Chapter 5
Identification of Requirements

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Abstract In this chapter, the process of requirement definition is described, starting with the definition of the intended application together with the customer. Especially the derivation of technical parameters from the customers expectation and useful tools for this step are discussed. Further, the analysis of the intended interaction and the effects on the requirement identification are discussed. To alleviate the identification of requirements, main requirement groups are derived from the intended type of interaction and presented in five technical solution clusters. A review of relevant standards and guidelines on safety serves as another source of requirements of a haptic systems.

5.1 Definition of Application—The Right Questions to Ask

At the beginning of a technical design process the requirements for the product which, usually, are not clear and unambiguous, have to be identified. Frequently, customers formulate wishes and demands respectively solutions instead of requirements. A typical example is a task of the kind: "to develop a product just like product **P**, but better/cheaper/nicer". If an engineer accepts such a kind of order without getting to the bottom of the original motivation the project will be doomed to failure. Normally, the original wish of the customer concerning the product has to fulfil two classes of requirements:

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The product shall have

- a certain **function**
- in a distinct **technical** and **market oriented** framework

Phrasing market oriented requirements are manifold yet not in the focus of the following analysis (for details of a general systematic product development see [12, 23]). They may be motivated by an existing product **P** to compete with, but usually they are much more comprehensive and cover questions of budget, time-frame of development, personal resources and qualifications and customers to address.

With regard to the technical framework, the customer typically gives just unspecific details. A statement like "a device shall provide a force on a glove" is not a definition of a requirement but already a solution on the basis of existing knowledge on the part of the customer. The complexity of a real technological solution spans from a single actuator to provide e.g. a vibration to complex kinematics addressing single fingers. Questioning the customer's original statement, it may even come out, that his intention is e.g. to simulate the force impression when switching the gears of a clutch in a passenger car. The knowledge about the actual application and following that knowledge about the interaction itself allows the developer a much broader approach, leading to a more optimized technical solution.

5.1.1 Experiments with the Customer

The customer formulates requirements—as mentioned before—typically in an inexact instead of a specific way. Additionally, there is the problem of a very unspecific terminology with regard to the design of haptic systems For the description of haptic sensual impressions there are numerous adjectives difficult to quantify, like: rough, soft, smooth, gentle, mild, hard, viscous, as well as others derived from substantives such as: furry, silky, hairy, watery, and sticky which can be compared to real objects. So what could be more obvious than asking the customer to describe his/her haptic impressions by comparisons?

> Ask the customer to describe the intended haptic impression with reference to objects and items in his/her environment. These items should be easily at hand, like e.g. vegetables and fruits which offer a wide spectrum of textures and consistencies for comparison.

Sometimes the customer first needs to develop a certain understanding of the haptic properties of objects and items. This can best be achieved by his/her directly interacting with them. Examples of haptically extreme objects have to be included in a good sample case, too. The evolving technology of 3D printing allows for a very flexible design of such samples.

Provide a sample case including weights and springs of different size, even marbles, fur, leather and silk. Depending on the project, add sandpaper of different granularity. Use these items to explain haptic parameters to the customer and help the customer to optimize the description of the product performance expected!

From practical experience, we can recommend also to take spring balances and letter balances or electronic force sensors with you to customer meetings. Frequently, it is possible to attach a handle directly to the items and ask the customer to pull, until a realistic force is reached. This enables customers of non-technical disciplines to quickly get an impression of the necessary torques and forces.

Take mechanical measurement instruments with you to the customer meetings and allow the customer to touch and use them! This gives him / her a good first impression of the necessary force amplitudes.

In order to give a better impression of texture, mechanical workshops may produce patterns of knurls and grooves of different roughness on metals. Alternatively, sandpaper can be used and, by its defined grade of granularity, can provide a standardized scale to a certain extent.

Use existing materials with scales to describe roughness and simulate the impression of texture.

Recently, different toolkits for haptic prototyping are available. They are specific for certain types of applications, like for example cockpit knobs or texture recording, discrimination and replay. PENN HAPTIC TOOLKIT to record and replay haptic texture properties [5] is one of those systems being conceptually slightly different from the approach done by TU- MÜNCHEN's LMT texture recording and its database [30] at http://zeus.lmt.ei.tum.de/downloads/texture/. Further examples for lo-fi prototyping can be found in [14]. For more sophisticated setups, the usage of a ↪ COTS device and a virtual environment developed with a haptics toolkit could be considered. For vibrotactile feedback specialized prototyping environments like HAPTICLABS.IO are available. With focus on actuator sales, several companies provide a mixture of haptic consulting and actuator customization as a service (*Grewus*, *Nui Lab*, *Actronika*, ...).

Engineering Misconceptions when Asking About Haptics

A normal customer without expertise in the area of haptics will not be able to give statements concerning resolutions or dynamics of the haptic sense. This kind of information has to be derived from the type of interaction and the study of psychophysical knowledge of comparable applications. Therefore, the experience of the developing engineer is still indispensable despite all the systematizations in a technical design process.

> Do not confuse the customer by asking questions about the physical resolution! This is necessarily the knowledge of the haptic engineer. However, learn about the dynamics of the interaction and try to assess the application, e.g. by asking about the frame rate of a simulation, or the maximum number of load changes per seconds of a telemanipulator.

5.1.2 General Design Guidelines

Next to the ideas of the customer and/or user, there are also a number of different guidelines dealing with the design of haptic systems. These guidelines are summarized here very shortly, but a close look in the original references is advisable when applicable to the intended a haptic system.

Usability and Human-Computer-Interaction Guidelines Since all active haptic systems are intended to be used as a human-computer-interface, the applicable guidelines for these systems are also relevant for the design of haptic systems. As mentioned in Sect. 4.2, the ISO 9241-series deals with usability in general, the ISO 9241-9xx standards specifically address haptic systems and should be considered while working on requirement definitions and beyond. As of 2022 the activities of this ISO standardization committee is low, but the former documents still exist and did not outdate in their content. For the use of ↪ COTS devices, MUÑOZ ET AL. introduced a basic guideline for the design of ergonomic haptic interactions, that can be useful for these kind of applications [17].

Design of Haptic Icons The group of BREWSTER works on haptic and auditory icons and did publish several design guidelines for this kind of communication like for example [21]. With the increased availability of high-performance actuators in mobile devices, complex tactile patterns can be realized. The most relevant online resources for inspirations on such patterns was collected by SEIFI and her team, and is arranged at http://hastiseifi.com/VibViz/ according to sensational similarity [28].

HCI for Blind Users Sjöström developed guidelines for ↪ virtual systems for blind users in addition to existing guidelines for HCI [29].

Telepresence in Precision Assembly Tasks Acker investigated the usage of haptic and other feedback in precision assembly tasks [2].

Presence and Performance in Teleoperation Design factors leading to higher presence and improved performance were investigated by Deml [6]. With a strong focus on human factors, a guideline was developed to optimize the human-machine interface [7].

Design of VR and Teleoperation Systems Based on a literature review, a design guide for the development of haptic and multimodal interfaces was developed in [19]. The guide selects guidelines based on an interactive front end. The Haptics Industry Forum—HIF *www.hapticsif.org* contributed in 2021 an application guide how to introduce and use VR-applications in an industrial context efficiently.

Surface Haptics Basdogan et al. summarized how artificial haptics generated on actuated but closed surfaces such as touchpanels and touchscreens can be realized [3].

Minimal Invasive Surgery Tavakoli et al. present the design of a multimodal teleoperated system for minimal invasive surgery and address general questions like control strategies and the effect of time delay [31].

General Benefits of Haptic Systems Based on a meta-study, Nitsch identified several aspects of haptic feedback on task performance measures. Haptic feedback improves working speed, handling accuracy and the amount of force exerted in teleoperation and virtual systems. This holds mainly for kinaesthetic force feedback, vibrotactile feedback predominantly reduces only task completion time [20].

Automotive Haptics The Haptics Industry Forum—HIF *www.hapticsif.org* released a guideline for the automotive practice of haptic devices and their design with related specifications. It covers a range of car-related HCI topics up to specific technologies used in presence and in the future.

5.2 Interaction Analysis

Based on the demands of a customer and the clarifications obtained in conversation and experiments, a more technical interaction analysis can be performed. The first goal of this step is a technical description of the user with regard to the intended application. Normally, this will include information about the perception thresholds in the chosen grip configuration, information about the movement capabilities, and the mechanical impedance of the user. Naturally, one will not find fixed values for these parameters, but probably only ranges in the best case. In the worst case, own perception studies and impedance measurements have to be conducted.

The second goal of this step is a definition of suitable evaluation parameters and appropriate testing setups. If a reference system (that has to be improved or equipped with haptic feedback in course of the development) is given, reference values of these parameters should be obtained in this stage of the requirement identification as well.

The following steps are advisable for an interaction analysis that will obtain meaningful information for the following requirement specification as stated in Sect. 5.5. They are based on the works of HATZFELD ET AL. [10, 11].

1. **Task Analysis** Analyze the interaction task as thoroughly as possible. Interaction primitives as described in Sects. 1.4.1 and 2.2 are helpful at this point. Research possible grip configurations suitable for this kind of interactions (3.1.3), if the hand is intended as the primary interface between user and haptic system. Depending on the intended application, other body sites like the torso, the back of the hand or other limbs can be suitable locations for haptic interactions. For the ease of reading, the rest of this section will only mention the hand as primary interface without loss of generality with regard to other body sites.
   Take the usage of tools into account (stylus, gripper, etc.) as well as possible restrictions of the manipulator in a teleoperation scenario (see example below). After his, one should have one or more possible interaction configurations, that will be able to convey all interaction primitives needed for the intended usage. If one plans to build a teleoperation, comanipulation or assistive system that adds haptic feedback to interactions that do not already have such, it is probably worthwhile to discuss if all haptic signals have to be measured, transmitted and displayed. Sometimes, the display of categorized haptic information (OK/Not OK, Material A/Material B/Material C etc.) could be sufficient in terms of intended usage of the system, facilitates the technical development, and lowers the cost of the final product.
   It is advisable to also have a look on some multimodal aspects of the application as well as other environmental parameters: If a visual channel has to be or can be used, special concepts like pseudo-haptic feedback can be considered in the design of the system. If the system is to be used in a highly distractive environment, robust communication schemes have to be incorporated or an adjustable feedback mode has to be included. These information will help with formulating the system structure and the detailed requirement list.
2. **Movement Capabilities** Select the one or two most promising grip configurations. Based on these, one should define the maximum and comfortable movement spaces of the user and the typical interaction and maximum exertable forces. Section 2.2.4 gives some values for handling forces and velocity, data for typical movement spaces can be found in applicable standards like ISO 7250 or DIN 33402. These are relevant boundaries for the user input kinematics in terms of workspace and structural load. Interaction forces can be further used to define forces on the slave side of a telemanipulation system (as well as input forces in a virtual system that have to be dealt within the software).
3. **Mechanical Impedance** Research or measure the mechanical impedance of the selected grip configuration. This impedance is relevant for several control issues like stability (local stability of the haptic interface and overall stability in case of teleoperation systems) and haptic transparency as discussed in Sect. 3.2.

