

Achim Schweikard · Floris Ernst

Medical Robotics

Achim Schweik

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Achim Schweikard
Institute for Robotics
and Cognitive Systems
University of Lübeck
Lübeck, Germany

Floris Ernst
Institute for Robotics
and Cognitive Systems
University of Lübeck
Lübeck, Germany

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Preface

Medical robotics is an interdisciplinary field, with methods from computer science, mathematics, mechanical engineering, and medicine. The field emerged in the 1980s as a new branch of robotics. Robotics itself was then a branch of artificial intelligence. However, a number of technical and mathematical problems had to be solved to bring robots to routine clinical use. These problems were far outside the scope of artificial intelligence, and this supported the emergence of the new field.

When comparing medical robotics to industrial robotics, we see that the latter field is the one that sells most robots. By contrast, some of the most challenging research problems arise in medical robotics: there is a need for improving the accuracy of surgical procedures, and image guidance has become a central element of this. If we imagine that robotic exoskeletons can help paralyzed patients, it becomes clear that we will need methods for motion learning and brain-computer interfaces.

We wrote this book as a textbook for a one-semester class on medical robotics. When writing this book, we were guided by two thoughts:

- Computer scientists and engineers should learn to understand application domains, and medicine is an ideal application domain for this purpose.
- The book should be suitable as a first course in robotics.

Comparing to standard textbooks on robotics, four elements have been added here: (1) seven-joint robots; (2) navigation, calibration, and registration; (3) connection to machine learning; and (4) applications in surgical robotics, rehabilitation robotics, and neuroengineering. The text relies entirely on the most elementary mathematical tools, and we give a detailed introduction for each new method. At the end of each chapter, we provide exercises, preparing the grounds for the tools in the next chapters, while linking to the methods in the current chapter. Chapter 1 introduces the main applications of medical robotics.

Chapter 2 presents basic methods for describing position and orientation as well as forward robot kinematics. This includes matrices, angles, and the analysis of simple linkages.

Chapter 3 introduces inverse kinematics for robots. We develop the inverse kinematics for a seven-joint lightweight robot, called the DLR-Kuka arm. This robot is designed for applications requiring direct interaction with an operator. To obtain an inverse solution, we first solve the kinematic equations for a standard six-joint robot with revolute joints, called the elbow manipulator with spherical wrist. We obtain a building-block strategy with which common types of robots can be analyzed.

Geometric methods for inverse kinematics are an alternative to algebraic methods. We illustrate geometric methods for the kinematic analysis of common medical devices.

In Chap. 4, we consider Jacobi-matrices. There are two types of Jacobians: the analytic Jacobian and the geometric Jacobian. The analytic Jacobian offers alternative methods for the inverse analysis of robots. The geometric Jacobian is a basic tool for velocity kinematics and for analyzing the relationship between joint torques and static forces/torques acting at the tool. We apply the geometric Jacobian to problems involving C-arm X-ray imaging and robot design.

Chapter 5 establishes a connection to the classical tools from medical imaging, i.e., MR, CT, ultrasound, and X-ray imaging. With this tool set, we address several problems, such as navigation, registration, image calibration, and robotic hand-eye calibration.

Chapter 6 describes methods for treatment planning. Computer programs have been used for treatment planning in radiation oncology since the 1950s. Until the 1990s, conventional systems for radiation

oncology irradiated tumors from a small set of beam directions (typically three to five directions). To move the beam source, five-joint mechanisms with revolute and prismatic joints were used. This changed with the introduction of robotic radiosurgery. Up to 1000 distinct directions can now be used in a single treatment. This greatly increased the complexity of treatment planning.

Chapter 7 is the first chapter (in a series of three chapters) with basic methods from machine learning. We address the problem of tracking anatomical motion (heartbeat, respiration) with a robot. To this end, we learn the motion of a difficult-to-image anatomical target via the motion of a surrogate.

