Chapter 6
General System Structures

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Abstract Haptic systems exhibit several basic structures defined by the mechanical in- and outputs, commonly known as impedance or admittance system structures. This chapter describes these structures in open-loop and closed-loop variants and presents commercial realizations as well as common applications of these structures. Based on the different properties of the structures and the intended application, hints for the selection of a suitable structure are given.

When starting the design of haptic devices, the engineer has to deal with the general structures they can be composed of. Haptic devices of similar functionality can consist of very different modules. There are four big classes of possible system designs:

1. "open-loop admittance controlled systems"
2. "closed-loop admittance controlled systems"
3. "open-loop impedance controlled systems"
4. "closed-loop impedance controlled systems".

6.1 Open-Loop and Closed-Loop Systems

An open-loop system is a system in which there is no feedback. Thus, the noise effects appear in output of the system. Moreover, the input has no reaction to different noises (Fig. 6.1a).

Christian Hatzfeld deceased before the publication of this book.

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But in closed-loop systems, the output influences the input, and the input is changed according to the last output. Thus, in these systems, there is a feedback signal that sends the last output to the input (Fig. 6.1b). So, this system can deal with the noise better.
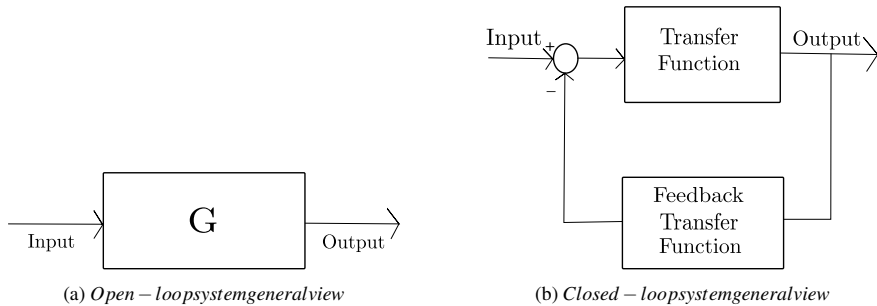

(a) *Open − loop system general view*   (b) *Closed − loop system general view*

Fig. 6.1 Different loop states

6.2 Open-Loop and Closed-Loop Systems Comparison

The most important difference between these two types of systems is in the usage of the error signal. In closed-loop systems, there is an ability to provide the minimum error. Thus, this system is more precise and independent of the noise. However, the open-loop systems are more simple and easy to implement. They are mostly used in a combination with closed-loop systems.

6.3 Impedance and Admittance Concept

The word impedance is coming from the word "impedire" which means "to hinder something". Impedance is a kind of resistance in mechanical and electrical systems. In an electric circuit, the current is related to the number of electrons passing the circuit at a certain time. The voltage is the energy that helps them to go through it. But, the resistance in the circuit decreases the speed of the electrons. So when we need more voltage to reach a certain amount of current means that the resistance is bigger and when we reach a smaller current by a certain voltage means that there is a bigger resistance. Thus, resistance (impedance) is directly related to voltage and reverse current. This is the concept of electrical impedance. It is similar to a spring in which force is voltage, spring stiffness is impedance, and the spring displacement is current. In the spring, to reach a certain displacement, when you push it by more
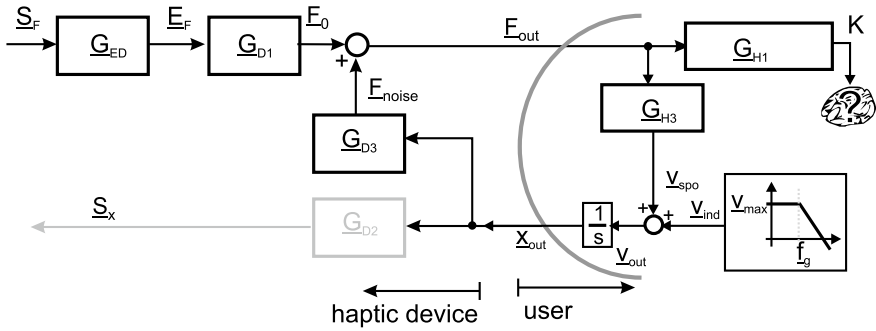
Fig. 6.2 Block-diagram of an open-loop impedance controlled haptic system

force means that the stiffness is bigger and vice versa. This stiffness is the mechanical impedance (Z) that is in the mechanical systems. It is the resistance of the system against force.