4. **Perception Parameters** Research or measure relevant perception parameters for the selected grip or body site configuration. Normally, absolute and different thresholds are needed for an estimation of sensor and actuator resolutions as well as tolerable errors. Based on the intended usage, other perception parameters or other interpretations can be meaningful as well. For example, successiveness limens (SL) and two-point-thresholds will affect the design of communication interfaces on all body sites. For an energy-limited system, small JNDs could be beneficial, since they probably will result in a large number of possible transferable information with a small amount of energy.

   Keep in mind, that force and deflection thresholds can be calculated from each other by using the mechanical impedance according to Eq. (2.7). If possible, obtain data in more than one dimension to facilitate the requirement definition in the intended ↪ DoF. Be sure to check if there are external conditions, that will influence perception favorably for the technical development. This could be a maximum contact area or a minimum contact force that will lead to higher perception thresholds for the given contact situation. With means of the system developer these conditions can be influenced, for example by the design of the grip or the measurement of a minimum contact force, that has to be applied by the user to make the haptic system functional.
5. **Evaluation Criteria** Define suitable evaluation criteria regarding the intended task performance. Chapter 13 gives possible criteria depending on the application class of the haptic system. Despite these measures of task performance, measurements of haptic quality (if applicable) and ergonomic measures can be taken into account. The latter will quantify the cost and benefit of a haptically enhanced system compared to a system without haptics. The definition this early in the development allows for the measurement of reference values and eases the final evaluation, since the intended testing procedure of the haptic system can be incorporated in the design process.

A final decision for a grip configuration can either be made based on the values obtained in this interaction analysis in favor of the technical less-demanding option or by conducting user tests considering ergonomic factors like fatigue and task performance, if this is technically possible (for example with ↪ COTS devices). Obviously, this could involve some iterations of the above mentioned points. With this structured approach to interaction, a lot of purposeful information is generated for the derivation of requirements. The approach is illustrated with a short example in the following.

Example: *FLEXMIN Interaction Scheme*

The surgical system FLEXMIN is developed to enhance single port surgery procedures like for example transanal rectum resection [4] with haptic feedback, additional intracorporal mobility compared to rigid instruments and a more ergonomic working posture of the surgeon. Task-analysis as described above was conducted based on an example rectum resection with commercial available, stiff instruments (TEO system, *Karl Storz*, Tuttlingen, Germany) on an anatomical model. Based on the recordings of the surgeon's movements, system constraints like workspace, dexterity, instruments and principal manipulation tasks were identified [16]. This analysis led to the requirements of two manipulators with at least four movement ↪ DoF (positioning in space and rotation along the longitudinal axis) and preferably another DoF for gripping instruments like scissors or forceps.

Based on additional aspects like the request for displaying stiff structures and elements and the available construction space, a parallel kinematic structure was chosen for the intracorporal manipulator already at this point of development [15]. In that case, the ↪ TCP will be at the end of the last part of the lead chain of the parallel mechanism. The movement of this part was chosen as the general form of interaction of the haptic interface used to operate the manipulator [18]. The resulting concept for the haptic interface is shown in Fig. 5.1.

Ergonomic considerations about the surgeon handling two of these interfaces led to a passive linear bearing at the one end of the main kinematic chain of the user interface. On the other end, a parallel delta kinematic structure was chosen to actuate three DoF of the haptic interface. Additional feedback for the rotatory and the grasping DoF is integrated in the grasping part of the user interface. This is shown in Fig. 5.2.

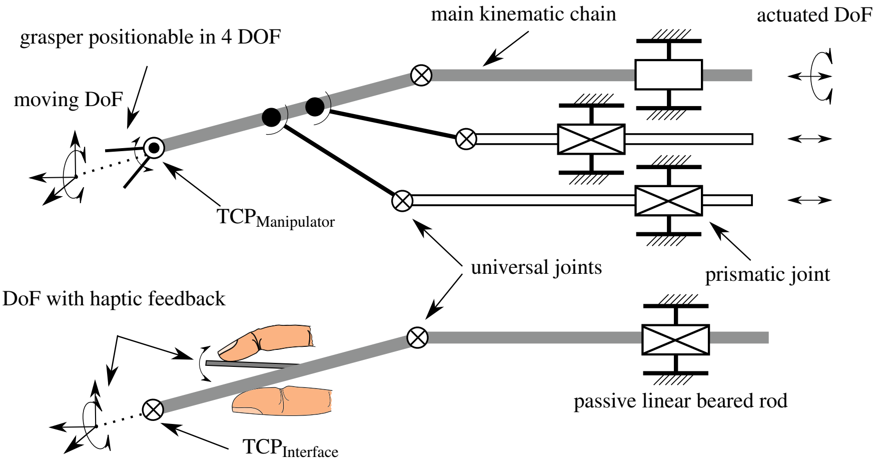

Fig. 5.1 Derivation of the concept of the haptic user interface of FLEXMIN (lower part) from the kinematic structure of the intracorporal manipulator (upper part). Figure adapted from [18]

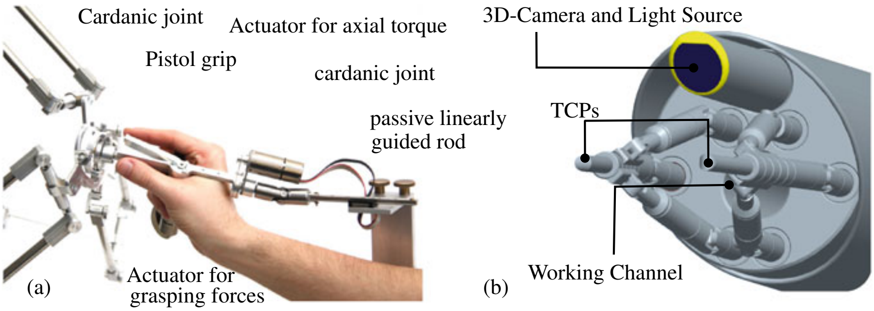

Fig. 5.2 **a** Realization of the haptic user interface of FLEXMIN, **b** Rendering of the intracorporal robot with two manipulator arms, working channel and visual instrumentation. Further information can be found in [15]

5.3 Technical Solution Clusters

After the interaction analysis and the discussion of the customer's expectations towards the haptic system, one should have a in-depth knowledge about the intended function of the haptic system. Based on a quite basic description of this function, general types of haptic systems and the interactions therewith can be identified. Based on these, this section identifies possible technical realizations and summarizes the necessary questions in clusters of possible applications. The list does not claim to be complete, but is the essence of requirement specifications of dozens of developments achieved during the last few years.

The core of the requirements' identification is the definition of the type of haptic interaction. The first question asked should always refer to the type of interaction with the technical system. Is it a simulation of realistic surroundings, the interaction with physically available objects in terms of telepresence; or is the focus of the interaction on the pure communication of abstract information? In the former cases the variants are less versatile than in the latter, as described below. In Fig. 5.3 a decision tree for the identification of clusters of questions is sketched. It is recommended to follow the tree from top to bottom in order to identify the correct application and the corresponding cluster of questions.

Simulation and Telepresence of Objects Does the interaction aim at touching virtual or via telepresence available objects? If this is the case, does the interaction take place directly via fingers, hands or skin, or is a mediator, e.g. a tool the interacting object? Does the user hold a specific tool—a pen, a screw driver, a surgical instrument, a joystick of a plane, in his hands and control one or more other objects with it, or does the user touch a plurality of objects during the interaction with his or her hands? In the case of a tool-interaction the chosen solution can be found in cluster ① "kinaesthetics", in the case of a direct interaction another detail has to be considered.

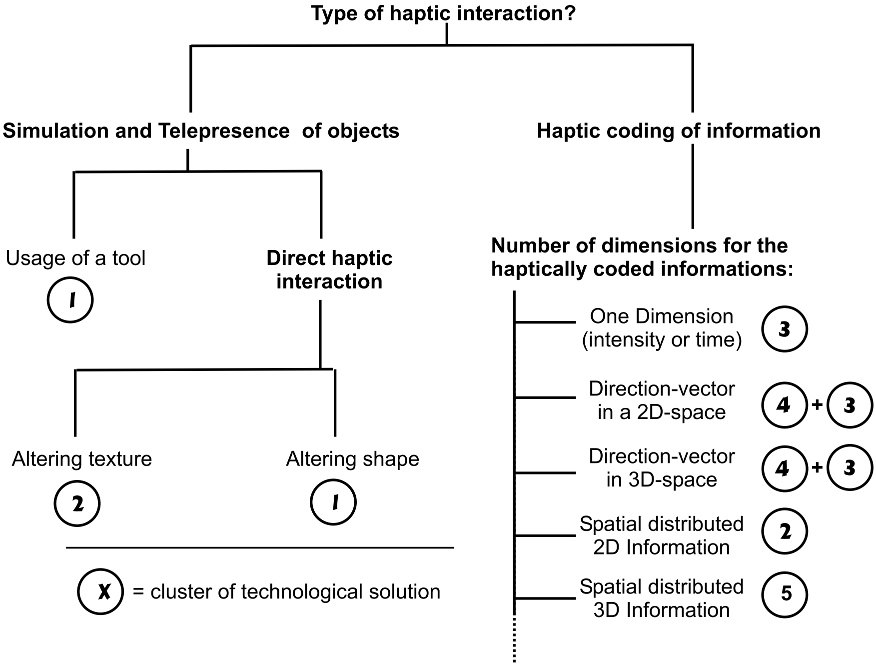

Fig. 5.3 Structure for identifying relevant clusters of questions by analyzing the intended haptic interaction

Direct Haptic Interaction By touching physical objects, the user can notice the differences in all physical attributes of the volume like mass, elasticity, plasticity and inner friction, and their texture. In the case of interacting with shapes, the questions of cluster ① "kinaesthetics" remains relevant, in the case of interacting with textures the questions of cluster ② "surface-tactile" have to be considered. This is not necessarily an alternative decision, however, with the same object interaction, both aspects can be required at the same time or one after the other.