In Chap. 8, we predict respiratory motion to compensate for the time lag of the robot, while tracking a target. Again, machine learning is one of the main elements. In addition, we need a connection to basic methods from signal processing.

In Chap. 9, we consider motion replication. Robots for motion replication are the most commonly used surgical robots. The surgeon moves a passive robot, and thereby issues motion commands to a small replicator robot. We apply tools from machine learning to classify different types of motions, i.e., intended motion, tremor, and noise. In the replication process, we must separate these types of motions (all of which are part of the motion signal). In the same context, we apply the geometric Jacobian to the analysis of static forces and torques.

The three applications in Chaps. 7–9 all converge to a set of methods, which we term “motion learning.” Humans learn motion, and it is obvious that we need dedicated tools for motion learning not only in medical robotics.

Chapter 10 discusses integrated systems in medical robotics. The methods developed in Chaps. 1–9 are the building blocks for such systems. It should be noted that the methods in Chaps. 1–9 have already found their way to the clinic, and have become routine tools, especially in oncology, but also in orthopedics and neurology, most of them via the connection to medical imaging and motion learning.

Chapter 11 gives an overview of methods for neuroprosthetics, brain-machine interfaces, and rehabilitation robotics.

In the appendix, we derive the geometric Jacobian matrix for the six-joint elbow manipulator and for the DLR-Kuka seven-joint robot. We also include solutions to selected exercises.

Additional material is available at <https://medrob-book.rob.uni-luebeck.de>.

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Lübeck, Germany

Achim Schweikard
Floris Ernst

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Chapter 1

Introduction

Robots are now used in many clinical sub-domains, for example: neurosurgery, orthopedic surgery, dental surgery, eye surgery, ear-nose and throat surgery, abdominal surgery/laparoscopy, and radiosurgery. This gives rise to a large number of new methods. However, medical robotics is not limited to surgery. In recent years, four main types of medical robots have emerged:

1. **Robots for Navigation.** The surgical instrument is moved by a robot arm. This allows precise positioning, based on pre-operative imaging. The motion of anatomic structures (e.g. caused by respiration and pulsation) can be tracked.
2. **Robots for Motion Replication.** The robot replicates the surgeon's hand motion, via a passive robotic interface. Thus we can down-scale the motion, reduce tremor and improve minimally invasive methods.
3. **Robots for Imaging.** An imaging device is mounted to a robotic arm, to acquire 2D or 3D images.
4. **Rehabilitation and Prosthetics.** Mechatronic devices can support the recovery process of stroke patients. Robotic exoskeletons controlled by brain-computer interfaces can replace or support damaged anatomical structures.

We will discuss basic methods for each of the four cases. In the following section, we will begin by looking at several examples for surgical navigation.

1.1 Robots for Navigation

A first example of a medical robot is shown in Fig. 1.1. A robot guides a surgical saw. Before the intervention, the surgeon defines a cutting plane for a bone cut. During the operation, the robot places the saw in the predefined plane, and the surgeon can move the saw within this plane. This restricts the motion of the saw, and allows for placing the cuts with high precision.

In the figure, we see two types of robot joints: revolute joints and prismatic joints. For a revolute joint, a rigid link rotates about an axis. A prismatic link slides along a translational axis. The last joint in Fig. 1.1 is a prismatic joint. Here, the prismatic joint is passive, i.e. it is not actuated by a motor. Thus, the surgeon moves the saw by hand, while the motion plane is given by the robot.

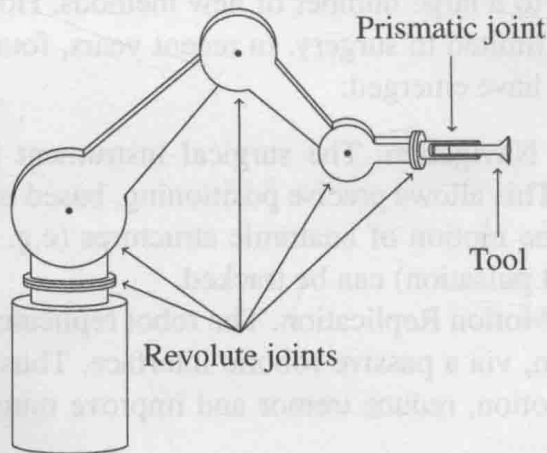


Fig. 1.1: Surgical saw mounted to a robotic arm. The arm itself consists of revolute joints. The saw is mounted to a passive component (prismatic joint). The surgeon moves the saw manually (sliding motion only). By construction, the manual motion of the saw is restricted to a single axis [6]