Therefore, Impedance controlled systems are based on the transfer characteristics of a mechanical impedance $\underline{Z} = \frac{F}{\underline{v}}$ and are typical of the structure of many kinaesthetic devices. They generate a force as output and measure a position as input. Admittance controlled systems instead, are based on the definition of a mechanical admittance $\underline{Y} = \frac{\underline{v}}{\underline{F}}$, describing transfer characteristics with force-input and velocity-output. These systems generate a position change as haptic feedback and get a force reaction from the user as an input source. In the situation of a closed-loop controlled system, this force is measured and used for the correction of the position. This analysis can be regarded as analog in the case of torque and angle replacing force and position for rotary systems. Nevertheless, for readability purposes, the following descriptions concentrate on translational movements and devices only.

6.4 Open-Loop Impedance Controlled Devices

Open-loop impedance controlled systems are based on a quite simple structure (Fig. 6.2). A force signal $\underline{S}_F$ is transferred via a driver $\underline{G}_{ED}$ into a force-proportional energy form $\underline{E}_F$. This energy is then altered into the output force $\underline{F}_0$ by an actuator $\underline{G}_{D1}$. This output force interferes with a disturbing force $\underline{F}_{noise}$. This noise is a result of movements generated by the user $\underline{x}_{out}$ and the mechanical properties of the kinematic design $\underline{G}_{D3}$. Typically, such disturbing forces are friction and inertia. The sum of both forces is the actual output force $\underline{F}_{out}$ of the impedance controller system. Usually, there is an optional part of the system, a sensor $\underline{G}_{D2}$, which measures the movements and the actual position of the haptic system.

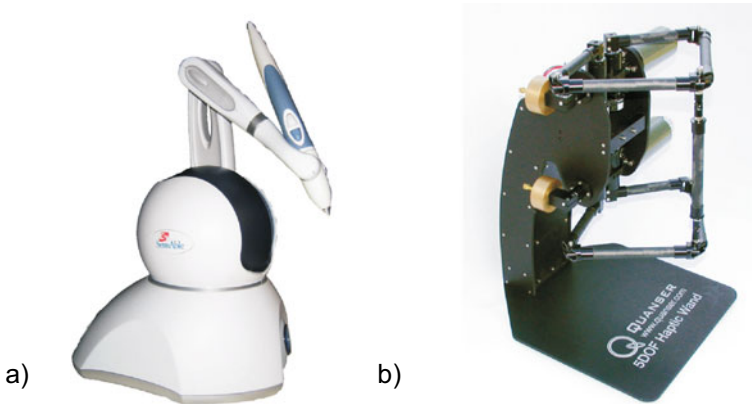**Examples**: *Universal Haptic Interfaces*

Fig. 6.3 Example of an open-loop impedance controlled system with **a** serial-kinematic (*Geomagic Touch*, *3D Systems geomagic Solutions*) and **b** parallel-kinematic (5 DOF Haptic Wand, *Quanser*) structure. Images courtesy of *3D Systems geomagic Solutions*, Morrisville, NC, USA and *Quanser*, Markham, Ontario, Canada, used with permission

