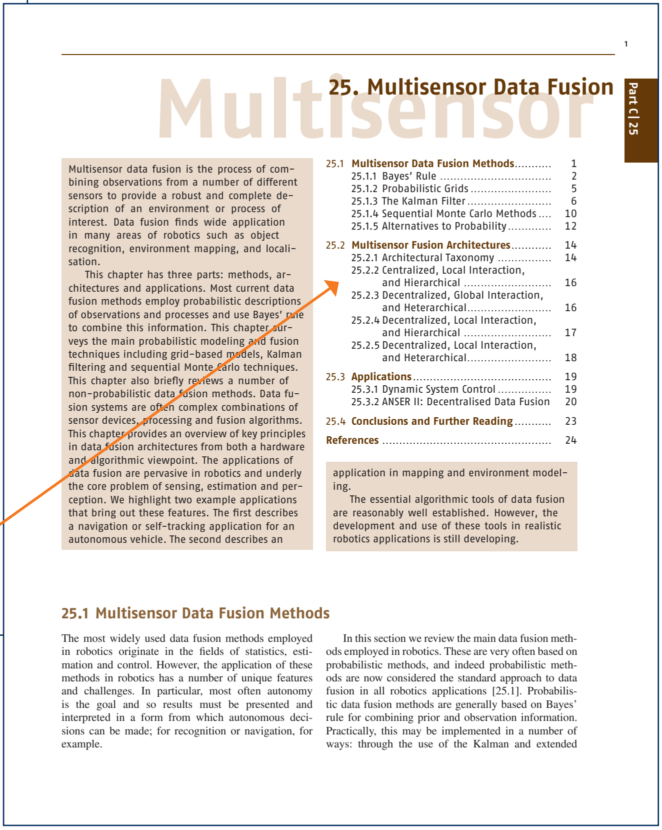
Kinematics pertains to the motion of bodies in a robotic mechanism without regard to the forces/torques that cause the motion. Since robotic mechanisms are by their very essence designed for motion, kinematics is the most fundamental aspect of robot design, analysis, control, and simulation. The robotics community has focused on efficiently applying different representations of position and orientation and their derivatives with respect to time to solve foundational kinematics problems.

This chapter will present the most useful representations of the position and orientation of a body in space, the kinematics of the joints most commonly found in robotic mechanisms, and a convenient convention for representing the geometry of robotic mechanisms. These representational tools will be applied to compute the *workspace*, the *forward* and *inverse kinematics*, the *forward* and *inverse instantaneous kinematics*, and the *static wrench transmission* of a robotic mechanism. For brevity, the focus will be on algorithms applicable to open-chain mechanisms.

The goal of this chapter is to provide the reader with general tools in tabulated form and a broader overview of algorithms that can be applied together to solve kinematics problems pertaining to a particular robotic mechanism.

1.1 Overview

Unless explicitly stated otherwise, robotic mechanisms are systems of rigid bodies connected by joints. The position and orientation of a rigid body in space are collectively termed the *pose*. Therefore, robot kinematics describes the pose, velocity, acceleration, and all higher-order derivatives of the pose of the bodies that comprise a mechanism. Since kinematics does not address the forces/torques that



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25. Multisensor Data Fusion

Part C | 25

Multisensor data fusion is the process of combining observations from a number of different sensors to provide a robust and complete description of an environment or process of interest. Data fusion finds wide application in many areas of robotics such as object recognition, environment mapping, and localisation.

This chapter has three parts: methods, architectures and applications. Most current data fusion methods employ probabilistic descriptions of observations and processes and use Bayes' rule to combine this information. This chapter surveys the main probabilistic modeling and fusion techniques including grid-based models, Kalman filtering and sequential Monte Carlo techniques. This chapter also briefly reviews a number of non-probabilistic data fusion methods. Data fusion systems are often complex combinations of sensor devices, processing and fusion algorithms. This chapter provides an overview of key principles in data fusion architectures from both a hardware and algorithmic viewpoint. The applications of data fusion are pervasive in robotics and underly the core problem of sensing, estimation and perception. We highlight two example applications that bring out these features. The first describes a navigation or self-tracking application for an autonomous vehicle. The second describes an application in mapping and environment modeling.