Remark 1.1

Fig. 1.2 illustrates a schematic notation for jointed mechanisms, for the robot in Fig. 1.1. Revolute joints are denoted by cylinders, where

the cylinder axis specifies the axis of rotation. Prismatic joints are denoted by boxes. The lid of the box indicates the direction of motion.

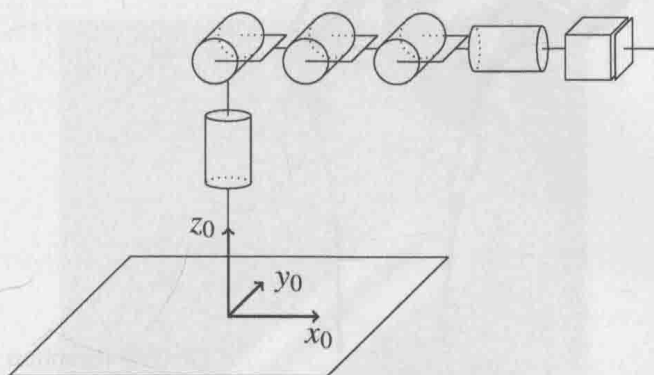


Fig. 1.2: Schematic notation for the robot in Fig. 1.1

In the figure, notice that the first two joint axes (revolute joints) intersect in space. Furthermore, the axes of joints two, three and four are parallel. We also see the axes x_0, y_0 and z_0 of a *base coordinate system*.

(End of Remark 1.1)

1.1.1 Navigation for Orthopedic Surgery

We will now show several examples for navigation problems arising in orthopedic surgery.

Figure 1.3 shows a femur bone. The region shown with the dashed pattern is the target area (e.g. a tumor). The instrument for removing the tumor is a surgical drill. The skin cut is made on the right side (an arrow indicates the drilling direction). The target is on the left side. The tumor is well visible in the CT image, but often not visible in an X-ray image. To remove the tumor, we must guide the drill. Notice also that the drill must not penetrate the joint surface. Here, the pre-operative 3D images must be matched to the intra-operative situation. Figure 1.4 shows the head of a femur bone. A small gap between the head and the rest of the bone is visible (see arrow). Epiphyseolysis is

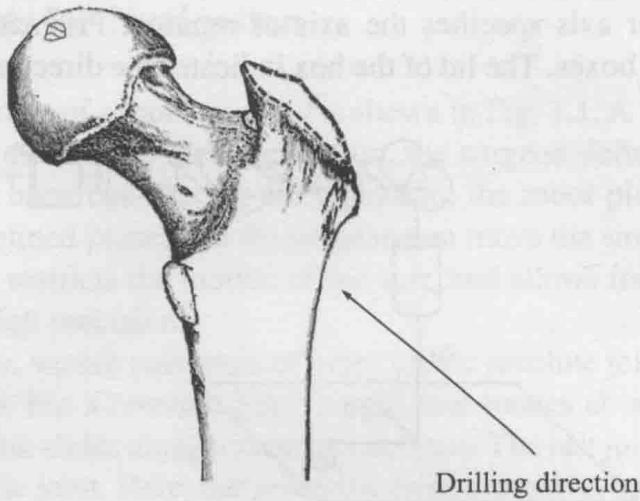


Fig. 1.3: Navigating a surgical drill. Femur figure from [3, Fig. 245]