Open-loop impedance controlled systems are the most frequently available devices on the market. As a result of their simple internal design, a few standard components can already be used to build a quite useful design with adequate haptic feedback, if at least some care is taken of the minimization of friction and masses. Among the cheapest designs available on the market today, the *PHANTOM Omni*, recently renamed to *geomagic Touch*, (Fig. 6.3a), connected via Fire-Wire to the control unit, is among the best known. It is frequently used in research projects and for the creative manipulation of 3D-data during modeling and design. In the higher-price segment there are numerous products, e.g. the devices of the company *Quanser* (Markham, Ontario, Canada). These devices are usually equipped with a real-time *MatLab™*(*The MathWorks*, Natick, MA, USA) based control station, adding some flexibility to the modifications of the internal data processing by the end customer. The doubled pantograph-kinematics of the "Haptic Wand" (Fig. 6.3b) allow force feedback in up to five degrees of freedom with three translations and two rotations. Although all these devices may be open-loop impedance controlled, the software usually includes simple dynamic models of the mechanical structures. This allows some compensation of inertial and frictional effects of the kinematics based on the continuous measurement of position and velocities.

6.5   Closed-Loop Impedance Controlled Devices

Closed-loop impedance controlled systems (Fig. 6.4) differ from open-loop impedance controlled systems in such a manner that the output force $\underline{F}_{\text{out}}$ is measured

by a force sensor $\underline{G}_{\text{FSense}}$ and is used as a control variable to generate a difference value $\Delta\underline{S}_F$ with the nominal value. An additional component typically is a controller $\underline{G}_{\text{CD}}$ in the control path, optimizing the dynamic properties of the feedback loop. The closed-loop makes it possible to compensate the force $\underline{F}_{\text{noise}}$ resulting from the mechanics of the systems. This has two considerable advantages: On one hand, at idle state the system behaves in a much less frictional and more dynamic way compared to similar open-loop controlled systems. Additionally, as the closed-loop design allows some compensation of inertia and friction, the whole mechanical setup can be designed stiffer. But it has to be noted that part of the maximum output power of actuators will then be used to compensate the frictional force, which makes these devices slightly less powerful than an open-loop design.

Example: **Force Dimension *Delta Series***

Closed-loop impedance controlled systems are usually used in research projects and as special purpose machines. The delta-series of *ForceDimension* (Fig. 6.5) is one example, as it is a commercial system with the option to buy an impedance controlled version. In this variant, force sensors are integrated into the handle, able to measure interaction forces in the directions of the kinematic's degrees of freedom. Closed-loop impedance controlled systems are technologically challenging. On the one hand they have to comply with a minimum of friction and inertia, on the other hand, with little friction, the closed loop tends to become unstable, as an energy exchange between user and device may build up. This is why controllers, typically, monitor the passive behavior of the device. Additionally, the force sensor is a cost-intensive element. In case of the delta-device, the challenge to minimize moving masses has been faced by a parallel-kinematics design.
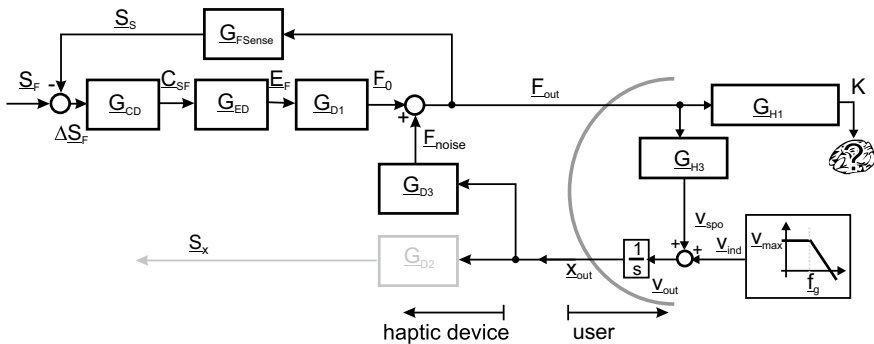

Fig. 6.4 Block-diagram of a closed-loop impedance controlled system with force-feedback

Fig. 6.5 Example of a
parallel-kinematic
closed-loop impedance
controlled system (delta3,
Force Dimension). Image
courtesy of *Force Dimension*,
Nyon, Switzerland, used
with permission