The essential algorithmic tools of data fusion are reasonably well established. However, the development and use of these tools in realistic robotics applications is still developing.

25.1 Multisensor Data Fusion Methods

The most widely used data fusion methods employed in robotics originate in the fields of statistics, estimation and control. However, the application of these methods in robotics has a number of unique features and challenges. In particular, most often autonomy is the goal and so results must be presented and interpreted in a form from which autonomous decisions can be made; for recognition or navigation, for example.

In this section we review the main data fusion methods employed in robotics. These are very often based on probabilistic methods, and indeed probabilistic methods are now considered the standard approach to data fusion in all robotics applications [25.1]. Probabilistic data fusion methods are generally based on Bayes' rule for combining prior and observation information. Practically, this may be implemented in a number of ways: through the use of the Kalman and extended

Each chapter comes with a summary and its own index for cross-referencing to sections

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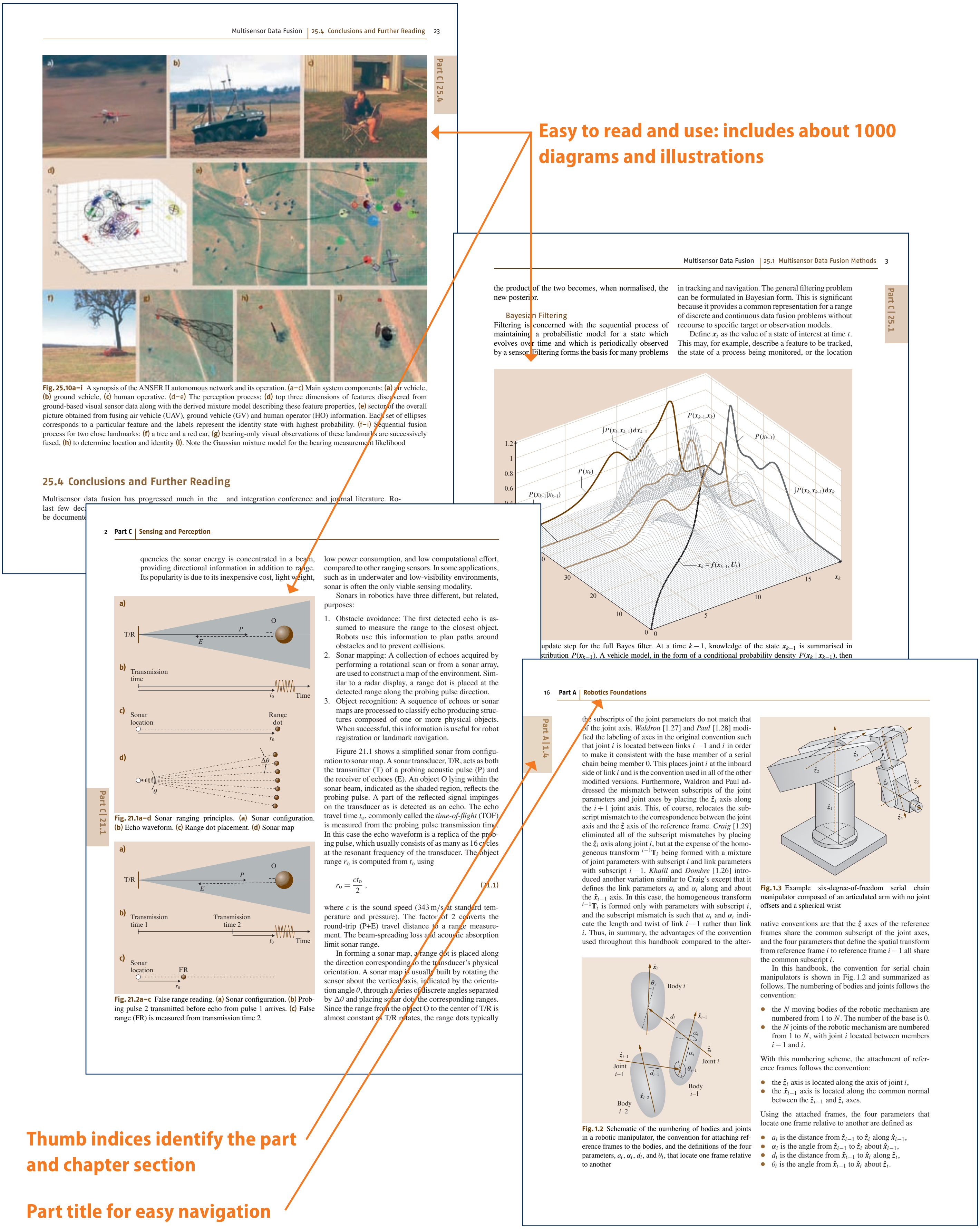