Haptic Coding of Information In the case of abstract, not physical, object- oriented information communication via the haptic sense the question of the dimension of information becomes relevant:

- Does the interaction include a single event which occurs from time to time (e.g. the call of a mobile phone) or is some permanently active information (e.g. a distance to a destination) haptically communicated? These questions are one-dimensional[1] and covered by cluster ③ "vibro-tactile".
- Is the interaction dominated by directional information coding an orientation in a surface (directional movement) or in a space? In this case the questions covered by cluster ④ "vibro-directional" are relevant. In such applications

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[1] As the information includes only one parameter.

frequently time respectively distal information is included, also making the questions in cluster ③ become relevant.

- Does the interaction aim at the communication of data distributed within a two-dimensional information layer, like geological maps, road-maps or texts on a page? In these cases the questions of cluster ② "surface-tactile" have to be answered.
- In case there is volumetric information—the electrical field of an atomic bonding or medical data sets—to be haptically transmitted, the questions of cluster ⑤ "omnidimensional" are to be be considered.

In the following sections the questions in the clusters are further discussed and some examples are given for the range of possible solutions to the questions aimed at.

5.3.1 Cluster ① — Kinaesthetic

Cluster ① has to be chosen either when an interaction between fingers and shapes happens directly or when the interaction takes place between tool and object. Both cases are technical problems of multidimensional complexity.[2] Each possible dimension movement corresponds to one degree of freedom of the later technical system. Therefore the questions to be asked are quite straightforward and mainly deal with the requirements for these degrees of freedom of tools and users:

- Which degrees of freedom do the tool/movement show? → rotatory, translatory, combinations[3]
- How large is the volume covered by the movements? → Maximum and minimum values of angles and translations
- How dynamic is the movement? → Identification of maximum and minimum velocities and accelerations. Usually, this question cannot be answered immediately. A close observation of the intended interaction will help and—as far as possible—measurements of movement velocities of instruments and fingers should be made e.g. with the aid of videos,.
- Which forces / torques happen at each degree of freedom[4]? → Definition of maximum and minimum forces and torques.
- What is the maximum dynamics of the forces and torques? → Bandwidth of forces and torques in frequency range, alternatively maximum slope in time-domain

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[2] A tool interaction can be a one-dimensional task, but such an assignment concerning the technical complexity can be regarded as an exception.

[3] In the case of a finger movement it has to be noted that not necessarily all movement directions have to be equipped with haptic feedback to provide an adequate interaction capability. Frequently it is even sufficient to provide the grasp-movement with haptic feedback, solely.

[4] Frequently the customer will not be able to specify these values directly. In this case creative variants of the question should be asked, e.g. by identifying the moving masses, or by taking measurements with one's own tools.

("from 0 to $F_{\max}$ in 0.1 s"). Usually, this question cannot be answered directly. Frequently, measurements are difficult and time-consuming, as an influence of the measurement on the interaction has to be eliminated. Therefore it is recommended to do an analysis of the interaction itself and the objects the interaction happens with. If it is soft—something typical of surgical simulation, simple viscoelastic models can be used for interpolating the dynamics. The most critical questions with respect to dynamics often address the initial contact with an object, the collision. In this case especially the stiffness of the object and the velocity of the contact describe the necessary dynamics. But is has to be stated that the resulting high demands are not seldom in conflict with the technical possibilities. In these cases, a splitted concept based on "events" can be considered, where kinaesthetic clues are transmitted in low frequency ranges, and highly dynamic clues are coded in pure vibrations (Chaps. 11 and 12).

5.3.2 Cluster ②—Surface-Tactile

Haptic texture represents the microstructure of a surface. The lateral movement between this microstructure and the finger tip results in shear forces generating the typical haptic impression of different materials. Haptic-bumps on the keyboard-keys J and F are a special form of texture. Another variant of texture are Braille-letters carrying additional abstract information. But there are also more straightforward textures such as the surface of all physical materials[5] Cluster ② has to be chosen when there is a need to present information on any surface via the tactile sense. This can be either coded information on a geological map on a more or less plane surface, but it can also be object specific features like the material itself. The resulting questions for the technical task are:

- Which body parts perform the interaction? → This trivial question has a significant impact, as the body part selected defines the resolution available on user side and consequently the requirements for the size of the texture-generating elements.
- Is the form of the texture-carrying shape subject to changes? If so, how much and in which areas? → If the shape changes a lot, it is likely that the unit providing the texture information has to be adapted to e.g. each finger (e.g. as a pin-array or piezoelectric disc), as the fingers will have to be positioned independently of each other. In this case it may even be necessary to provide a lateral movement between finger and texture-unit to generate shear forces in the skin. In case of the shape being fix, e.g. in the case of a map, a relative movement may happen by the fingers themselves and the texture unit can be designed with less size restrictions.
- How fast does the displayed information change? → Textures change rarely during the simulation of objects and display of maps. This is dramatically different when

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[5] Consider: The mechanical stimulus pattern is not the only dimension of haptic textures, especially the thermal conductivity of the surface contributes a lot to the realism of surface-rendering.

e.g. texts or the influences of fluids on textures have to be displayed. The answer to this question has a significant impact on the technical system.

- Which intensity range is covered by the texture? → In the simplest situation the answer can be given by definite displacements and a resolution in bit. Usually, only qualitative values of the properties of objects for interaction are available. These hints have to be complemented by one's own experiments. With regard to the definition of these requirements it is very important to make sure that the planned spatial addressability and maximum intensity change does not exceed the corresponding resolution of the user. A research on the corresponding psychophysical experiments is highly recommended, as otherwise it may not be possible to transmit the intended information density.
- In this category there are numerous established solutions for grounded and wearables devices. BASODGAN ET AL. [3] summarized a relevant state of the art on how to make grounded surfaces smart. See also Chap. 12 for more details on the software-considerations. PACCHIEROTTI ET AL. [22] summarized the state of research on wearable devices for inspirations on surface interaction.

5.3.3 Cluster ③—Vibro-Tactile

Cluster ③ is a solution space for simple one-dimensional technical problems and corresponding questions. It covers independent dimensions of information (e.g. coding an event in a frequency and the importance in the amplitude). In this cluster, distributions of intensity variations and /or time dependent distributions of single events are filed. Technological solutions are usually vibrational motors or tactons, as being used in mobile phones or game-consoles. But even if the technical solution itself seems quite straightforward, the challenge lies in the coding of information with respect to intensity and time and an appropriate mechanical coupling of the device to the user.

- Which mechanical interface for the transmission of haptic information to the user is planned? → More specifically: Is this interface influenced by mechanical limits like housings?
- Which design space is available? → Frequently, vibro-tactile solutions are limited as to the available space at an early stage of the design due to requirements for mobility.
- Which resolution is expected for the planned intensity variation? → The criteria are similar to those of the "surface-tactile" cluster. As the "vibro-tactile" cluster frequently deals with oscillating systems, the dependence of the perception of oscillations on its frequency has to be taken into account. The user's perception is the limiting factor for intensity variations, which themselves are dependent on the mechanical coupling between device and user, too.

5.3.4 Cluster ④—Vibro-Directional

Vibro-tactile systems code one-dimensional information in the form of intensities. It is obvious that by the combination of multiples of such information sources directional information can be transmitted. This may happen two-dimensionally in a plane surface, but also three-dimensionally. Cluster ④deals with such systems. One possible technical solution for directional surface information would be to locate a multitude of active units in the shape of a ring around a body part, e.g. like a belt around the belly. The direction is coded in the activity of single elements. This approach can also be transferred to a volumetric vector, whereby in these cases a large number of units is located on a closed surface, e.g. the upper part of the body. The activity of single elements codes the three dimensional direction as an origin of a normal vector on this surface. In addition to the questions of cluster ③this cluster deals with the following questions:

- What is the intended resolution on the surface/in the space? → As well as before dependent on the body surface used, it is likely that the human perception represents the limit for the achievable resolution. Corresponding literature [9, 32] has to be checked carefully before the technical requirements can be met.
- What number of simultaneously displayed vectors is expected? → The fact that users will be able to identify one direction does not guarantee that with a parallel display of two points the user will perform equally well. Simultaneous display of information frequently results in masking-effects hard to be quantified. Experiments and analysis of the intended application are strongly recommended.
- Which frame of reference is used? → The information displayed is usually embedded in a frame of reference, which is not necessarily identical with the user's frame of reference and his or her body. The user may change his position for example in a vehicle, which results in a loss of the position of the elements fixed to the body and their orientation in the vehicle. It is necessary to be aware of the active frame of reference (local user-oriented, or vehicle-oriented, or maybe even world-oriented) and to provide measurement equipment for identifying changes in user positions and frame of reference. Additionally, it may become necessary to present a haptic reference signal to the user, which calibrates the user's perception to the frame of reference, e.g. a "north"-signal.

5.3.5 Cluster ⑤—Omni-Directional

Cluster ⑤ deals with systems coding real volumetric information. Within such a three-dimensional space each point either includes intensity information (scalar field) or vector information (vector field). The sources of such data are numerous and frequent, may it be medical imaging data, or data of fluid mechanics, of atomic physics, of electrodynamics, or of electromagnetics. Pure systems of haptic interaction with such kinds of data are seldom. Frequently, they are combinations of the clusters "kinaesthetic" and "vibro-tactile" for scalar fields, respectively "kinaesthetic" with six active haptic degrees of freedom for vector fields.[6] Consequently, the specific questions of this cluster add one single aspect to already existing questions of the other clusters:

- Does the intended haptic interaction take place with scalar fields or with vector fields? → For pure vector fields kinaesthetic systems with the corresponding questions for six active degrees of freedom should be considered. In the case of scalar fields, an analysis of vibro-tactile systems in combination with three-dimensional kinaesthetic systems and the corresponding questions should be considered. Then the property of the scalar value corresponds to the dynamics of the coded information.

5.3.6 General Requirement Sources

For any development process there are several questions which always have to be asked. They often refer to the time-frame as well as to the resources available for the development. For haptic devices two specific questions have to be focused on, as they can become quite limiting for the design process due to specific properties of haptic devices:

- Which energy sources are available? → It is not a necessary prerequisite that electrical actuators have to be used for haptic devices, especially in the case of telemanipulation systems. The usage of pneumatic and hydraulic energy sources, especially for tactile devices is a real alternative and should be considered.
- The design, how expensive may it be? → The prices of current kinaesthetic haptic systems reach from 200 EUR of mass-products to 1,500 EUR of medium scale products to devices of 25,000 EUR for small series and 100,000 EUR for individual solutions. These prices only partly result from commercial acquisitiveness, but mostly from the technical requirements and the efforts which have to be taken.