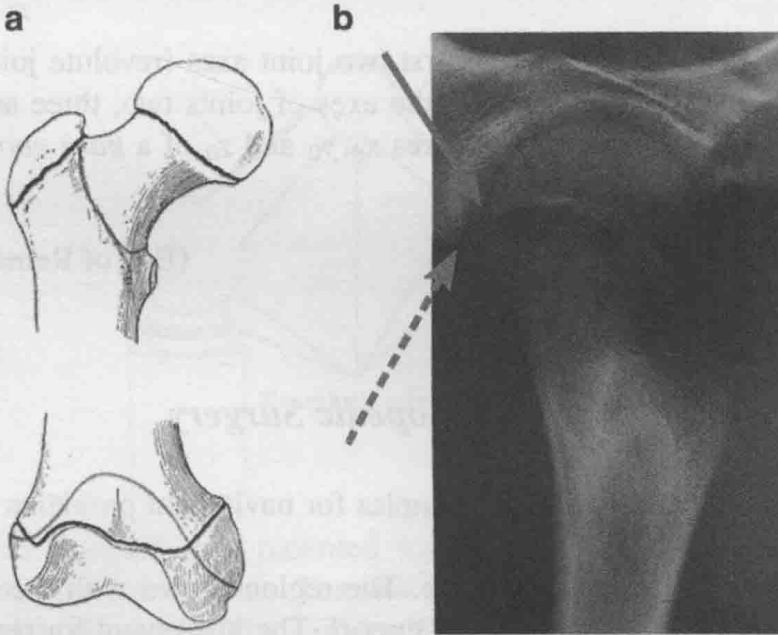


Fig. 1.4: Epiphyseolysis. *Left images:* epiphysal lines of the femur. *Source:* [3, Fig. 253]. *Right image:* X-ray image of epiphyseolysis. The femur bone is displaced against the head, the tips of the two arrows should coincide. **(a)** Epiphysal lines of the femur, shown in black. *Source:* [3, Fig. 253]. **(b)** X-ray of the femur, showing the epiphysal line at the femur head (*solid arrow*)

a condition, in which a fracture along this gap results in a downward slippage of the femur head (Fig. 1.4) [7].

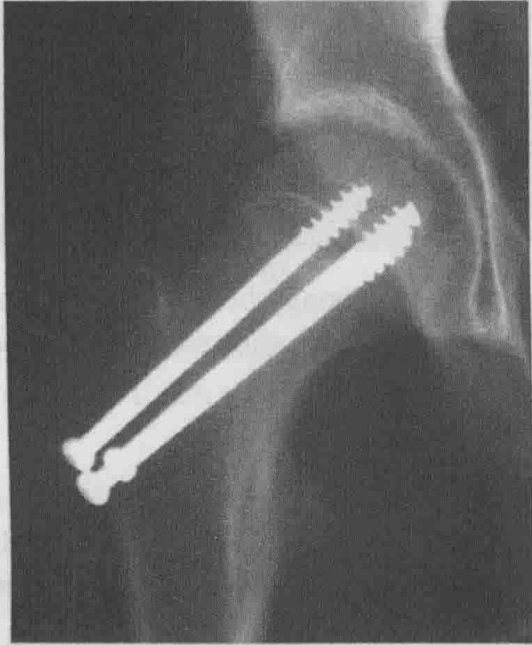


Fig. 1.5: Treatment of epiphyseolysis

To stabilize the femur head, screws are used (Fig. 1.5). However, placing the screws is difficult. The reason is that only the surface of the bone consists of hard material, the *cortical bone*. The interior of the bone, called *cancellous bone*, or spongy bone, is much softer. The screw tip must reach (but not penetrate) the cortical bone surface.

Figure 1.6 shows a cross-section (slice) of a CT-data set, side-by-side with the corresponding MRI slice. The cortical bone is visible as a ring (white/light grey in the CT image, and black in the MRI data). The spongy bone is inside this ring. When placing a screw (as in Fig. 1.5), the tip of the screw should reach, but not penetrate the thin cortical bone layer.