6.6 Open-Loop Admittance Controlled

Open-loop admittance controlled systems (Fig. 6.6) provide a positional output. Proportionally to the input value $\underline{S}_x$, a control chain with energy converter $\underline{G}_{ED}$ and kinematics $\underline{G}_{D1}$ provides a displacement $\underline{x}_0$. This displacement interferes with a disturbance variable $\underline{x}_{noise}$ which is dependent on the mechanical properties of the kinematics $\underline{G}_{D3}$ and a direct reaction to the user's input $\underline{F}_{out}$. In practice an open-loop admittance controlled system typically shows a design which allows to neglect the influence of the disturbance variable. Another optional element of open-loop admittance controlled systems is the measurement of the output force with a force sensor $\underline{F}_{Sense}$ without closing the control loop.
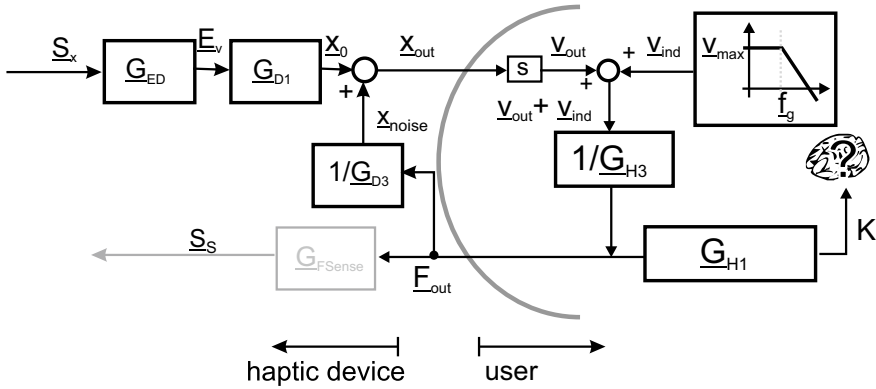
Fig. 6.6 Block-diagram of an open-loop admittance controlled haptic system

Example: **Braille Devices**

Open-loop admittance controlled systems are used especially in the area of tactile displays. Many tactile displays are based on pin arrays, meaning that they are generating spatially distributed information by lifting and lowering pins out of a matrix. These systems origins are Braille devices (Fig. 6.7) coding letters in a tactile, readable, embossed printing. For actuation of tactile pin-based displays a variety of actuators are used. There are electrodynamic, electromagnetic, thermal, pneumatic, hydraulic and piezoelectric actuators and even ultrasonic actuators with transfer media.

Fig. 6.7 Example of an open-loop admittance controlled system being a Braille row, image by RALF ROLETSCHEK, published under CC BY-SA 3.0

6.7 Closed-Loop Admittance Controlled Devices

Closed-loop admittance controlled devices (Fig. 6.8) provide a positional output and a force input to the controlling element identical to impedance controlled devices. The mandatory measurement of the output force $\underline{F}_\text{out}$ is used as control variable $\underline{S}_\text{S}$ for calculating the difference $\Delta\underline{S}_\text{F}$ with the commanding value $\underline{S}_\text{F}$. This difference is then fed through the controller $\underline{G}_\text{CD}$ into the control circuit. As a result, the displacement $\underline{x}_\text{out}$ is adjusted until an aspired force $\underline{F}_\text{out}$ is reached.

A variant of a closed-loop admittance controlled device is shown in Fig. 6.9. Closed-loop admittance controlled devices show considerable advantages for many applications requiring large stiffnesses. However, the force sensors $\underline{G}_\text{FSense}$ are quite complex and consequently expensive components, especially when there are numerous degrees of freedom to be controlled. As a variant, the system according to Fig. 6.9 does not use a sensor but just a force-proportional measure, e.g. a current, as control variable. When using e.g. a current with electrodynamic actuators, we can identify even the reaction of the user generating an induction as an additional velocity dependent value.