Furthermore, safety is a relevant source of requirements for haptic systems. Because of the importance of this issue, it is dealt within the next section seperately.

5.4 Safety Requirements

Since haptic systems will be in direct contact with human users, safety has to be considered in the development process. As with usability (Sect. 4.2), a consideration

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[6] The haptic interaction with objects in a mathematical abstraction always is an interaction with vector fields. In the vectors, forces of surfaces are coded, which themselves are time dependent, e.g. from movements and /or deformations of the objects themselves.

of safety requirements should be made as early in the development process as possible. Furthermore, certain application areas like medicine will require a structured, documented and sometimes certified process for the design of a product which also has to include a dedicated management of risk and safety issues. In this section, some general safety standards that may be applicable for the design of haptic systems are addressed and some methods for the analysis of risks are given.

5.4.1 Safety Standards

Safety standards are issued by the large standard bodies and professional societies like ↪ international Organization for standardization(ISO), the national standard organizations, ↪ institute of Electrical and Electronics Engineers(IEEE), and ↪ International Electrotechnical Commission (IEC) for example. Some relevant standards for the design of haptic systems are listed as follows. Please note that this section will not supersede the study of the relevant standards. For a more detailed view on the general contents of the standards, the websites of the standardizing organizations are recommended.

IEC 61508 This standard termed *Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-related Systems* defines terms and methods to ensure functional safety, i.e. the ability of a system to stay or assume a safe state, when parts of the system fail. The base principle in this standard is the minimization of risk based on the likelihood of a failure occurrence and the severity of the consequences of the failure. Based on predefined values of these categories, a so-called ↪ Safety Integrity Level (SIL) can be defined, that will impose requirements on the safety measures of the system. It has to be noted that the IEC 61508 does not only cover the design process of a product, but also the realization and operational phases of the life-cycle.

The requirements of functional safety impose large challenges on the whole process of designing technical products and should not be underestimated. The application of the rules are estimated to increase costs from 10 to 20 % in the automotive industry for example [27].

ISO 12100 This standard defines terms and methods for machine and plant safety. It can be considered as detailing the above mentioned IEC 61508 for the construction of machines, plants and other equipment. For the design of haptic systems, this standard is probably also useful to assess security requirements for the intended application of the system.

ISO 13485, **ISO 14971**, **IEC 62366**, **IEC 60601** The ISO 13485 standard defines the requirements on the general design and production management for medical devices, while the ISO 14971 standard deals with the application of risk management tools in the development process of medical devices. One has to note that these standards are a good starting point for devices intended for the European market, but further rules and processes of the ↪ Food and Drug Administration

(FDA) have to be considered for products intended for the American market. The IEC 62366 deals with the applicability of usability engineering methods for medical devices. IEC 60601 considers safety and ergonomic requirements on medical devices.

IEEE 830 This standard deals with the requirement specifications of software in general. It can therefore be applied to haptic systems involving considerable amounts of software (as for example haptic training systems). The general principles on requirement definitions (like consistency, traceability, and unambiguousness for example) from this standard can also be applied to the design of technical systems in general.

Since a large number of haptic systems are designed for research purposes and used in closely controlled environments, safety requirements are often considered secondary. One should note however, that industry standards as the ones mentioned above resemble the current state of the art and could therefore provide proven solutions to particular problems.

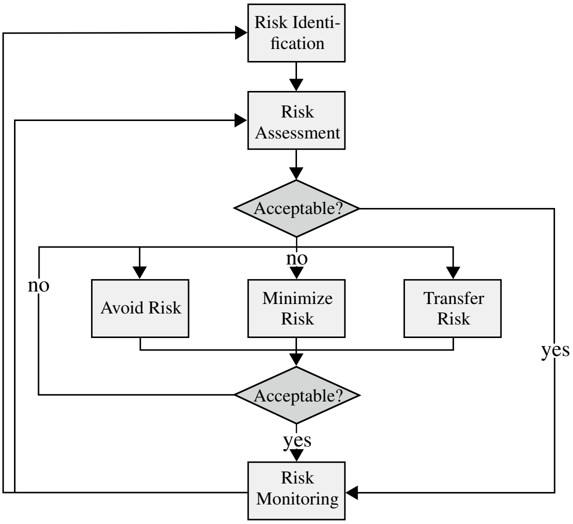
5.4.2 Definition of Safety Requirements from Risk Analysis

As mentioned above, modern safety standards will not only define certain requirements (like parameters of electrical grounding or automatic shut-down of certain system parts), but have also an impact on the whole design process. To derive requirements for the haptic system, the following steps are advisable during the design process:

1. Assess the relevant safety standards for the intended application and usage of the haptic system. Despite the standards itself, this also includes further regulations and applicable test cases.
2. Define your safety management and development process including project structure, needed certifications, documentation requirements and the life-cycle management.
3. Conduct a risk analysis and derive technical requirements from the results.

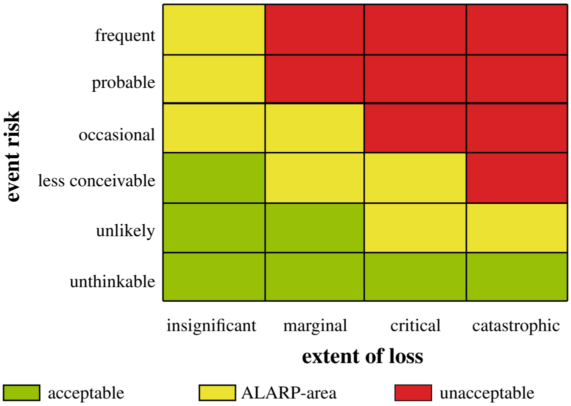
Figure 5.4 shows the general risk management flowchart. Based on a risk identification, a risk assessment is made to evaluate the failure occurrence and the severity of the consequences. There are two approaches to identify risks. In a bottom-up-approach, possible failures of single components are identified and possible outcomes are evaluated. This approach can be conducted intuitively, mainly based on the engineering experience of the developer or based on a more conservative approach using check-lists. On the other hand, a top-down-approach can be used by incorporating a ↪ Fault Tree Analysis (FTA). In that case, an unwanted system state or event is analyzed for the possible reasons. This is done consecutively for these reasons until possible failure reasons on component level are reached. In practice, both approaches should be used to identify all possible risks.

Fig. 5.4 General risk management flowchart



For each identified risk, the failure occurrence and the severity of the consequence has to be evaluated. Especially for hardware components this is a sometimes hideous task, since some occurrences cannot be calculated easily. Based on these values, a risk graph can be created as for example shown in Fig. 5.5. Acceptable risks do not require further actions, but have to be monitored in the further development process. Risks considered to be in the ↪ As Low As Reasonably Practicable (ALARP)—area are considered relevant, but cannot be dealt without an abundant (and therefore not reasonable) effort. Risks in the non-acceptable area have to be analyzed to be at least transferred to the ALARP-area. Please note that the definitions of the different axis in the risk graph and the acceptable, ALARP and non-acceptable area have to be

Fig. 5.5 Example of a risk graph



event risk	insignificant	marginal	critical	catastrophic
frequent	🟨	🟥	🟥	🟥
probable	🟨	🟥	🟥	🟥
occasional	🟨	🟨	🟥	🟥
less conceivable	🟩	🟨	🟨	🟥
unlikely	🟩	🟩	🟨	🟨
unthinkable	🟩	🟩	🟩	🟩

🟩 acceptable 🟨 ALARP-area 🟥 unacceptable defined for each project or system separately based on the above mentioned standards or company rules.

For each risk, one has three possibilities to deal with the risk, i.e. move it into more acceptable areas of the risk graph:

- First of all, risk can be avoided. If a piezoelectric actuator is used for a tactile application, the user can be exposed to high voltages, if the isolation fails. One can avoid this risk, if no piezoelectric (or other actuator principles) with high voltage demands are used.
- Secondly, the risk can be minimized. In the above mentioned example this could be an additional electrically insulating layer with requirements on breakdown voltage, mechanical endurance and surface texture properties.
- The third possibility is to transfer a risk. This principle is only applicable in a restricted way to the design of haptic interfaces. A possible example would be the assignment of the development of a certain sub-contractor to minimize the technical risks of the development.

After each risk is dealt with, the acceptability has to be evaluated again, i.e. the changes in the risk graph have to be analyzed. Obviously, moving risks into lower-risk regions will consume effort and costs. This considerations can lead to ethical dilemmas, when severe harm to humans has to be weighted against financial risks like damage compensations. For this reason, ↪ ALARP classifications for economical reasons are forbidden by ISO 14971 for medical devices starting with the 2013 edition.

The evolution of risks has to be monitored throughout the whole design and production process of a system. If all steps involved are considered, it is obvious that the design of safe systems will have an significant impact on the overall development costs of a haptic system and a thorough knowledge of all components is needed to find possible risks in the development.

5.5 Requirement Specifications of a Haptic System

The defined application together with the assumption from the customer and the interaction analysis will allow to derive individual requirements for the task-specific haptic system. These system requirements should be complemented with applicable safety and other standards to form a detailed requirement list. This list should not only include a clear description of the intended interactions. Also the intended performance measures (Chap. 13) and as much technical details as possible about the overall system and the included components should be documented. As stated above, the technical solution clusters shown in the preceding Sect. 5.3 will also give possible requirements depending on the intended class of applications.