Multisensor Data Fusion | 25.4 Conclusions and Further Reading 23

Part C | 25.4

Fig. 25.10a–i A synopsis of the ANSER II autonomous network and its operation. **(a–c)** Main system components; **(a)** air vehicle, **(b)** ground vehicle, **(c)** human operative. **(d–e)** The perception process; **(d)** top three dimensions of features discovered from ground-based visual sensor data along with the derived mixture model describing these feature properties, **(e)** sector of the overall picture obtained from fusing air vehicle (UAV), ground vehicle (GV) and human operator (HO) information. Each set of ellipses corresponds to a particular feature and the labels represent the identity state with highest probability. **(f–i)** Sequential fusion process for two close landmarks: **(f)** a tree and a red car, **(g)** bearing-only visual observations of these landmarks are successively fused, **(h)** to determine location and identity **(i)**. Note the Gaussian mixture model for the bearing measurement likelihood

25.4 Conclusions and Further Reading

Multisensor data fusion has progressed much in the last few deca… be documente… and integration conference and journal literature. Ro-

Multisensor Data Fusion | 25.1 Multisensor Data Fusion Methods 3

Part C | 25.1

the product of the two becomes, when normalised, the new posterior.

Bayesian Filtering

Filtering is concerned with the sequential process of maintaining a probabilistic model for a state which evolves over time and which is periodically observed by a sensor. Filtering forms the basis for many problems in tracking and navigation. The general filtering problem can be formulated in Bayesian form. This is significant because it provides a common representation for a range of discrete and continuous data fusion problems without recourse to specific target or observation models.

Define $\boldsymbol{x}_t$ as the value of a state of interest at time t. This may, for example, describe a feature to be tracked, the state of a process being monitored, or the location

…update step for the full Bayes filter. At a time $k-1$, knowledge of the state $\boldsymbol{x}_{k-1}$ is summarised in …stribution $P(\boldsymbol{x}_{k-1})$. A vehicle model, in the form of a conditional probability density $P(\boldsymbol{x}_k \mid \boldsymbol{x}_{k-1})$, then

2 Part C | Sensing and Perception

Part C | 21.1

quencies the sonar energy is concentrated in a beam, providing directional information in addition to range. Its popularity is due to its inexpensive cost, light weight, low power consumption, and low computational effort, compared to other ranging sensors. In some applications, such as in underwater and low-visibility environments, sonar is often the only viable sensing modality.

Sonars in robotics have three different, but related, purposes:

1. Obstacle avoidance: The first detected echo is assumed to measure the range to the closest object. Robots use this information to plan paths around obstacles and to prevent collisions.
2. Sonar mapping: A collection of echoes acquired by performing a rotational scan or from a sonar array, are used to construct a map of the environment. Similar to a radar display, a range dot is placed at the detected range along the probing pulse direction.
3. Object recognition: A sequence of echoes or sonar maps are processed to classify echo producing structures composed of one or more physical objects. When successful, this information is useful for robot registration or landmark navigation.

Figure 21.1 shows a simplified sonar from configuration to sonar map. A sonar transducer, T/R, acts as both the transmitter (T) of a probing acoustic pulse (P) and the receiver of echoes (E). An object O lying within the sonar beam, indicated as the shaded region, reflects the probing pulse. A part of the reflected signal impinges on the transducer as is detected as an echo. The echo travel time t_o, commonly called the *time-of-flight* (TOF) is measured from the probing pulse transmission time. In this case the echo waveform is a replica of the probing pulse, which usually consists of as many as 16 cycles at the resonant frequency of the transducer. The object range r_o is computed from t_o using

$$r_o = \frac{ct_o}{2}\,, \tag{21.1}$$

where c is the sound speed (343 m/s at standard temperature and pressure). The factor of 2 converts the round-trip (P+E) travel distance to a range measurement. The beam-spreading loss and acoustic absorption limit sonar range.