Examples: **Universal Haptic Interfaces**

At present, closed-loop admittance controlled systems are the preferred approach to provide high stiffnesses with little loss in dynamic properties. The idea to haptically hide the actual mechanical impedance from the user by closing the control loop makes it possible to build serial kinematics with a large workspace. The FCS HapticMaster (Fig. 6.10a) is such one meter high system with three degrees of freedom and a force of up to 100 N. It includes a force sensor at its handle. The axes are controlled by self-locking actuators. The device's dynamics is impressive, despite its size. However, a damping has to be included in the controller for security reasons resulting in a limitation of bandwidth depending on the actual application.
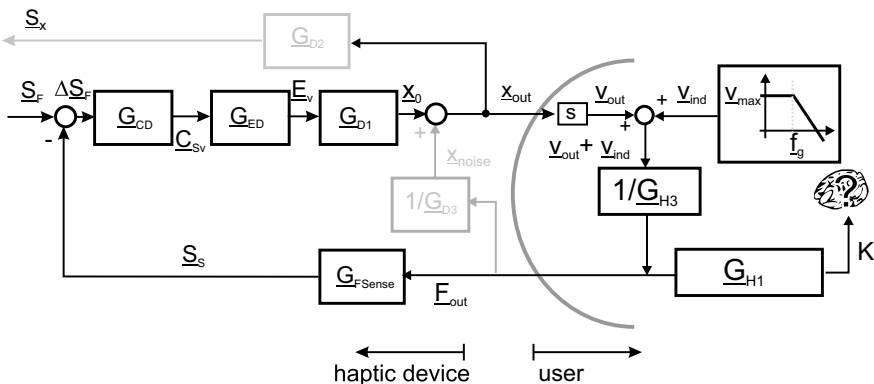

Fig. 6.8 Block-diagram of a closed-loop admittance controlled haptic system with force-feedback loop for control
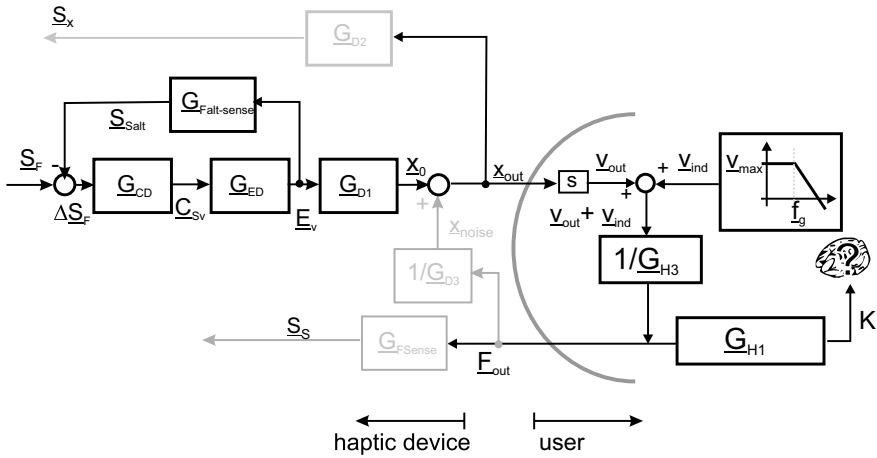
Fig. 6.9 Block-diagram of a closed-loop admittance controlled haptic system with a feedback loop measuring an internal force-proportional value

Fig. 6.10 Examples of closed-loop admittance controlled systems in variants with **a** direct force measurement (*HapticMaster*) and **b** measurement of the actual current (*Virtuose 6D35-45*). Images courtesy of *Moog FCS*, Nieuw-Vennep, the Netherlands and *Haption GmbH*, Aachen, Germany, used with permission

Realizations of the variant of closed-loop admittance controlled devices are the *Virtuose*-systems from *Haption* (Fig. 6.10b). In these devices the current is measured at electrodynamic electronic commutated actuators and fed back as a control value. The devices show impressive qualities for the display of hard contacts, but have limited capabilities in the simulation of soft interactions, e.g. with tissues. Therefore, the application area of such systems is mainly the area of professional simulation of assembly procedures for manufacture preparation.