Table 5.1 Example of a system specification for a haptic device

R/W	Description	Value	Source/Comment
Especially kinaesthetic-motivated parameters			
R	Number of DOFs	2x rot., 1x transl.	Shall give an idea of DOFs, name them!
R	Workspace	$100 \times 50 \times 50\,\text{mm}^3$	Minimum of workspace to be achieved
W	Maximum Workspace	$150 \times 100 \times 100\,\text{mm}^3$	Maximum workspace necessary
R	Maximum force in DOF “name”	5 N	
W	Maximum force in DOF “name”	7 N	Always define a range of forces!
R	Minimum force in DOF “name”	0.2 N	
W	Minimum force in DOF “name”	0.1 N	Always define a range of forces!
R	Maximum dynamics (bandwidth) for DOF “name” in a blocked situation	100 Hz	Shows (among other things) e.g. the maximum dynamics of the driver electronics
W	Maximum dynamics (bandwidth) for DOF “name” in a blocked situation	200 Hz	Shows the bandwidth the customer dreams of
R	Smallest border frequency when movement is blocked	static	There may be applications with pure dynamic movements without a static portion. This makes this question interesting
R	Maximum velocity of movement in idle mode	10 mm/s	This is a question regarding security too, as it defines the mechanical energy stored in the system
R	Maximum bandwidth of the velocity change	10 Hz	The change of velocity, which is the acceleration of the system, has a large influence on the energy the system requires
R	Maximum haptic impedance at the output	10 Ns/m	This is an alternative representation to the independent definition of force and velocity for dynamic (but passive) systems!
R	Minimum haptic impedance at the output	0.01 Ns/m	This is an alternative representation to the independent definition of force and velocity for dynamic (but passive) systems!
R	Smallest position resolution/measurement insecurity for DOF “name”	0.1 mm	Usually measurement of the position is self-evident for haptic interaction
W	Smallest position resolution/measurement insecurity for DOF “name”	0.05 mm	
R	Type of the mechanical interface	Button/pen/none	Is there a handle?
R	Mechanical reference point	Grounded, worn	Has influence on weight, size and energy
R	Direction(s) of the tactile stimulation	Normal to the skin	An alternative would be lateral stimulation or a combination of both
R	Maximum displacement-amplitude of the tactile elements	1 mm	Is especially relevant for pin-displays, but may be also understood as oscillation-amplitude of vibrational elements

(continued)

Table 5.1 (continued)

R/W	Description	Value	Source/Comment
Especially tactile motivated parameters			
R	Minimum amplitude resolution of displacements	Digital (on/off)	May include several levels for the pin to be moved to
R	Highest density of stimulation	2 mm distance from midpoint to midpoint	Varies extremely in dependency from the chosen skin area in contact
R	Maximum geometrical size of stimulation	2 mm diameter	
R	Maximum frequency range of stimulation	100 to 300 Hz	Relevant for tactile actuators only, of course
R	Minimum frequency-resolution	1 Hz	For vibrotactile actuators
R	Maximum force during displacement/stiffness	20 N	Pin-based actuators may not necessarily be stiff. Systems of lower admittance may be used too
R	Connection to the user	Attached to the environment / worn	Necessary to identify, whether there is a relative movement between skin (e.g. finger) and the display
R	Maximum number of fingers simultaneously in contact with the device	1–10	May have an large impact on the design when for example full-hand exploration is required
Digital interface			
R	Minimum resolution of the output data	12 bit	Usually slightly lower than the measurement error of force- and position-measurement
R	Minimum resolution of the input data	12 bit	Usually slightly larger than the resolution of force- and position input-data
R	Frequency of the haptic loop	1000 Hz	Should be at least two times, better would be 10 times, larger than the border frequency of the design. Has influence on the perceived stiffness
W	Other interface-requirements	Use USB/FireWire...	Typically the interface to be used is subject to company politics
R	Interface driver	API	As any other hardware a haptic interface needs an own software driver for abstraction
General parameters			
R	Maximum temperature range for operation	10–50c	May become very relevant for actuator principals with little efficiency in extreme environments (automotive)
R	Maximum volume	$500 \cdot 500 \cdot 200\,\text{mm}^3$	Device-size
R	Weight	1 kg	Especially relevant if the device is worn. This limit will strongly influence the mechanical energy generated
R	Electrical supply	Battery/ 110V/ 230V	Very important, devices were spotted on fairs, which ceased to function due to errors made when considering AC voltages of different countries
R	Maximum power	50 W	Primary power consumption including all losses

Table 5.1 will[7], [8], [9] give an example of such a requirement list with the most relevant technical parameters of a haptic system. However, it is meant to be an orientation and has to be adapted to the specific situation by removing obsolete entries and adding application specific aspects.

Additionally a system specification includes references to other standards and special requirements relating to the product development process. Among others, these are the costs for the individual device, the design-process itself and the number of devices to be manufactured in a certain time-frame. Additionally the time of shipment, visual parameters for the design, and safety-related issues are usually addressed.

5.6 Haptic Design of Mechanical Controls

Chapter 4 described the use of simulation is of advantage regarding development time and effort. The following chapter shows basic relations between technical parameters and subjective behavior of rotary and translatory switches. This chapter is a "how-to" guide regarding how haptic systems could or should feel like, and how ideal haptical designs can be reached. Starting with the rotary switches that describe and explore haptical characteristics, the turnover to the push buttons is done, showing the influences and differences deriving out of the event based perception that plays an important role in the haptical design of devices. The overall content relies on the Dissertation of [24].

5.6.1 Rotary Switches

Typically, rotary devices are described by a torque versus angle description. Due to the remaining shear forces on the finger tips it makes sense to derive these forces as a reference level to get a uniform force level dealing with different knob diameters ($F_{\text{shear}} =$ torque $\div$ ½ diameter). To be clear about what devices we are talking about and furthermore being the standard for rotary devices we use torque instead of shear force. Figure 5.6 shows the structure of a mechanical rotary switch.

A spring-driven tappet is affecting the cam disc with torque. The shapes of the cam disc and the tappet are defining torque over position which are the major parameters defining the haptic behavior of the system. The spring itself is in general "just"

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[7] R: requirement, W: wish.

[8] The combination of requirements and wishes (R and W) may be used for almost any element of the system specification. It is recommended to make use of this method, but due to clarity in the context of this book this approach of double-questions is aborted here.

[9] A "haptic loop" is a complete cycle including the output of the control-variable (in case of simulators this variable was calculated the time-step before) and the read operation on the measurement value.

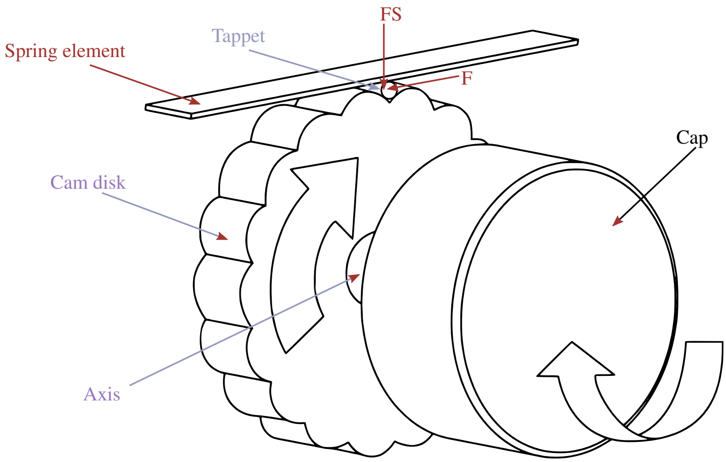

Fig. 5.6 Mechanical setup of a rotary switch [24]

relevant for the overall torque level. Therefore, the main haptical behavior is defined by the cam disc and the tappet while the force level can be adjusted with the spring parameters. Additionally, strongly influencing is the friction and it needs to be considered in a general level not to influence the system negatively. Even the construction of the system influences this particular parameter strongly.

5.6.1.1 Rest Position and Transition Point

The most important issue is the orientation within the torque characteristics. Figure 5.7 shows a simplified characteristic curve without the influence of friction.

The torque versus angle characteristics is not intuitively readable. For example, the rest position of the switch often interpreted to be in a local minimum of the curve. Of course, when looking at the details, the rest position is located in a zero

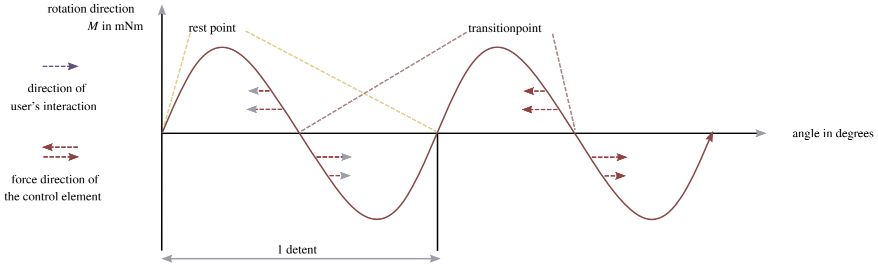

Fig. 5.7 Simplified characteristic curve without friction, showing the basic points for orientation as well as the directions of the user interaction and the force directions

torque position, otherwise it might move due to the remaining forces. Due to the effective direction of movement, resulting out of the torques' sign, a positive torque for example moves the knob to the left/clockwise, while a negative torque moves it to the right/counterclockwise.

Two specific points remain out of this in the zero-crossings of the curve: Thus if both torques, positive and negative, point to a zero-crossing, this point will be stable and become a rest position, where the switch will remain in, until it is forced to move out by external (user) forces. The second type is the opposite. Both torques point away from the zero-crossing, so a little deviation from the zero torque level leads to an increasing torque pulling the knob away from it. That is why it is not a stable position like the rest position, typically actively leading the knob from one stable position to the next and we call it the transition point. This is the typical "changing point" where the user recognizes the physical barrier also called "detent" and its change from one position to the next.

Concluding a rising zero crossing's flange typical is a rest position while a falling flange's zero-crossing is the transition point of the curve.

5.6.2 Friction

While the shape of the curve is relevant for the overall feeling (the "how" the device is moving from one position to the next), the friction is an add-on parameter which affects that overall feeling and the operation of the device. High friction makes the device feel dull and the detents are becoming imprecise, while low friction can cause beating and vibration of the device when snapping into the rest position. Regarding operational issues, a high amount of friction can lead to a sticking of the device at the transition points. Therefore, the remaining spring force becomes too low to move the device out of these positions. This situation can lead to undefined states, where the device remains stuck between two defined positions. Of course, one could cause this to happen intentionally. This may be relevant for security issues and a steep flange may avoid it, at all, unfortunately contrary to a "good feeling".

What happens to the characteristic curve: friction is shifting it vertically, increasing the perceived forces, and because friction is always directing against the control's movement, it causes a hysteresis of the measured curve. In short, low friction has a small hysteresis, and high friction a big hysteresis.

The friction value can be derived from the delta of the hysteresis $F_{\text{friction}} = ½F_{\text{Hysteresisdelta}}$.

The frictional effects described before can be compared to a static offset as shown in Fig. 5.8, mostly generated by the bearings and additionally, by varying amounts, by the tappet and cam disc.

Even the friction between tappet and cam disc shows some very specific behavior that can help to identify the frictional source in a component. The relation of diameters of the knob and the cam disc or the bearing are quite relevant for the influence of the added friction and can be a possibility to influence it efficiently.