In forming a sonar map, a range dot is placed along the direction corresponding to the transducer's physical orientation. A sonar map is usually built by rotating the sensor about the vertical axis, indicated by the orientation angle θ, through a series of discrete angles separated by $\Delta\theta$ and placing sonar dots the corresponding ranges. Since the range from the object O to the center of T/R is almost constant as T/R rotates, the range dots typically

Fig. 21.1a–d Sonar ranging principles. **(a)** Sonar configuration. **(b)** Echo waveform. **(c)** Range dot placement. **(d)** Sonar map

Fig. 21.2a–c False range reading. **(a)** Sonar configuration. **(b)** Probing pulse 2 transmitted before echo from pulse 1 arrives. **(c)** False range (FR) is measured from transmission time 2

16 Part A | Robotics Foundations

Part A | 1.4

the subscripts of the joint parameters do not match that of the joint axis. *Waldron* [1.27] and *Paul* [1.28] modified the labeling of axes in the original convention such that joint i is located between links $i-1$ and i in order to make it consistent with the base member of a serial chain being member 0. This places joint i at the inboard side of link i and is the convention used in all of the other modified versions. Furthermore, Waldron and Paul addressed the mismatch between subscripts of the joint parameters and joint axes by placing the $\hat{z}_i$ axis along the $i+1$ joint axis. This, of course, relocates the subscript mismatch to the correspondence between the joint axis and the $\hat{z}$ axis of the reference frame. *Craig* [1.29] eliminated all of the subscript mismatches by placing the $\hat{z}_i$ axis along joint i, but at the expense of the homogeneous transform ${}^{i-1}\mathbf{T}_i$ being formed with a mixture of joint parameters with subscript i and link parameters with subscript $i-1$. *Khalil* and *Dombre* [1.26] introduced another variation similar to Craig's except that it defines the link parameters a_i and α_i along and about the $\hat{\boldsymbol{x}}_{i-1}$ axis. In this case, the homogeneous transform ${}^{i-1}\mathbf{T}_i$ is formed only with parameters with subscript i, and the subscript mismatch is such that a_i and α_i indicate the length and twist of link $i-1$ rather than link i. Thus, in summary, the advantages of the convention used throughout this handbook compared to the alternative conventions are that the $\hat{z}$ axes of the reference frames share the common subscript of the joint axes, and the four parameters that define the spatial transform from reference frame i to reference frame $i-1$ all share the common subscript i.

In this handbook, the convention for serial chain manipulators is shown in Fig. 1.2 and summarized as follows. The numbering of bodies and joints follows the convention:

- the N moving bodies of the robotic mechanism are numbered from 1 to N. The number of the base is 0.
- the N joints of the robotic mechanism are numbered from 1 to N, with joint i located between members $i-1$ and i.

With this numbering scheme, the attachment of reference frames follows the convention:

- the $\hat{z}_i$ axis is located along the axis of joint i,
- the $\hat{\boldsymbol{x}}_{i-1}$ axis is located along the common normal between the $\hat{z}_{i-1}$ and $\hat{z}_i$ axes.

Using the attached frames, the four parameters that locate one frame relative to another are defined as

- a_i is the distance from $\hat{z}_{i-1}$ to $\hat{z}_i$ along $\hat{\boldsymbol{x}}_{i-1}$,
- α_i is the angle from $\hat{z}_{i-1}$ to $\hat{z}_i$ about $\hat{\boldsymbol{x}}_{i-1}$,
- d_i is the distance from $\hat{\boldsymbol{x}}_{i-1}$ to $\hat{\boldsymbol{x}}_i$ along $\hat{z}_i$,
- θ_i is the angle from $\hat{\boldsymbol{x}}_{i-1}$ to $\hat{\boldsymbol{x}}_i$ about $\hat{z}_i$.

Fig. 1.3 Example six-degree-of-freedom serial chain manipulator composed of an articulated arm with no joint offsets and a spherical wrist

Fig. 1.2 Schematic of the numbering of bodies and joints in a robotic manipulator, the convention for attaching reference frames to the bodies, and the definitions of the four parameters, a_i, α_i, d_i, and θ_i, that locate one frame relative to another

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