6.8 Qualitative Comparison of the Internal Structures of Haptic Systems

As the haptic human-machine interaction is based on an impedance coupling, it is always the combination of action and reaction, be it via force or position, which has to be analyzed. In fact, without any knowledge about the internal structure of a device, it is impossible to find out whether the system is open-loop impedance controlled, closed-loop impedance controlled or closed-loop admittance controlled. With experience of the technological borders of the most important parameters like dynamics and maximum force, an engineer can make a well-founded assumption about the internal structure by simply using the device. But concerning the abstract interface of in- and output values, all the devices of the above three classes are absolutely identical to the user as well as to the controlling instance. Despite this fact the technical realizations of haptic systems differ widely in their concrete technical design, of course the parameters influencing this design have to be balanced against each other. Such parameters are:

- Number of components
- Maximum impedance to be achieved at slow motion
- Minimum impedance to be achieved at fast motion
- Force-resolution
- Impedance of mechanical components (e.g. inertia of kinematics)

These parameters and their mapping onto the technical designs are given qualitatively. In Fig. 6.11 the impedance generated by a device in absolute values and the impedance range covered may be one criterion for the performance of a device. Analyzing the systems according to this criterion shows that open-loop admittance controlled systems may have high impedance, which shows smaller variability in tighter borders. Closed-loop admittance controlled systems extend these borders by their ability to modulate the impedance due to the feedback loop. Depending on the design, closed-loop admittance controlled systems vary in the width of this modulation. In the lower area of possible, realizable impedances the open-loop impedance controlled systems follow. They stand out more by simplicity in their design than by large impedance ranges covered. In comparison to the closed-loop admittance controlled systems they gain some impedance width at the lower border of impedances. In order to be able to equally cover lower as well as higher impedances, the choice should be made of closed-loop impedance controlled systems.

Tactile devices

Normally, pure open-loop admittance controlled systems are suitable for tactile devices only, as, with tactile devices, usually there is no active feedback by the user to be measured. The haptic interaction is limited to tensions being coupled to the skin of the user's hands. Such devices show high internal impedance ($\underline{Z}_D$). The dynamics and the resolution concerning the displacement are very high.
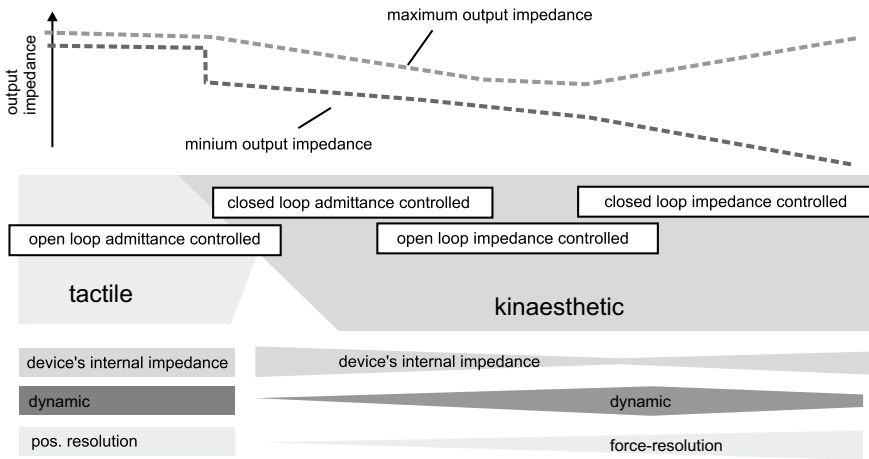
Fig. 6.11 Qualitative comparison of the application areas for different device-structures

Kinaesthetic devices

Can be built with systems allowing a modulation of the displayed impedances. The closed-loop admittance controlled systems excel due to the possibility to use mechanical components with high impedances. The dynamics of these systems are accordingly low (<100 Hz) and the force-resolution is, due to the typical frictions, not trivial when realized. Open-loop impedance controlled systems show a wider dynamic range due to the missing feedback loop with, at the same time, limited dynamic range. Only closed-loop impedance systems allow covering a wide impedance range from lowest to very high impedances, whereby with increasing requirements of force resolution the dynamics of the maximum velocities achieved by the control loop are limited and limitations of the measurement technology become noticeable.