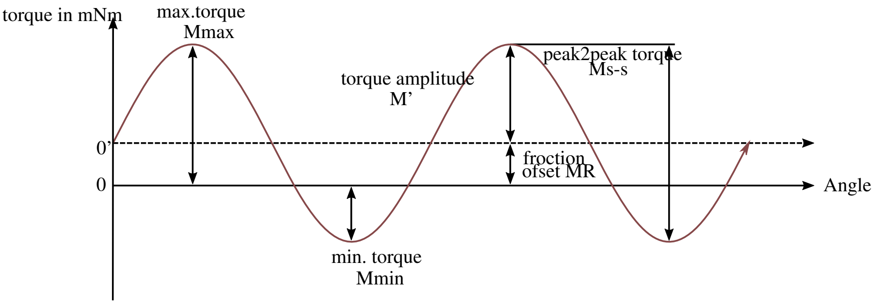

Fig. 5.8 Friction offset of a right turn characteristic curve, without showing a hysteresis

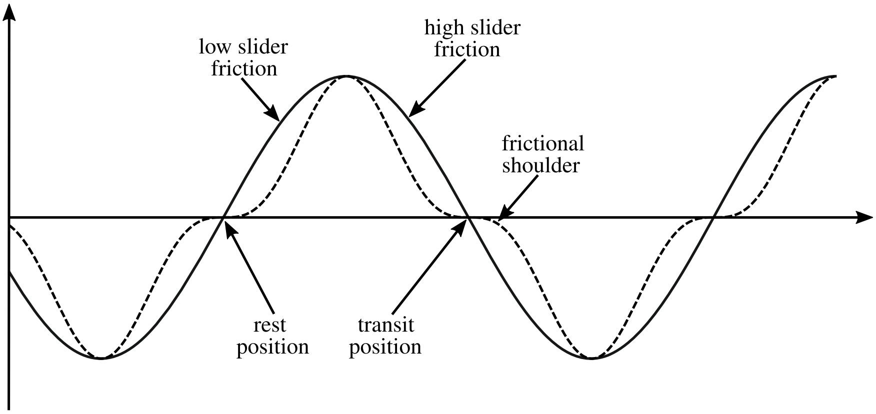

Fig. 5.9 Friction influence caused by slider and cam disc

So how does this friction influence the curve additionally: The friction between tappet and disc is not constantly. While a flat cam disc gradient typically increases the frictional influence, the gradient of the spring plays also an important role. Furthermore, a more compressed spring leads to a higher spring force and a higher friction. Therefore, a steep gradient has comparably low friction.

All the zero crossings, i.e. the rest position and the transition point, typically have a high friction. For the rest position, this is not critical, but for the situation of a standing still in the transition point, as previously described, it is an unwanted thing.

Figure 5.9 shows the impact of this kind of friction, leading to a flatting of the characteristic curve at the zero-crossings, which we call "frictional shoulders". This effect is very practical for identifying the sources of friction during development of devices by measurement.

5.6.2.1 The Integral-Representation

As mentioned before, the intuitive readability of the torque-characteristics is not given. Thus the question if there is an intuitive representation is answered in [26] and [24] describing the integral representation. It shows that the integration of torque-angle characteristics leads to an intuitively readable description. It is possible to describe the behavior of the device as well as a basic mechanical derivation of the cam disc with this principle. The big advantage of this description is the intuitive readability of the "shape". This helps to divide between important and unimportant parameters and indicates the location of problems intuitively. This makes development much more efficient. Equation (5.1) shows the basic mathematical description of the integral representation.

$$I(\varphi) = \int\limits_{\varphi_1}^{\varphi_2} M(\varphi)\,\mathrm{d}\varphi \tag{5.1}$$

To prove the hypothesis, [24] executed several tests. Figure 5.10 shows examples of basic characteristics displayed by a haptic interface to the subjects. The diagrams on the left show the torque representations and those on the right show its associated integral representation. The subjects had to choose the intuitively fitting representation. Significantly, the subjects selected the integral representation. As an example, against all expectations regarding the torque representation the sine (a) and triangle (b) characteristics both feel comparably smooth and more "sine-like", even the triangle a little "weaker" than the sine. The triangle expected to be crisp and sharp, and absolutely did not fulfill any of those expectations.

The integral representation shows a fitting picture: the integrated sine-shape results in cosine and the integrated triangular shaped results in parabolic shapes that are very similar to the sine shape. In addition to this, the area under the triangle is smaller than the sine and its maximum is slightly lower than the sine in integral representation that fully fits to the derived results out of pair comparison studies.

Another Example, the saw tooth shapes expected to be one-sided sharp are fitting well with the integral representation describing the behavior very intuitively. Finally, the square shape leads to a triangular feeling, also represented correctly by the integral.

5.6.2.2 Identification of Parameters for Rotary Haptic Devices

Knowing the integral representation is the basis for identifying relevant parameters, because the transformation helps understanding the perceptional influence. Due to technical reasons, the torque representation is still the describing low-level representation and used for the overall parametrization. The chosen torque parameters shown in Fig. 5.11, which are mainly the rising and falling slope of a rectangular shape.

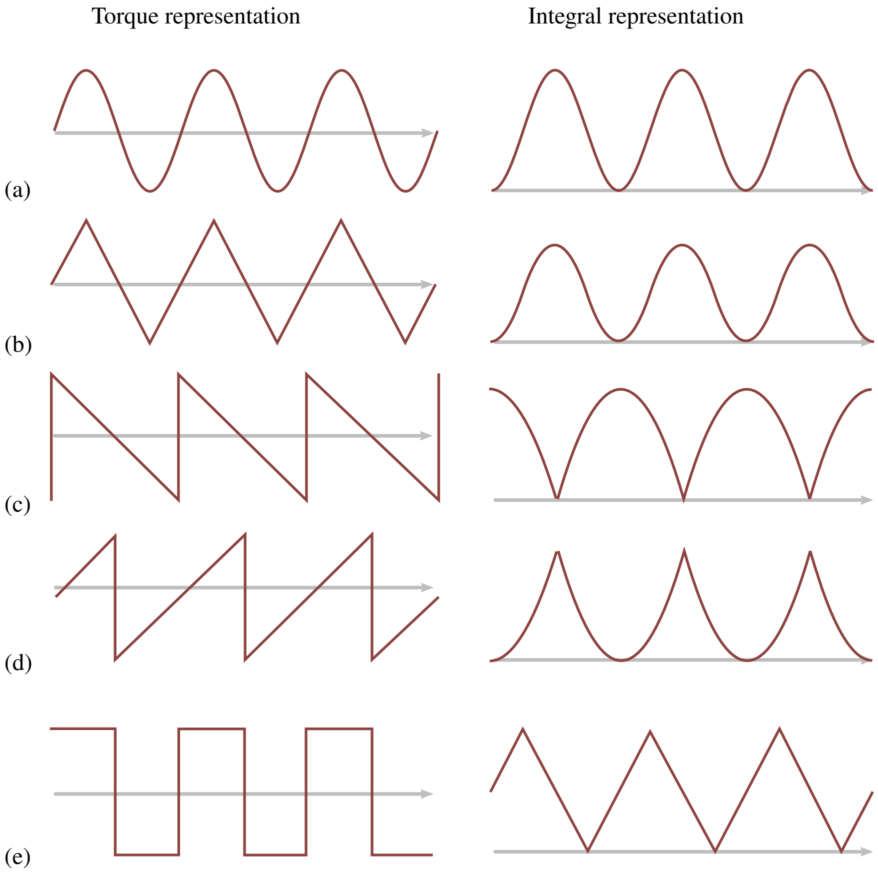

Fig. 5.10 Shapes that were represented by [24] to the subjects to identify the intuitive way to represent haptical feelings graphically

Changing their steepness independently can convert it to the entire shapes shown in Fig. 5.10 that pointed out to be the most relevant ones. The amplitude appeared to be an overall parameter not influencing the character/feeling of the shape. Its influence is the overall force level or resistance, which allows using it to adjust the ease of movement without changing the basic character of the effect.

To identify the parameters and their influence, the different characteristics presented to subjects on the haptic display for rotary switches. Questionnaires as well as pair-comparison tasks helped to identify and quantify the parameters. Figure 5.12 shows the variety of the presented parameters in integral representation. Looking at the rest position, the "width" or "precision" of the device presented quite realistically. Relations to the adjectives shows a steep rising slope at the rest position increases the precision and hardness, while a steep falling slope at the transition point reduces controllability and increases the hardness. The integral representation displays this

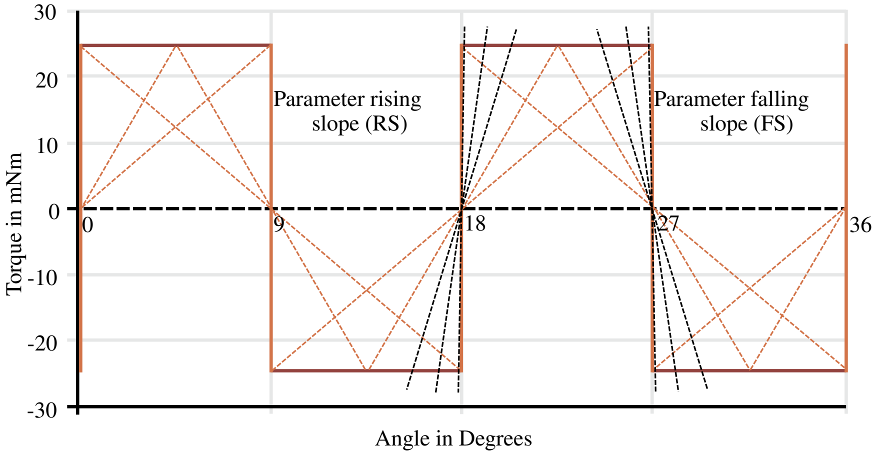

Fig. 5.11 Variation of torque-parameters used for the haptic representations [24]

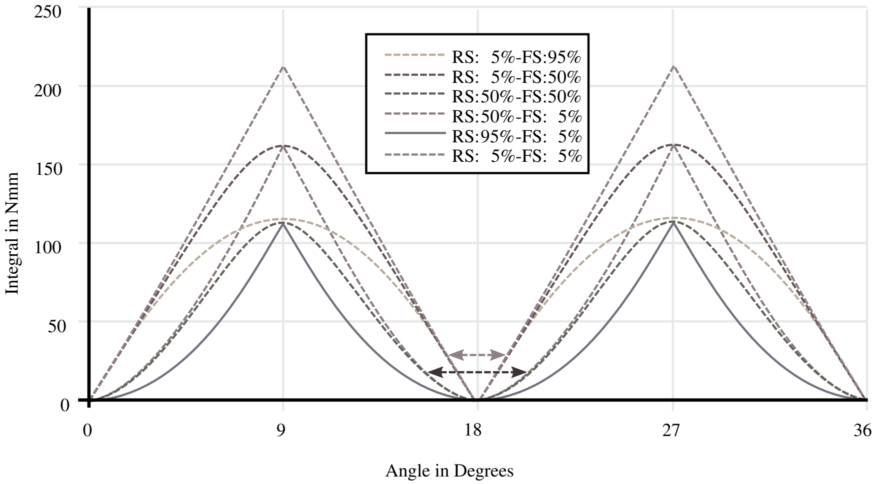

Fig. 5.12 Integral representation of the varied haptic representations [24]

in the width of the rest position, i.e. more precise when it is narrow and less precise when it is wide. Moreover, the transition point is controllable when a round shape leading to the next position given, while it is not controllable when the shape is forming a sharp peak.