The decision on the design of a haptic system has significant influence on the application range and vice versa. On one hand, it is necessary to identify the requirements to make such a decision. For this purpose, it is necessary to ask the right questions and to have an insight into possible technical realizations of single elements of the above structures. This is the general topic of the second part of this book. On the other hand, it is necessary to formulate an abstract system description of the device. An introduction of how to achieve this is given in the following section.

6.9   How to Choose a Suitable System Structure

The selection of a suitable system structure is one of the first steps in the design of a task-specific haptic systems. Based on the interaction analysis, one should have a sufficient insight into the intended interactions between system and user and should be
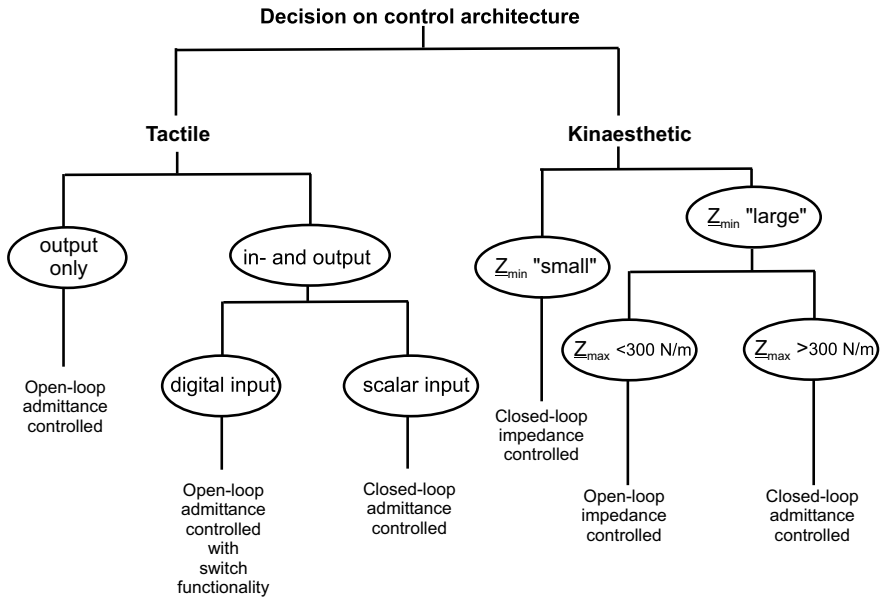
Decision on control architecture

Tactile   Kinaesthetic

output only   in- and output $\underline{Z}_{min}$ "small" $\underline{Z}_{min}$ "large"

digital input   scalar input $\underline{Z}_{max}$ <300 N/m $\underline{Z}_{max}$ >300 N/m

Open-loop admittance controlled

Open-loop admittance controlled with switch functionality

Closed-loop admittance controlled

Closed-loop impedance controlled

Open-loop impedance controlled

Closed-loop admittance controlled

Fig. 6.12 Aid for the decision on the choice of the control structure

able to decide between a mainly tactile and mainly kinesthetic device structure. Based on further criteria like input and output capabilities and the mechanical impedance to be displayed, Fig. 6.12 gives an decision tree for the control structure.

Especially when the application will include an interaction in a multi-modal or virtual environment, further additions to the system structure could be wise to consider, since they promise a large technical simplification while maintaining haptic quality. This includes the approaches of Event-Based-Haptics as well as Pseudo-Haptics (Fig. 6.12).