Bringing all parameters together, the period that describes the "length" of the detent and the force amplitude, the slopes at the rest position and the transition point are the main parameters of the subjective impression.

Thus, the steepness of the rising slope influences the impression of a precise rest position, where 5% slope was showing the best precision.

The hardness influencing by both flanges. The steeper both are, the harder the impression. Furthermore, the area under the integral representation seems to behave proportionally to the hardness impression. The rising flange of 5% and the falling flange of 50% concluding to be an ideal pairing.

Combining both slope parameters means increasing the precision by the rest position's slope that automatically increases the hardness effect. The falling transition point's slope only affects the hardness.

The falling slope furthermore influences the controllability and the willingness of the device. Thus, a steep falling slope shows a bad controllability of the switch. Explaining it with the hard change of the torque at that point, when the device is working against the user's movement until reaching the transition point. At this position, it suddenly changes its sign suddenly pulling the knob into users moving direction. The steeper the slope the stronger the change. Also, out of a control theories' point of view a very difficult task to handle.

The amplitude of the overall signal is just proportionally influencing the overall impression, but not changing the relations between the adjectives.

The length of the detent influences the signals overall impression also strongly. A reduced angle reduces the influence of the parameters, comparable to a reduction of the resolution because no parameters angles are reducing, not representing flat slopes anymore.

5.6.2.3 Asymmetry

One very specific "trick" is the use of asymmetric characteristics. Figure 5.13 shows the torque representation where the area under the curve is bigger at the left turn than at the right turn by different angles, at all, requiring more energy to overcome. Figure 5.14 shows the integral representation thus the subjective behavior of the device clearly by a curve descending to the right side.

An example of an active electromechanical rotary input device described by Audi patent [25]. The advantage of this specific asymmetric behavior is, it generates the illusion of a descending direction, but using the whole bandwidth of an actuator for every detent. It is not requiring a higher torque bandwidth to decrease the detent's torque between each detent to generate a decreasing impression. Because the asymmetry in energy is providing this feature. Furthermore, the angular range is without any limits, it is possible to descend indefinitely. As mentioned, the classical strategies need a reduction of the torque for each detent, so that the whole range limited by the bandwidth of the actuator and only a part of the overall torque of the motor used to generate the detents torque difference.

An example of passive mechanical haptics would be the Mercedes-Benz Light switches that have been using an asymmetric characteristic in the market since 2012. Describing the use of asymmetry in [8] for creating a haptic barrier between the parking and the driving light sections to make operation more intuitive.

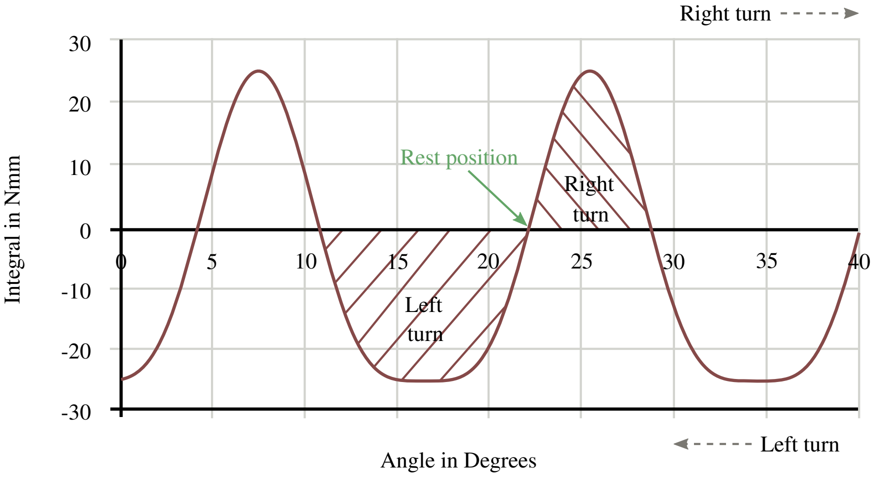

Fig. 5.13 Asymmetric torque characteristic with angular asymmetry [24]

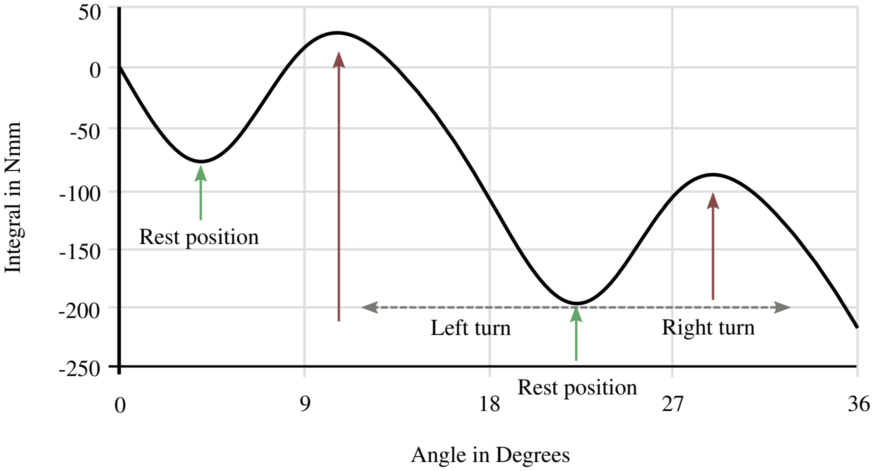

Fig. 5.14 Integral representation that intuitively shows the behavior of the asymmetrically designed control element [24]

5.6.2.4 Construction of the Cam Disc

The basic development of a haptic characteristic using the integral characteristics as an intuitive guide described before. As previously mentioned, the integral relation also serves as a guideline in designing and constructing the mechanical shape of the cam disk and the tappet itself.

Derived out of the basic mathematical description of the Integral representation $\frac{I(\varphi)}{\mathrm{d}\varphi} = M(\varphi)$ the gradient of the cam shape is proportional to the Torque M. We are considering the following elements: the shape of the cam disk, the shape of the tappet, the frictional pairings, and the stiffness and pretension of the spring element. The radius between rotational center and the contact point between the tappet and the cam disk are relevant as well as the radius of the end effector/cap where the finger is grasping.

The gradient at the contact point is nothing more than the derivation of the cam shape, so the relation between shape and force is the required angle α of the shape resulting in the specific force F_{finger} at this point. The gradient angle α of the cam in the contact point calculated as shown in Eq. (5.2). It is a simplified version to explain the basic principle:

$$\alpha = \frac{1}{2} \arcsin\left(2 \cdot \frac{F_{\text{finger}}}{c_{\text{spring}} \cdot l_{\text{spring}} + F_{\text{spring0}}} \cdot \frac{r_{\text{finger}}}{r_{\text{cam}}}\right) \tag{5.2}$$

Equation (5.2): calculation of the gradient α at position φ out of the required finger force $F_{\text{finger}}(\varphi)$ at position φ or of course its torque $(M_{\text{finger}}(\varphi) = F_{\text{finger}}(\varphi) \cdot r_{\text{finger}})$
The parameters of Eq. (5.2) are:

α	Gradient angle of the cam
$F_{\text{finger}}(\varphi)$	wanted force at the finger at position (φ)
M_{finger}	torque at the finger
c_{spring}	spring constant, estimated as constant
l_{spring}	length of the spring; estimated as constant
F_{spring}	spring pre-tension at zero length (l_0)
c_{spring}	spring rate
r_{finger}	radius at finger contact point; estimated as constant
r_{cam}	radius at tappet contact point; estimated as constant, but maybe varying across φ

5.6.2.5 Correction of the Tappet Geometry

The calculations consider a point-contact between tappet and cam with a tappet-diameter of "ZERO" which is quite unrealistic. Especially smaller sized systems are strongly influenced by the tappet. Therefore, the radius of the tappet causes a shift of the contact point as shown in Fig. 5.15.

A very simple principle to consider the influence partly should also show how the correction might take place. Equation (5.3) describes the shift in angular direction to be considered as well. In addition, considering the vertical influence of the shift not described here.

$$s_v = r_{\text{tapped}} \cdot \sin(\alpha) \tag{5.3}$$

Equation (5.3): Correction of the contact point caused by the tappets' radius r_{tappet}

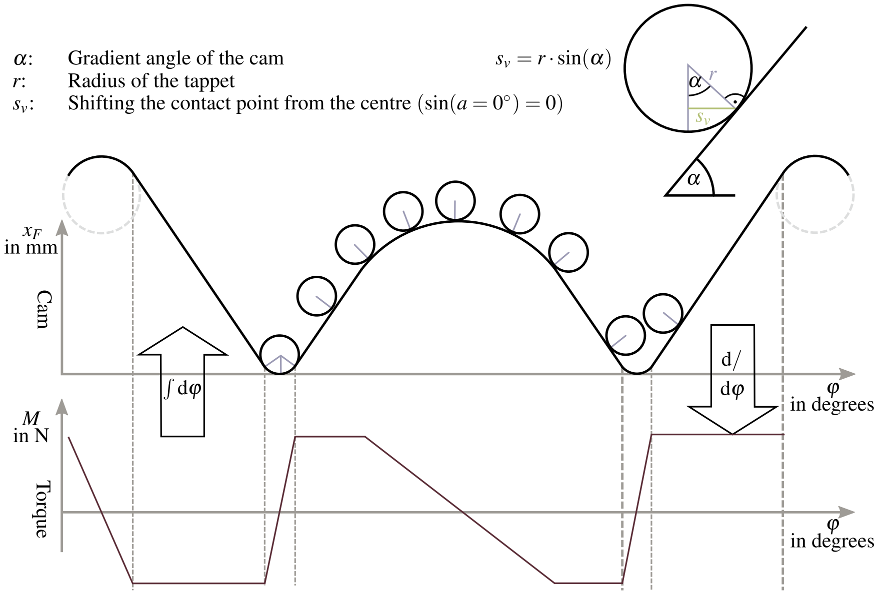

Fig. 5.15 Principle of the tappet's influence on the cam construction and the principle of the relation between gradient of the cam shape and the torque characteristic

5.7 Push Buttons

The second large group of control elements are push buttons. The differences between translatory (push) and rotary controls are quite strong: the linear movement is dominant, characteristic curves of force-travel look different in addition to the behavior, as well as the use case (positioning vs. activating) and the mechanical principle behind it. A closer look at the details indicates that the principles and description are quite different, but anyway are still compatible. The differences appear in the technical ranges and the type of psychophysical stimuli being useful in both domains. Even help understanding (vibrotactile) active haptic systems more clearly.

5.7.1 Characteristic Curve

The typical characteristic curve of push buttons, describing force versus travel (Fig. 5.16), is comparable to the rotary torque versus angle/travel characteristics.

A basic characteristic of the push button is having a single rest position. This rest position needs to be reached by the push button's mechanics on its own, because, due to the cap's geometry, the user cannot typically bring it back there. In principle, the user is positioning the rotary switch to a specific detent. That is why the rotary switch might not return to the same position, it also can move to the next one. This explains why it typically has several zero crossings and transition points. Compared to this, the user can control the push button only in the direction of the push. The device always needs to provide a force working backwards into the direction of the rest position to be able to return to it. Maybe you had already the experience with a hanging button; it is difficult to get the cap returning to the rest position. For this, the force always needs to be positive, or due to friction even higher. So the typical characteristic curve is located in the first quadrant, while the rotary curve typically occupies the first and second, or even all four quadrants.

There is a difference between the measurement points and a typical specification, because the measurement probe first has to approach the cap before the measurement starts. That is why the measurement probe does not see the relevant force until contact. Therefore, the measurement characteristics show a travel until contact at zero-force and no negative forces that would push the button into the rest position while pulling the cap (compare Fig. 5.16). Compared to this, the specification even needs to define this behavior as well, to keep it stable and not jiggling. The origin of Fig. 5.17 shows exactly that behavior where the curve passes the zero level continuing with the same steepness into negative force to generate a stable rest position. In this point, we can see a comparable behavior like the rest position of rotary switches.

5.7.2 The Snap

Looking at the push buttons characteristic its most important parameters are describing the snap and its position. It is the relevant event communicating to the user that his goal, the activation of the function, has been reached.

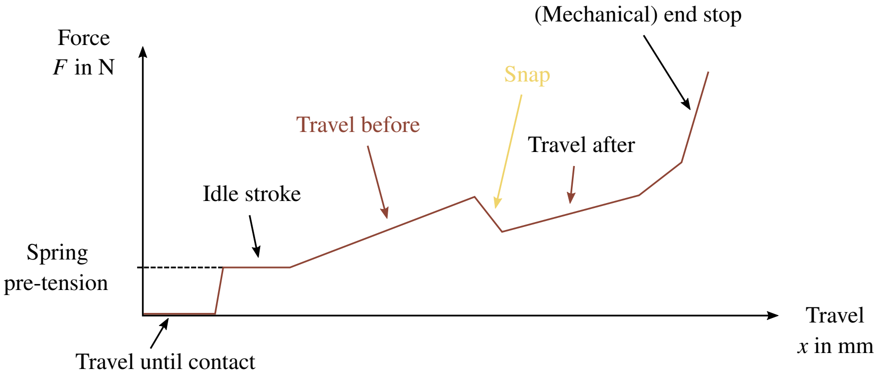

Fig. 5.16 Typical segments of a force-travel characteristic curve of a push button appearing during measurement

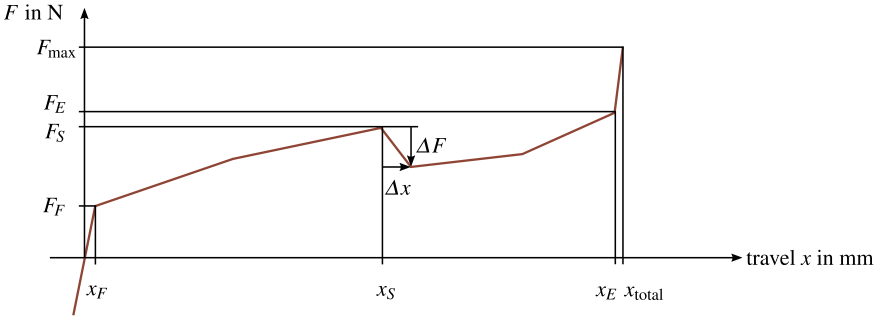

Fig. 5.17 Basic force travel parameters of push buttons without frictional hysteresis

The snap is the falling flange seen in the force-travel depiction. Typically, vertices, also, the snap's ending points, they all refer to the point of origin because of measurement practice. The perceptional point of view shows that considering steepness and height of the flange as a relative definition of the snap is a much better choice. The tolerance ranges can even result in much higher production efficiency, because the factors that affect the overall perception less can be assigned lower tolerance levels.

For example, even if the switching point (F_S/x_S) is moving in $x-$ or $F-$ direction, the snap may remain of the same haptic quality. Therefore, $\Delta F/F_S$ and Δx are the parameters to focus on /to prioritize. Figure 5.17 shows the parameter set.

The tests conducted on the psychophysics of rotary controls repeated for push buttons show that besides the subjective parameter estimation, some further interesting effects presented themselves. While flat and longer snaps showed a comparable rating to the rotary controls, steep and short snaps received a very different rating from the subjects.

F_F/x_F	Spring pre-tension
F_S/x_S	Actuation point
$\mathrm{d}F/\mathrm{d}x$	Snap
F_E/x_E	Start of the mechanical end stop
$F_{\max}$	Maximum force Level
x_{total}	Total travel at $F_{\max}$

5.7.3 *Event-Based Perception*

This observed difference in perception fits perfectly to the phenomenon of event-based perception described in [13] and approves it for the use of linear control elements.

Looking at a measurement, force versus time in Fig. 5.18 shows two haptic events snap and back-snap. Both show a strongly dampened vibration, having the ability to stimulate even Pacinian mechanoreceptors that are sensitive to high vibrotactile

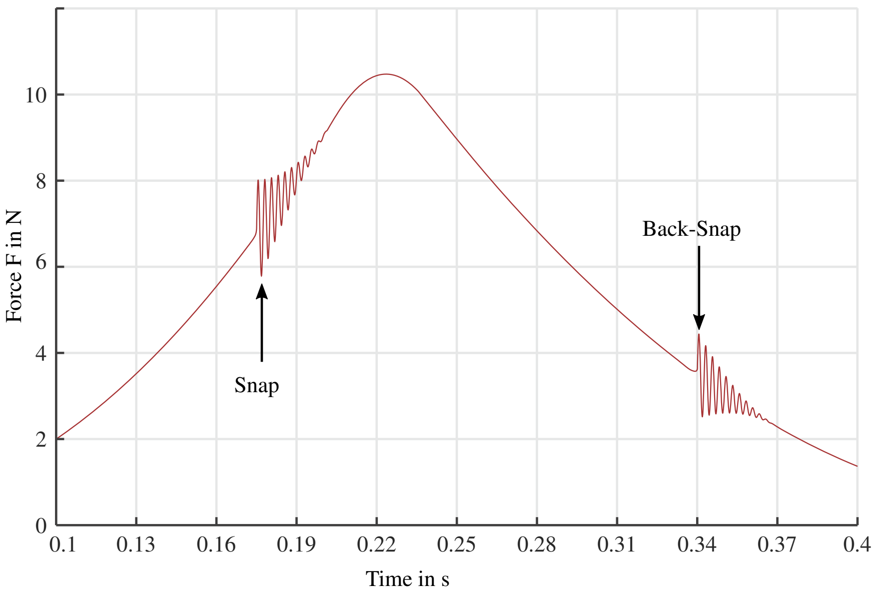

Fig. 5.18 Dynamic snap and back-snap of a push button force versus time

frequencies and acceleration. They may also be able to activate reflexes. In this sense, sharp snaps like micro switches activate a reflex-like perception, just saying "Hi—here was something", while long snaps are perceived to be more explorative, showing greater detail like a shape or resistance, or more visually spoken like a smooth or a long "hill" of the controls behavior showing more detail and catching more attention by exploration.

Concluding, the kind of the snap provides either a reflex-like quick or a detailed shape-like event of different content, speed and mental load.

5.7.4 Relevance of the Probes' Impedance

In conclusion, this event-based perception mechanism shows that the classical approach of the force versus travel description does not show up all information being necessary. Therefore, if vibrations appear within a characteristic curve, an interpretation of those vibrations is essential. Zhou et al. [34] explains an Interaction-based Dynamic Measurement principle (IDM) measuring with a human finger-like probe analyzing the specific vibrations due to subjective impressions. He found that the mechanical impedance of the finger is of high importance to allow realistic vibration of the event, lying in the working point. If it deviates, it will appear as a vibration differing from reality. The common impedance range of a probe goes from a stiff static probe to no-probe-influence. The former stiff one suppresses nearly all vibrations, thus only Zero-Hz-Frequencies—such as static forces—remain in the measurement data while the latter contactless one does not affect the device and allows it to vibrate at its natural frequency, for example measuring with a laser vibrometer.

If a probe or human finger were in contact with the device, it will put it out of tune. For this reason, it makes sense to use a probe with a comparable mechanical impedance such as a human finger. More details regarding IDM in Chap 14. A comparable approach with a different goal *Syntouch* is realizing [1]. They are mimicking a human fingertip to quantify surface haptic properties like identification of materials and their haptic dimensions [33]. It includes besides specific mechanical impedances the surfaces' fingerprint to get the system at a realistic working point.

Recommended Background Reading

[13] Kuchenbecker K.J. & Fiene J. & Niemeyer G.: **Improving contact realism through event-based haptic feedback**. In: IEEE Transactions on Visualization and Computer Graphics, vol. 12, no. 2, pp. 219–230, March-April 2006, doi: 10.1109/TVCG.2006.32
A key paper describing the origins of enhancing contact sensations by high-dynamics haptic accelerations. Inspiration for many researchers and still valid in its fundamental approach for many teleoperation-systems.

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Reviews the effect measures of several evaluation of VR and teleoperation systems. Recommended read for the design of haptic interaction in teleoperation and VR applications.

[14] Magnusson, C. & Brewster, S.: **Guidelines for Haptic Lo-Fi Prototyping**, Workshop, 2008.
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